SECTION I

SWITCHGEAR AND SUB-STATION APPARATUS

1

Introduction

Significance—Energy Management System—Switchgear Protection and Network Automation—Power Systems—Network Phenomena—Normal and Abnormal Conditions—Faults-Fault clearing—Network Configurations—Switchgear—Circuit Breakers—Protective Relays —Substations—EHV AC Transmission Systems—HVDC Transmission Systems —Interconnected Systems—Load Flow Studies—Grounding of Neutrals—Transient Overvoltages and Surge Arresters—Static relays—Microprocessor based integrated protection and control—Power System Calculations—Load Flow Calculations—Computer and Microprocessor in Energy System Studies—Scope of Subject.

Significance of Switchgear, Protection and Power Systems

Electrical Energy Management system ensures supply of energy to every consumer at all times at rated voltage, rated frequency and specified wave form, at lowest cost and with minimum environmental degradation. The Switchgear, Protection and Network Automation are integral part of the Modern Energy Management System and National Economy. The modern 3 phase, 50 Hz, AC interconnected power system has several conventional and non-conventional power plants, EHV AC and HVDC Transmission Systems, Back-to-back HVDC Coupling Stations, HV Transmission network, Substations, MV and LV Distribution Systems, and Connected Electrical Loads. The energy in electrical form is supplied to various consumers located in a vast geographical area, instantly, automatically and safely with required quality at *all times*. The service continuity and high-quality of power supply have become very important.

Generation Planning, Transmission Planning, System Expansion, Installation, Operation Control and Maintenance of Electrical Energy Systems, Fault Calculations, Network Calculations, Load Flow Studies have become very essential functions of Modern Power Engineers. Switchgear and Controlgear are also essential with every power consuming devices at Utilization Level.

Switchgear and Protection/Control-Panels are installed at each *voltage* levels at each switching point for

(1) normal routine switching, control and monitoring and

(2) automatic switching during abnormal and faulty operating conditions such as short circuits, undervoltage, overloads.

The Computer Controlled Network Automation by Load Control Centre, Power Station Control Rooms and Substation Control Rooms and communication channels together ensures the Control of National and Regional Grids and control of Voltage, frequency, Power and waveform under prevailing and ever changing load conditions. This Text-Book covers the principles and practice in Modern Power Systems, *Switchgear. Protection, Fault Calculation. Load Flow Calculations and Computer Aided Energy Management Systems. This Chapter gives an Overview and the Scope.*

1.1. SWITCHGEAR AND PROTECTION

Everyone is familiar with low voltage switches and rewirable fuses. A switch is used for opening and closing in electric circuit and a fuse is used for over-current protection. Every electric circuit needs a switching device and a protective device. The switching and protective devices have been developed in various forms. Switchgear is a general term covering a wide range of equipment concerned with switching and protection.

A circuit-breaker is a switching and current-interrupting device in a switchgear. The circui breaker serves two basic purposes:

(1) Switching during normal operating conditions for the purpose of operation and maintenanc

(2) Switching during abnormal conditions such as short circuits and interrupting the fault cu rents.

The first function mentioned above is relatively simple as it involves normal currents whic are easy to interrupt. The second function is complex as the fault currents are relatively high an they should be interrupted automatically within a short time of the order of a few cycles. One cycl in 50 Hz system takes 1/50 second. There are several types of faults and abnormal conditions. Th fault currents can damage the equipment and the supply installation if allowed to flow for a long duration. In order to avoid such a damage every part of the power system is provided with a prote tive relaying system and an associated switching device. The protective relays are automatic devic which can sense the fault and send instructions to the associated circuit-breaker to open. The circu breaker opens and clears the fault. All equipment associated with the fault clearing process a converted by the term 'Switchgear'. Switchgear is an essential part of a power system and also tha of any electric circuit. In addition to circuit-breaker and protective relays, the associated equipme for controlling, regulating and measuring can also be considered as switchgear devices. Switchgea includes switches, fuses, circuits-breakers, isolators, relays, control panels, lightning arresters, cu rent transformers and various associated equipments.

Switchgear are necessary at every switching point in AC power system. Between the generatin station and final load point, there are several voltage levels and fault levels. Hence, in the variou

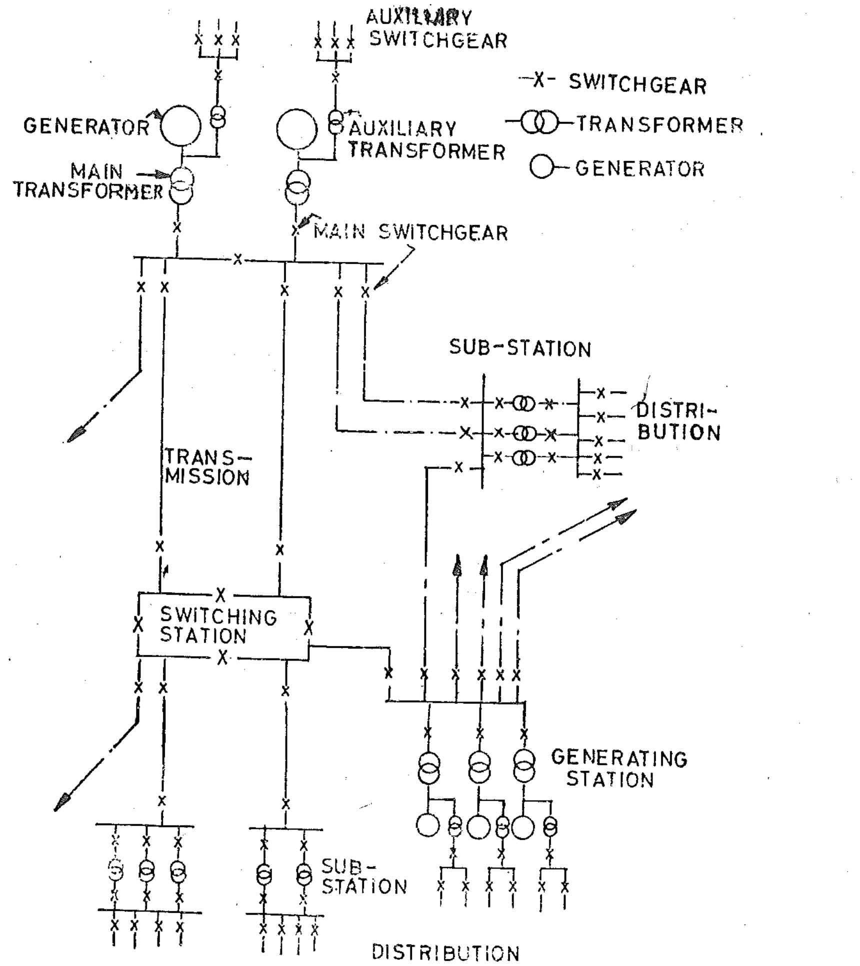


Fig. 1.1. Location of Switchgear in Typical Power System (Single line, simplified diagram).

applications, the requirements of switchgear vary depending upon the location, ratings and switching duty. Besides the supply network, switchgear is necessary in industrial works, industrial projects, domestic and commercial buildings. A *controlgear* is used for switching and controlling power-consuming devices.

1.2. SUB-STATION EQUIPMENT

In every electrical sub-station, there are generally various indoor and outdoor switchgear equipment. Each equipment has a certain functional requirement (Ref. Table 1.1). The equipment are either indoor or outdoor, depending upon the voltage rating and local conditions. Generally indoor equipment is preferred for voltages up to 33 kV. For voltage of 33 kV and above, outdoor switchgear is generally preferred. However, in heavily polluted areas indoor equipment may be preferred even for higher voltages. SF_6 Gas Insulated Substations (GIS) are preferred in large cities for voltages above 33 kV.

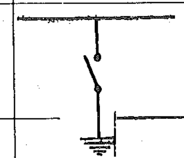
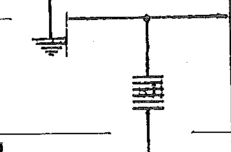
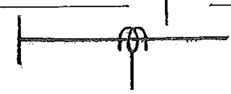
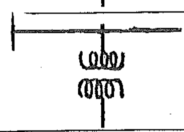
The outdoor equipment is installed under the open sky. The indoor switchgear is generally in form of metal enclosed factory assembled units called metal-clad switchgear.

Circuit-breakers are the switching and current interrupting devices. Basically a circuit-breaker comprises a set of fixed and movable contacts. The contacts can be separated by means of an operating mechanism. The separation of current carrying contacts produces an arc. The arc is extinguished by a suitable medium such as dielectric oil, air, vacuum, SF_6 gas. The circuit-breakers are necessary at every switching point in AC sub-station (Ref. Fig. 1.1)

Isolators are disconnecting switches which can be used for disconnecting a circuit under no current condition. They are generally installed along with the circuit breaker. An *isolator*, can be opened after the circuit breaker. After opening the isolator, the *earthing switch* can be closed to discharge the trapped electrical charges to the ground. The *current transformers* and *potential transformers* are used for transforming the current and voltage to a lower value for the purpose of measurement, protection and control. *Lightning arresters* (surge arresters) divert the over-voltages to earth and protect the sub-station equipment from over-voltages. The further details about the sub-station equipment are given in Section I of this book.

Table 1.1

AC Sub-station equipment*

S. No.	*Symbol*	*Equipment*	*Function*
1.		Circuit-breaker	Switching during normal and abnormal conditions, interrupt the fault currents.
2.		Isolator (Disconnecting switch)	Disconnecting a part of the system from live parts under no load condition.
3.		Earthing-switch	Discharge the voltage on the lines to earth after disconnecting them.
4.		Surge arrester	Diverting the high voltage surges to earth and maintaining continuity during normal voltage.
5.		Current transformer	Stepping down the current for measurement protection and control.
6.		Potential transformer (Voltage transformer)	Stepping down the voltage for the purpose of protection, measurement and control.

* For 400 kV, and above Series Capacitors are used for increasing power transfer ability. Shunt reactors are used for compensation of reactive power.

1.3. FAULTS AND ABNORMAL CONDITIONS

A fault in an electrical equipment is defined as a defect in its electrical circuit due to which the current is diverted from the intended path. Faults are generally caused by breaking of conductors or failure of insulation. The other causes of faults include mechanical failure, accidents, excessive internal and external stresses, etc. The fault impedance being low, the fault currents are relatively high. During the faults, the voltages of the three phases become unbalanced. The fault currents being excessive, they can damage the faulty equipment and the supply installation. During the faults, the power flow is diverted towards the fault and the supply to the neighbouring zone is affected. Voltage becomes unbalanced.

The faults can be minimised by improving the system, design, quality of the equipment and maintenance. However the faults cannot be eliminated completely.

For the purpose of analysis, AC faults can be classified as

- single line to ground fault
- double line to ground fault
- three phase fault
- line to line fault
- simultaneous fault
- open circuit., etc.

The other abnormal conditions in AC system include:

- voltage and current unbalance
- under frequency
- temperature rise
- instability, etc.
- over-voltages
- reversal of power
- power swings

Some of the abnormal conditions are not serious enough to call for tripping of the circuit-breaker. In such cases the protective relaying is arranged for giving an alarm. In more serious cases, the continuation of the abnormal condition (such as a fault) can be harmful. In such cases the faulty part should be disconnected the system without any delay. This function is performed by protective relaying and switchgear.

As a fault occurs in a power system, the current increases to several times the normal current because of the low fault impedance. The value of the fault current depends on the voltage at the faulty point and the total impedance upto the fault. The voltage at the fault location changes from its normal value. Fault MVA is reactive MVAr.

During the fault, the current and voltage undergo a continuous change and the phenomena observed are called *'transient phenomena'*. The word 'transient' refers to a 'temporary happening' which lasts for a short duration of time. The fault current varies with time. During the first one to three cycles, the fault current is very high but decreases very rapidly. This zone in which the current is very high, but decreases very rapidly is called the *Sub-transient State*. After the first few cycles, the decrease in current in less rapid. This region of slow decreases in the short-circuit current is called the *Transient State.* The transient state lasts for several cycles. After the transient state, *Steady State* is reached. During the Steady State the r.m.s value of the short-circuit current remains almost constant.

The circuit-breakers operate during the Transient State.

1.4. FAULT CALCULATIONS

The knowledge of the fault currents is necessary for selecting the circuit-breakers of adequate rating designing the sub-station equipment, determining the relay settings, etc. The fault calculations provide the information about the fault currents and the voltages at various points of the power system under different fault conditions.

The per-unit system is normally used for fault calculations. The symmetrical faults such as three phase faults are analyzed on per phase basis. For calculations on unsymmetrical faults, the method of *Symmetrical Components is adopted.* The network analyzer and digital computers are used for fault calculations of larger systems. (Ref. Sec. II).

1.5. THE FAULT CLEARING PROCESS

The protective relays are connected in the secondary circuits or current transformers and/or potential transformers. The relays sense the abnormal conditions and close the trip circuit of the associated circuit-breaker. The circuit-breaker opens its contacts. An arc is drawn between the contacts as they separate. The arc is extinguished at a natural current zero of the AC wave by suitable medium and technique. The stresses occurring on the circuit breaker while interrupting the arc, can be analysed by studying the following transient phenomena:

- transient variation of the short-circuit currents.
- transient variation of the voltage after final arc interruption (transient recovery voltage)
- the arc extinguishing phenomenon

After final arc extinction and final current zero, a high voltage wave appears across the circuit-breaker contacts tending to re-establish the arc. This transient voltage wave is called Transient Recovery Voltage (TRV). The TRV comprises a high frequency transient component superimposed on a power-frequency recovery voltage.

These phenomena have a profound influence on the behaviour of the circuit-breakers and the associated equipment (Ref. Ch. 3, 4).

1.6. PROTECTIVE RELAYING

AC power system is covered by several protective zones. Each protective zone covers one or two components of the system. The neighbouring protective zones overlap so that no part of the system is left unprotected. Each component of the power system is protected by a protective system comprising protective transformers, protective relays, all-or-nothing relays, auxiliaries, trip-circuit, trip coil etc. During the abnormal condition, the protective relaying senses the condition and closes the trip circuit of the circuit-breaker. Thereby the circuit-breaker opens and the faulty part of the system is disconnected from the remaining system.

The various power, system elements include generators, transformers, bus-bars, transmission lines, motors, etc. The protective relaying requirements of the various elements differ. Various types of protective systems have been developed to satisfy these requirements. For example, the over-current protection responds to increased currents. The differential protection responds to the vector difference between two or more similar electrical quantities.

The protective schemes for large electrical equipment comprise several types of protective systems. For low voltage equipment of relatively small ratings, fuses and thermal relays are generally adequate. The protective schemes of large power system-equipment are generally designed with due regards to power swings, power system stability and associated problems. (Ref. Sec. III and IV).

1.7. NEUTRAL GROUNDING (EARTHING) AND EQUIPMENT GROUNDING

The term Grounding or Earthing refers to the connecting of a conductor to earth. The neutral points of generator and transformer are deliberately connected to the earth. In 3 phase a.c. systems the earthing is provided at each voltage level. If a neutral point is not available, a special Earthing Transformer is installed to obtain the neutral point for the purpose of earthing. Neutral points of star connected VTs and CTs are earthed. The neutral earthing has several advantages such as :

- Freedom from persistent arcing grounds. The capacitance between the line and earth gets charged from supply voltage. During the flash-over the capacitance get discharged to the earth. The supply voltage charges it again. Such alternate charging and discharging produces repeated arcs called *Arcing Grounds*. The neutral grounding eliminates the problem of 'arcing grounds'.
- The neutral grounding stabilises the neutral point. The voltages of healthy phases with respect to neutral are stabilised by neutral earthing.
- The neutral earthing is useful in discharging over-voltages due to lightning to the earth.

— Simplified design of earth fault protection.

— The grounded systems require relatively lower insulation levels as compared with un-grounded systems.

The modern power systems are 3 phase a.c systems with grounded neutrals.

The **Equipment Grounding** refers to the grounding of non-current carrying metal parts to earth. It is used for safety of personnel. If a metal part is grounded, its voltage with respect to earth does not rise to a dangerously high value and the danger of a severe shock to personnel is avoided (Ref. Ch. 18).

1.8. OVER-VOLTAGES AND INSULATION CO-ORDINATION

The over-voltage surges in power systems are caused by various causes such as : lightning switching resonance etc.

The power system elements should withstand the over-voltages without insulation failure. The insulation level of a power system element refers to its values of power frequency and impulse voltage withstand. The insulation levels of various power system elements are graded in such a way that the damage caused by the over-voltages is minimum and the design of insulation of the equipment is economical. The protective measures against over-voltages due to lightning include.

— use of overhead ground wires

— low tower footing resistance

— use of lightning arresters (surge arresters)

Over-voltages are also caused during switching operations. The magnitude and wave shape of the switching over-voltages depend upon the values of equivalent inductance, capacitance and resistance in the system, the magnitude of the current to be interrupted and other local conditions. Over-voltages are produced during opening of a circuit-breaker. The amplitude of such over-voltages can be reduced by incorporating opening resistors across the circuit-breaker interrupters. Over-voltages are also produced during the closing operation of circuit-breaker especially while closing on unloaded transmission lines. Such over-voltage can be minimized by incorporating pre-closing resistors across the interrupters of the circuit-breakers.

The surge arresters offer low resistance to over-voltages and divert and over-voltages to earth.

1.9. SOME TERMS IN THE TEST

Controlgear. Controlgear is a general term covering switching devices and their combination with associated control, measuring and protective equipment intended for *control of power consuming devices.* (Ch. 15)

Circuit-breaker. A device capable of making, breaking an electric circuit under normal and abnormal conditions such as short circuits.

Isolator (Disconnecting Switch). A switching device which can be opened or closed only under no current condition. It provides isolation of a circuit for the purpose of maintenance.

Earthing Switch. It is a switch which connects a conductor to the earth so as to discharge the charges on the conductor to the earth. Earthing switches are generally installed on the frames of the isolators.

Relay. An automatic device which closes its contacts when the actuating quantity/quantities reach a certain predetermined magnitude/phase.

Current Transformer (CT). The current ratio of current transformers is generally high (*e.g.* 500 A/5A) and volt-ampere capacity is relatively low (*e.g.* 50 VA) as compared with that of the power transformers.

Potential Transformer (PT), Voltage Transformer (VT). The volt-ampere capacity of a potential transformer is low (*e.g.* 100 VA) and the voltage ratio is relatively high (*e.g.* 132 kV/100V). The protective relays are connected in the secondary circuits of CTs and PTs.

Lighting Arrester (Surge Arresters). The equipment connected between the conductor and ground, to discharge the excessive voltages to earth.

Fault Clearing Time. The time elapsed between the instant of the occurrence of a fault and the instant of final arc extinction in the circuit-breaker. The fault clearing time is usually expressed in cycles. One cycle of 50 Hz system is equal to 1/50 second. The fault clearing time is the sum of the relay time and the circuit breaker time.

Auto-reclosure

Automatic closing of the circuit breaker after its opening. Auto reclosure is provided to restore the service continuity after interrupting a transient fault. High voltage circuit-breakers used for controlling overhead transmission lines are provided with such a feature.

Contactor. Contactor is a switching device capable of making carrying and breaking electric current under normal and overload conditions.

HRC Fuse. High rupturing capacity cartridge fuse is used for over-current protection of low voltage and high voltages circuits.

Protective Scheme. A selected set of protective systems which protect one or two components of the power system against abnormal conditions, *e.g.*, generator protection scheme, transformer protection scheme, etc.

1.10. STANDARD SPECIFICATIONS

The various standards institutions in the world publish the standards specifications of high voltage circuit breakers, isolators and other substation equipment. Standards have been published on various types of protections and protective relaying schemes for various electrical equipment. These standards protective the guide-line to the manufactures and users regarding the following :

— terms and definitions (vocabulary)

— ratings

— conditions of service

— constructional details

— tests to be performed, standard test procedures, methods of evaluation of the test results.

— guidelines for selection, erection and maintenance.

The standards are generally drafted for a wider application and they generally do not cover specific cases. IEC (International Elector-Technical Commission) recommendations are generally accepted all over the world and the IS (Indian standards) specifications Published by Bureau of Indian Standards (BIS) are generally based on IEC recommendations.

Quality Standards

The following Standards Organisations are associated with the Standards on Quality.

— International Standards Organisation (ISO), Headquarters: Geneva, Switzerland.

— Bureau of Indian Standards, New Delhi (BIS)

— Bureau Veritas Quality International (BVQI)

The ISO and IS Standards on Quality are:

ISO	*IS*	*Title*
ISO: 9000	IS: 14000	Quality Management and Quality Assurance Standard. Selection and Use: 20 System Elements
ISO: 9001	IS: 14001	Level 1: Design/Development Production, Testing in factory, installation and Servicing
ISO: 9002	IS: 14002	Level 2: Production and installation all elements, some less stringent
ISO: 9003	IS: 14003	Level 3: Final Inspection and Tests-half the elements, low stringency
ISO: 9004	IS: 14004	Guidelines: Maximising benefits and minimising costs.

The *ISO 9000 Certificate* is given to manufacturers and Organisations as a recognition of the Quality. ISO Certification is essential for Switchgear and Controllgear Manufacturers for effective marketing and customers Satisfaction.

Switchgear and Protection are vital equipment in the electrical installations. It should have *Perfect Quality.*

1.11. ELECTRO-MECHANICAL RELAYS AND STATIC RELAYS

The electromechanical relays, are based on the comparison between operating torque/force and restraining torque/force. The VA burden of such relays is high. The characteristics have limitations. Each relay unit can perform only one protective function. Such relays are used for simple and less costly protection purposes. For important and costly equipment and installation, static relays are preferred.

In static relays the sensing, comparison and measurement are made by static (electronic) circuits having no moving parts. Static relays were developed during 1960's and have been accepted all over the world for almost all protective relaying, control and automation purposes.

- Static relays have versatile characteristics, offer low burden, and incorporate several protective/control/monitoring functions in one compact unit. Recently (1980's) programmable static relays incorporating microprocessor have been introduced. Microprocessor based relays have several superior features such as :
- Indication or operating values on demand and thereby no need of separate indicating instruments on panel.
- A single relay can perform 10 or more different protective functions thereby reducing number of separate relays and increasing reliability.
- Internal monitoring of own relays circuit.
- Memory function *e.g.* a relay which has tripped on fault can remember and flash on the display, the magnitude of current and instant of time at the time of tripping.
- Better properties and extended range of application for generation, transmission, distribution and industrial application.

The range of static relays in rapidly spreading. Details about static relays are covered in section IV.

1.12. APPLICATIONS OF ON-LINE DIGITAL COMPUTERS MICROPROCESSORS AND STATIC PROTECTIVE/CONTROL DEVICES IN POWER SYSTEM

Complex tasks associated with data logging, monitoring, measurements, protection, control and automation are now being performed with the aid of new type of on-line programmable devices including on-line digital computers, microprocessors, static protective and control devices, data transmission and processing devices etc. These tasks include.

- Checking fault levels periodically
- Loading of plants for economical and reliable operation
- Protection analysis, setting of trip levels to suit network configuration and loading status.
- Back-up protection.
- Real-time energy management from National Load Control Centre, Regional Load Control Centre.

The task of power system protection control and automation are performed by SCADA systems*.

* Supervisory Control And Data Acquisition Systems (Ref. Ch. 50).

The equipments for automatic control of power system are either fixed wire or programmable type. These include :

- Data collection and processing equipment
- Data transmission (telemetry)
- Data monitoring equipment
- Man-machine interface.

The Data includes current, power, voltage, status etc. Load Control Centre receives the following :

- Data regarding generating stations
- Data regarding major sub-stations
- Data regarding receiving stations.

The variables are scanned periodically and conveyed to load control centres as required.

The data is collected at sources by transducers, it is processed in data loggers. It is transmitted to load control centres through one or more of following channels:

- Power line carrier communication channels
- Pilot wire communication
- Microwave communication
- Satellite communication

Now fibre-optics is being used for short lengths of upto 50 km for data transmission. Data is converted into digital form in A/D convertors.

Applications of Digital computers and microprocessors in power system protection are described in Section V.

1.13. INTERCONNECTED POWER SYSTEM

Modern electrical power systems are large interconnected AC Networks. The total network is divided a few regional zones (Areas). Each Area controls its own loud, frequency and generation. Adjacent independently controlled areas are interconnected to from a Regional/National Grid.

For example, the Power Map of India is covered by the following five regional zones:

- Central zone
- Southern zone
- North eastern zone
- Western zone
- Northern zone

Some zones are already interconnected to form the Regional Grids. Each zone has its load control centre. National load control centre is in Delhi. However the total National Grid is under development.

In an Interconnected network, the National Load Control Centre determines the exchange between Regional Zones. Regional load control centres control generation in the respective zone to match the prevailing load so as to maintain the regional frequency within target limits (49-51 Hz.) During the low frequency/high load; the region imports power from adjacent surplus region. During low load/high frequency, the region exports power.

Advantages of Interconnections

- During the period of need, a Region (Area) imports power from adjacent region and maintains stability and frequency.
- The transient stability limit of each region is increased without increasing the installed capacity as the rotating reserve of adjacent region is used by interconnection.
- Optimum economic loading of hydro/thermal/nuclear generating stations depending upon energy reserves. Economic loading of power plants.
- Bulk transfer of energy as per agreed schedule.

Peak loads of each region may occur at different hours during the day. During this period, the region imports the power.

HVDC Back-to-Back HVDC Interconnections

After 1975, the Back-to-Back HVDC Coupling stations have become extremely successful fo interconnections between adjacent AC Grids. The rating of HVDC Coupling Stations are in th range of 500 MW, 1000 MW. By means of an HVDC Coupling Station, power exchange betwee two AC systems can be controlled rapidly, precisely and with minimum transmission losses. Th Transient Stability of both the AC Regional Grids is improved. The Regional-Grids in India ar getting interconnected by Back-to-Back HVDC Stations.

Multiterminal HVDC Interconnections has been introduced in Canada-USA during 198 By means of an Multi-Terminal HVDC Interconnections, power, exchange between three or mor AC systems can be controlled rapidly, precisely and with minimum transmission losses. The tran sient Stability of entire National Grid is improved. The MTDC Interconnection is not yet planne in India (1995). It may be introduced during 2000-2010.

Economic Load Despatch. The economic operation of large AC grid can be controlled fro a centralized 'load control centre' or 'load despatch centre'.

The load control centre determines the allocation of generation by various plants on the basi of economic load distribution considering incremental operating costs λ and penalty factors fo transmission losses (Ln) for each plant. The load control centre sends command to power stations control rooms periodically by telemetric data transmission. The automatic load-frequency contro in the control system of Generator-Turbine-Governor basically aims at maintaining constant fre quency/speed as a primary control. But the setting of governor to turbines (secondary load frequenc control) is changed according to the instructions of the load control centre. Thus the input to tur bines of generators gets automatically adjusted by primary load-frequency control and the frequen cy is maintained. And the governor setting is determined by economy load dispatch instructions.

The total load frequency control is achieved jointly by:

(*a*) Load Control Centre

(*b*) Telemetry and Telecontrol Equipment and

(*c*) Power Station Control Room.

Automatic Economic Load Despatch is illustrated in Chapter 46-B.

1.14. LOAD-FREQUENCY CONTROL, LOAD SHEDDING

Load-frequency Control of AC grid is achieved by continuous matching of generation (production) of electrical power with prevailing load conditions by joint action of control rooms in generating stations. Voltage control is achieved by appropriate tap-changing and shunt compensation in respective sub-stations.

The regulations of power supply insist that the supply frequency variation should remain within 2% about the declared frequency of 50 Hz.

The frequency of a generator and generating station is controlled partly by the action of the mechanical governors controlling the turbine speed and partly by changes in load conditions. The plants output is increased by increasing input. How much load the plant should share is decided by grid control loading engineer.

Load Shedding. When the load increases beyond limits of generation, the system frequency starts dropping. Drop in frequency below 49 Hz is not permitted. To control the further drop of frequency, load is shed (disconnected) at distribution level. Load shedding may cause voltage rise. Tap changing should be arranged to prevent voltage rise beyond safe limits.

Reduced frequency causes vibrations and failures of stream turbine blades, overfluxing of transformer cores, drop in synchronous speed, error in clock time etc. Excellent power system operates within targetted frequency continuously.

Network Segregation (Islanding). In case of major fault or outage, the network has a tendency of cascade tripping and large blackout. It is difficult to resynchronise. To avoid such happen-

ing. The network is quickly segregated in smaller zones. Drop in frequency and rate of drop (df/dt) is used in frequency relay for segregation action.

1.15. VOLTAGE LEVELS IN NETWORK AND SUB-STATIONS

The network has various voltage levels for generation, transmission distribution, utilization, control and protection.

— Generation is at voltages up to 30 kV AC r.m.s. (phase to phase). This is due to design limitations of AC generators.

— Long distance high power transmission is by EHV AC lines rated 220 kV, 400 kV, 760 kV AC. For longer distance and higher powers, higher voltages are economical and essential. In special cases, HVDC transmission is preferred. The rated voltages of long distance HVDC transmission are ± 400 kV, ± 500 kV, ± 600 kV.

— Backbone transmission network is by EHV AC transmission lines (400 kV AC).

— Distribution is at lower AC voltages between 132 kV AC and 3.3 kV AC.

— Utilisation is at low voltage (up to 1 kV) and medium voltages upto 33 kV.

— The factory sub-stations receive power at distribution voltage upto 33 kV and step it down to 440 volts AC. Larger factories receive power at 132 kV and have internal distribution at 3.3 kV, to 440 volts AC.

TABLE 1

Reference Values of Nominal Voltages in A.C. and HVDC Sub-stations

		A.C. Sub-stations		
400 kV	220 kV	132 kV	110 kV	
66 kV	33 kV	22 kV	11 kV	6.6 kV
3.3 kV	400 V a.c. rms. phase to phase.			
		H.V.D.C. Sub-stations		
± 250 kV, ± 400 kV, ± 500 kV, ± 600 kV				
		Station Auxiliaries		
Auxiliary A.C. supply :		11 kV, 6.6 kV, 3.3 kV		
400 V, 3 ph, phase to phase				
230 V a.c. single phase				
Auxiliary L.V.D.C. : 220 V, 110 V, 48 V.D.C.				

1.16. VOLTAGE CONTROL OF AC NETWORK

Voltages of various sub-stations buses should be held within specified limits, the variation allowed ± 10% (Refer Table 2).

Whereas the active power flow (P) determines directly the frequency (f), it does not affect the voltages significantly.

Voltages are affected significantly by the flow of reactive power Q.

$$|\Delta V| = \frac{Q.X}{|V_R|}$$

where $|V_R|$ = Receiving end voltage of the line, magnitude

Q = Reactive power flow through the line

X = Series reactance of line

$|\Delta V|$ = Voltage drop in line, $[V_S] - [V_R]$, magnitude

Voltages are controlled by supplying reactive power (Q). This is called compensation.

Basic Methods of Voltages Control

— Voltages Regulators and Excitation Control of Synchronous Generators.

— Tap-changing transformers at various sub-stations. Off-load tap changers are used for seasonal voltage variations. On load tap changers are used for daily load variation. By changing the turns ratio of the transformer N_1/N_2 the voltages ratio V_1/V_2 is changed.

— Series compensation (series capacitors) used for long lines. The inductive reactance drop in the line (IX_L) is compensated by the drop in series capacitors (IX_C). Series capacitors are generally used for long extra high voltage transmission lines.

— Shunt Capacitors are used for voltage control in transmission and distribution networks. They are connected near the load terminals, factory sub-stations, distribution substations. Capacitors supply reactive power and improve power factor, they are switched in during heavy loads.

Shunt capacitors should be switched-in during low voltage and switched off during high voltage.

TABLE 2 Reference Values of Voltage Limits in AC Network

Class	*System Voltage Nominal*	*Highest Voltage*	*Permissible Lowest System Voltage*
	ph. to ph. R.M.S.	*ph. to ph. R.M.S.*	*ph. to ph. R.M.S.*
LV(1 ph)	240 V	264 V	216 V
MV	415 V	457 V	347 V
M.H.V.	3.3 kV	3.6 kV	3 kV
M.H.V.	6.6 kV	7.2 kV	6 kV
M.H.V.	11 kV	12 kV	10 kV
M.H.V.	22 kV	24 kV	20 kV
M.H.V.	33 kV	36 kV	30 kV
H.V.	66 kV	72.5 kV	60 kV
H.V.	132 kV	145 kV	120 kV
E.H.V.	220 kV	245 kV	200 kV
E.H.V.	400 kV	420 kV	380 kV
U.H.V.	760 kV	800 kV	750 kV

Note. L.V. = Low Voltage M.V. = Medium Voltage
M.H.V. = Medium High Voltage H.V. = High Voltage
E.H.V. = Extra High Voltage U.H.V. = Ultra High Voltage
Permissible variation is approximately ± 10% Nominal value.

— Shunt reactors are used with EHV AC lines for compensation of reactive power during low loads.

Compensation of Long Lines

During Low Loads and High Receiving Voltage	Switch-off shunt capacitors. Shunt-reactors-unswitched
During High Loads and Low Receiving Voltage	Switch-in shunt capacitors at load end shunt-reactors-unswitched
Varying Load	Static VAr Source (SVS)

The voltage control of each sub-station bus is achieved by appropriate action in that sub-station.

1.17. STATIC VAr SOURCES (SVS)

Static VAr sources are installed in receiving sub-stations, load sub-stations for fast, stepless control of reactive power compensation for voltage control. In conventional switched schemes the capacitors/reactors are switched in/out by circuit-breakers. In SVS, the capacitors/reactors are controlled by controlling the delay angle of thyristor triggering. The duration and magnitude of current flowing through reactor/capacitor is controlled. Thereby amount of compensation is controlled. Fast static compensation schemes are used for controlling voltage of AC buses in EHV AC sub-stations. Formerly synchronous compensators were used for similar purpose.

Voltage control techniques are described in Chapter 45 B.

1.18. POWER SYSTEM STABILITY

Synchronous generators connected to AC network have a tendency in synchronism with the Network. The tendency to remain in synchron called *Stability*. The tendency to fall out-of step is called unstable condition.

Steady state stability limit denotes the maximum power transfer possible with very small disturbing forces. This occurs at load angle of 90° electrical. The load angle δ of a synchronous machine is the angle between the emf vector (corresponding to axis of rotating magnetic field) and the voltage vector (V). The power transfer is given by equation.

$$P = \frac{|V| \cdot |E|}{X} \sin \delta$$

where $|V|$ = Terminal voltage, magnitude; $|E|$ = Induced emf, magnitude
δ = angle between V and E vectors; X = Synchronous reactance.

Steady state stability limit occur at $\delta = 90°$ and is equal to

$$P_{SS} = \frac{|V| \cdot |E|}{X} \sin 90° = \frac{|V| \cdot |E|}{X}$$

However, if a sudden disturbance occurs, the angle delta overshoots beyond 90° and the stability may be lost. Hence the limit of loading permitted (P_{ts}) for given amount of disturbance ΔP is defined. It is called Transient Stability Limit (P_{ts}) A synchronous generator can be loaded safely upto its transient stability limit. The transient stability limit (P_{ts}) is much lesser than steady state stability limit. Assuming safe load angle of 30° electrical,

$$P_{ts} = \frac{|V| \cdot |E|}{X} \sin 30° = \frac{|V| \cdot |E|}{X} \cdot \frac{1}{2}$$

i.e. $P_{ts} = 1/2\, P_{ss}$. .... for critical $\delta = 30°$

Transient state stability limit is half of steady state limit.

A similar analysis is applied to power transfer through an AC interconnecting transmission line

$$P_{st} = \frac{|V_1| \cdot |V_2|}{X} \sin \delta$$

where $|V_1|$, $|V_2|$ = Sending and receiving voltage magnitudes
X = Series reactance of line ; δ = Angle between vectors V_1, V_2

Transient stability lmit can be improved by several methods associated with switchgear and protection. These include the following :

— Use of faster and superior protection system.

— Use of faster circuit-breakers.

— Use of rapid auto-reclosing of circuit-breakers.

By improving transient stability limit, the installed generating stations can be loaded to higher levels resulting in major economy.

Details about transient stability limit are covered in Chapter 44.

1.19. HVDC OBTION

400 kV a.c. transmission links and sub-stations were established in India during 1970's. Thre HVDC projects have been executed, (1992). By the year 2000, about five HVDC projects are likel to be commissioned in India. HVDC transmission systems are selected as an alternative to EH and UHV a.c. transmission system for any one of the following reasons only for specific projects.

— Long distance high power transmission lines (say above 1000 MW and 800 km) for economi advantage. HVDC links are economical for long distance high power transmission line when the saving in line cost is more than the additional cost of conversion sub-station. Fo backbone AC network, generation transmission and distribution AC is definitely superio and continues.
— Asynchronous interconnection (Tie) between two a.c. systems having their own load-fre quency control systems.
— Back-to-back asynchronous tie sub-stations between two a.c. systems without tie-line.
— Underground/submarine cables at voltages above 66 kV and length more than 25 km fo technical reasons.
— Multi-Terminal HVDC Systems.

The HVDC obtion introduced in electrical network during early 1970's provides.

— faster and accurate control of real power (e.g. 30 MW/minute),
— higher power system stability-limit for transmission of power without limit of sin δ, an improved stability of the connected AC Networks.
— HVDC line has no reactive power flow and therefore no need of intermediate compensatin substations. The line losses are reduced. HVDC Line losses are about 5% of power transfe as against 25% line losses for equivalent AC power Transmission.

Three Phase, 50 Hz AC Systems will continued universally for power system generation, trans mission and distribution networks as it has natural tendency for load-frequency stability an several economical AC Voltages Levels through Transformers.

Modern Power System is a combination of Interconnected AC Systems with a few HVDC Cou pling Stations ; a few Long Distance 2 Terminal Bipolar HVDC Links and possibly a high powe Multi Terminal 2-Pole HVDC Interconnecting System.

Switchgear; Protection and Control of HVDC Transmission Systems and their interaction wit AC system have been illustrated in Ch. 47.

1.20. POWER SYSTEM ANALYSIS

Power System Analysis deals with: various network phenomena, interaction between the net work and the machines, stresses on equipment. The System Studies evaluate the present and futur power system operating performance/reliability/availability and to provide data and guidelines fo satisfactory operation and control. The scope includes the following topics which have been covere in separate chapters of this book:

— Load flow calculations
— Load Frequency Control
— Short circuit calculations
— Transient overvoltage studies.
— Insulation-coordination, Neutral grounding.
— Stability studies
— Reliability Studies
— Voltage Control and Reactive Power Flow Control
— HVDC and EHV-AC Transmission Systems, Interaction with Network.
— Economic Operation of the Power System
— Computer Aided Power System Studies

1.21. POWER SYSTEM NETWORK CALCULATIONS AND LOAD FLOW

The numerical problems in power System Analysis deal with the power system variables V, I, P, Q, S, f, δ and network constants Z, Y, R. A network has several and buses and interconnecting branches. Basic Kirchoff's laws, network theorems, fundamentals electrical equations and mathematical tools are applied to solve numerical problems in power systems. The Network Calculations are simplified by writing the Kirchoff's Current Law in terms of Nodal Voltage Equations.

$$I = Y \text{ bus } V$$

I and V are current and Voltage matrices. Y bus is the Bus-Admittance Matrix for the given network.

The methods of Network Calculations have been explained clearly Ch. 19 to 24 and in Ch. 57 with the help of several *solved numerical problems*.

Load Flow Calculations

Load Flow Studies deal with calculation of the following variables for the various busses and branches of the given network (power system) under given steady state operating conditions of generation and load.

Variables associated with a Load flow study are:

Vk Bus voltage magnitude	P_k Real Power entering/leaving bus-k
δk Phase angle of voltage	Q_k Reactive Power entering Leaving bus
Complex power $= P + j\,Q$	P_{mn} Real power flow in branch mn
I_{mn} Branch Current	Q_{mn} Imaginary power flow in branch

These variables influence each other and their co-relation is expressed in terms of the Load Flow Equations. Load Flow Studies are the used for evaluating the steady state performance and provide valuable data to power system engineers for operation, control and system planning and design. The Gauss Siedel Interactive Method and Newton Raphson Interactive Method of Load Flow Studies have been clearly explained in Ch. 58 with the help of solved numerical problems.

1.22. OBJECTIVE AND TASKS

Every electricity supply company aims at the following:

— Supply of required electrical power to all the consumers continuously at all times.
— Maximum possible coverage of the supply network.
— Energy conservation and use of Renewable energy sources.
— Maximum security of supply.
— Shortest possible fault-duration.
— Optimum efficiency of plants and the network.
— Supply of electrical power at specified frequency and waveform.
— Supply of electrical power within specified voltage limits.
— Supply of electrical energy to the consumers at the lowest cost.

The work of a power engineer is to cover a wide range of activities such as:

— design and development of the products, systems stations for systems stations, products
— research and development
— manufacturing, testing, quality control.
— project planning, monitoring, execution
— purchase sale of equipment, specifications
— Erection, testing and commissioning, safety.
— Operation and maintenance, energy conservation.
— Power system control, operation, automation.

This book covers the basis aspects. For gaining expertise in the activities further study and experience is necessary.

High-voltage A.C. Circuit-Breakers

The fault clearing process—Types of circuit breakers—Circuit-breaker assembly—Operating mechanism—Materials—Summary

2.1. INTRODUCTION

In this chapter, the constructional aspects of circuit-breakers have been briefly discussed. Th theoretical aspects regarding transient variation of current and voltage, arc extinction process an the various of circuit-breakers have ~~been~~ described in detail in subsequent chapters.

The circuit-breakers are automatic switches which can interrupt fault currents. In some ap plications like single phase traction system, *Single pole* circuit-breakers are used. The part of th circuit-breakers connected in one phase is called the *pole*. A circuit-breaker suitable for three phas system is called a *'triple-pole* circuit-breakers'.

Each pole of the circuit-breaker comprises one or more *interrupters* or *arc-extinguishing cham bers*. The interrupters are mounted on support insulators. The interrupter encloses a set of *fixe and moving contact*. The moving contacts can be drawn apart by means of the operating links the operating mechanism. The operating mechanism of the circuit-breaker gives the necessary ene gy for opening and closing of contacts of the circuit-breakers.

The arc produced by the separation of current carrying contacts is interrupted by a suitab medium and by adopting suitable techniques for arc extinction. The circuit-breaker can be classifie on the basis of the arc extinction medium.

2.2. THE FAULT CLEARING PROCESS

During the normal operating condition the circuit-breaker can be opened or closed by a statio operator for the purpose of switching and maintenance. During the abnormal or faulty condition the relays sense the fault and close the trip circuit of the circuit-breaker. Thereafter the circuit breaker opens. The circuit-breaker has two working positions, *open and closed*. These correspon to open circuit-breaker contacts and closed circuit-breaker contacts respectively. The operation o automatic opening and closing the contacts is achieved by means of the *operating mechanism* o the circuit-breaker. As the relay contacts close, the trip circuit is closed and the *operatin mechanism* of the circuit-breaker starts the opening operation. The contacts of the circuit-breake open and an arc is drawn between them. The arc is extinguished at some natural current zero o a.c. wave. The process of current interruption is completed when the arc is extinguished and th current reaches final zero value. The fault when the arc is extinguished and the current reache final zero value. The fault is said to be cleared. The process of fault-clearing has the following se quence:

— Fault occurs. As the fault occurs the fault impedance being low, the currents increase and the relay gets actuated. The moving part of the relay move because of the increase in th operating torque. The relay takes some time to close its contacts.

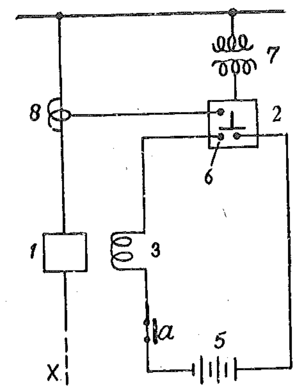
— Relay contacts close, the trip circuit of the circuit-breaker closes and trip coil is energized

— The operating mechanism starts operating for the opening operations. The circuit-breake contacts separate.

— Arc is drawn between the beaker contacts. The arc is extinguished in the circuit-breaker by suitable techniques. The current reaches final zero as the arc is extinguished.

2.3. THE TRIP-CIRCUIT

Fig. 2.1 illustrates the basic connections of the circuit-breaker control for the opening operation.



1. Circuit-breaker
2. Relay
3. Trip coil of c.b. (Shunt Release)
4. Trip circuit
5. Battery
6. Relay Contacts
7. Potential transformer
8. Current transformer

a Auxiliary switch contacts
x Protected element.

Fig. 2.1. Simplified diagram of circuit-breaker control for the opening operation.

The Protected circuit x is shown by dashed line. When a fault occurs in the protected circuit, the relay (2) connected to the CT. and PT actuates and closes its contacts (6) Current flows from the battery (5) in the trip circuit (4). As the trip coil of the circuit breaker (3) is energized, the circuit-breaker operating mechanism is actuated and it operates for the opening operation. Auxiliary switch is an important item in the circuit.

2.4. RECENT ADVANCES

Before 1970s in medium voltage range and high voltage range, air-break, bulk-oil; minimum oil, air blast circuit breakers ruled the world market. During 1970s vacuum circuit-breakers were introduced for applications up to rated voltages of 36 kV. Single pressure puffer type SF_6 breakers were introduced for rated voltages from 3.3 kV to 760 kV. SF_6 Gas Insulated Substations (GIS) were introduced for 12 kV to 760 kV. Fault levels * and rated voltages in the system have increased. ** The bulk-oil breakers, minimum oil breakers, air-blast breakers have become obsolete. However you will find them in the existing installations during 1990s.

The vacuum breakers and SF_6 breakers are maintenance-free and of superior switching performance. They are now preferred for various switching duties in new installations. In low voltage range Air-break circuit-breakers and contactors rule the market.

During 1970s and 1980s, the research and development was focussed on in various switching phenomena, switching overvoltages, short-circuit testing, development of Vacuum/SF_6 and HVDC CBs, SF_6, GIS.

The Standards on circuit breakers were totally revised with the introduction of TRV concept and rigorous testing. Short circuit testing laboratories with synthetic testing facilities were built in various countries. Reliable, maintenance-free, simpler circuit breakers and compact indoor SF_6 Gas Insulated Substations (GIS) are now manufactured and installed in India for various rated voltages from 3.6 kV to 420 kV.

* Fault MVA = $\frac{\sqrt{3} \times V \times I}{10^6}$, where V is the service voltage in volts and I is the fault current in amperes.

In low voltage range air-break circuit breakers/contactors ; miniature circuit breakers, moulde case circuit breakers and solid state switching devices, HRC fuses have been developed to meet th requirements of control gear.

The Circuit Breaker technology has matured and circuit-breakers are available for every faul level*, rated voltage** and switching duty in power system.

2.5. CLASSIFICATION BASED ON ARC QUENCHING MEDIUM

The a.c circuit-breakers can be classified on the basis of rated voltages. Circuit-breakers belov rated voltage of 1000 V are called low voltage circuit-breakers and above 1000 V are called higl voltage a.c. circuit-breakers.

The type of the circuit-breaker is usually identified according to the medium of arc extinctio The classification of the circuit breakers based on the medium of arc extinction is as follows:

(1) Air break circuit-breaker/Miniature circuit-breaker.

(2) Oil circuit-breaker (tank type of bulk oil)

(3) Minimum oil circuit-breaker.

(4) Air blast circuit-breaker.

(5) Sulphur hexafluoride circuit-breaker. (Single pressure or Double Pressure).

(6) Vacuum circuit-breaker.

Each circuit-breaker will be studied thoroughly in the subsequent chapters. These circuit breakers employ various techniques to extinguish the arc resulting from separation of the curren carrying contacts. The mode of arc extinction is either 'high resistance interruption' or 'zero-poin interruption'.

High Resistance Interruption. In this process the resistance of the arc is increased by lengthening and cooling it to such and extent that the system voltage is no longer able to maintain the arc and the arc gets extinguished. The technique is employed in airbreak circuit-breakers and d.c. circuit-breakers.

Low Resistance or Zero Point Interruption. In this process, the arc gets extinguished at natural current zero of the alternating current wave and is prevented from restriking again by rapid build up of dielectric strength of the contact space. This process is employed in almost all a.c. circuit-breakers. HVDC circuit-breakers employ *'artificial current zero method'*.

Each leading manufacturer of circuit-breaker develops two or more types of circuit-breakers for every voltage class. (Ref. Table 2.1). The construction of the circuit-breakers depends upon its type (arc-quenching medium), voltage rating and structural form.

Air-break Circuit-breakers. Utilize air at atmospheric pressure for arc-extinction (Ref. Ch. 5).

Air-blast Circuit-breakers. Utilize high pressure compressed air for arc extinction (Ref. Ch. 6). They need compressed air plant.

Bulk-oil and Minimum-oil Circuit-breakers. Utilize Dielectric oil (Transformer oil) for arc extinction. In Bulk-oil circuit breakers, the contacts are separated inside a steel tank filled with dielectric oil. In minimum oil circuit-breakers the contacts are separated in an insulating housing (interrupter) filled with dielectric oil.

SF_6 Circuit-breakers. Sulphur-hexa-fluoride gas is used for arc extinction. There are two types :

— **Single Pressure puffer type SF_6 Circuit-breakers,** in which the entire circuit-breaker is filled with SF_6 gas at single pressure (4 to 6 kgf/cm^2). The pressure and gas flow required for arc extinction is obtained by piston action.

— **Double pressure type SF_6 Circuit-breaker,** in which the gas from high-pressure system is released into low pressure system over the arc during the arc quenching process.

* Fault MVA = $\dfrac{\sqrt{3} \times V \times I}{10^6}$, where V is the service voltage in volts and I is the fault current in amperes.

** Rated Voltages of circuit-breakers refer to higher system voltage *e.g. 3.6 kV, 12 kV, 36 kV, 145 kV, 245 kV, 420 kV, 800 kV, rms ph. to ph.*

Table 2.1 Comparison of Circuit-breakers

	Type	*Medium*	*Voltage-Breaking Capacity*	*Design Features*	*Remarks*
1.	Air-break-circuit-beaker	Air at atmospheric pressure	430-600V, 5-15-35 MVA recently 3.6-12 kV, 500 MVA	**Incorporates :** Arc runners arc splitters magnetic coils	Used for medium low voltages A.C. D.C. Industrial circuit-breakers. Have current limiting features.
	Miniature C.B.	Air at atmospheric pressure	430-600 V	Small size, current limiting feature	Used for Low and Medium Voltages.
2.	Bulk-Oil circuit-breaker	Dielectric oil	12 kV, 3.6 kV	One tank upto 36 kV, 3 tanks above 36 kV, fitted with arc control devices	Getting obsolete used upto 12 kV, 500 MVA.
3.	Minimum oil circuit-breaker	Dielectric oil	Preferred for 3.6 kV to 145 kV	The circuit breaking chamber is separate from supporting chamber. Small size, Arc control device used.	Used for metal enclosed switchgear upto 36 kV, Outdoors type between 36 and 245 kV. Now superseded by SF_6 CB.
4.	Air-blast circuit-breaker	Compressed air (20-30) kg/cm^2	245 kV, 35,000 MVA upto 1100 kV, 50,000 MVA	Unit type construction several units per pole, auxiliary compressed air system required.	Suitable for all EHV applications, fast opening closing. Also for Arc Furnace Duty. Now Superseded by SF_6 CB for 145 kV, and above
5.	SF_6 circuit-breaker Single pressure puffer type SF_6 GIS	SF_6 gas (5 kg/cm^2)	145 kV, 7500 MVA 245 kV, 10,000 MVA 12 kV, 1000 MVA 36 kV, 2000 MVA 420 kV, 40 kA	One interrupter pole upto 245 kV	Suitable for SF_6 switchgear and Medium voltage swgr. EHV circuit breaker. Maintenance free.
6.	Vacuum circuit-breaker	Vacuum	Preferred for indoor switchgear rated upto 36 kV, 750 MVA	Variety of designs, long life, modest maintenance.	Suitable for a variety of application from 3.6 kV to 36 kV
7.	H.V.D.C. Circuit-breaker	Oil or Air-Blast	33 kV, 2kA	Artificial current zero by switching in capacitors.	Used for Metallic Return Transfer Breaker.

This type has been superseded by single pressure puffer type.

In Vacuum circuit-breakers, the fixed and moving contacts are housed inside a permanently sealed Vacuum interrupter. The arc is quenched as the contacts are separated in high vacuum. (Ref. Ch. 9)

2.6. TECHNICAL PARTICULARS OF A CIRCUIT-BREAKER

A circuit-breaker is identified by the following particulars :

(1) Type of medium for arc-extinction.

(2) Rated voltage. This corresponds to highest power-frequency voltage between phase to phase, e.g. 3.6 kV, 7.2 kV, 12 kV, 36 kV, 72.5 kV, 145 kV, 245 kV.

(3) Rated breaking current
(4) Other rated characteristics, (Ref. Ch. 3)
(5) Type of construction :
— Indoor metal-clad type, draw-out type
— outdoor type
— Metal-clad SF_6 gas insulated type.
(6) Type of operating mechanism.
(7) Total break-time e.g. 2 cycle, 3 cycle, 5 cycle.
(8) Structural form
(9) Additional feature for overvoltage limiting.
— Surge suppressor — Switching resistor.

2.7. ASSEMBLY OF OUTDOOR CIRCUIT-BREAKERS

The design features of an individual circuit-breaker depends upon its voltage, other ratings and the type. The circuit-breakers manufactured by different companies may have quite different design patterns. However, a general description of an EHV circuit breaker can be given to cover the various types. The low voltage circuit-breakers, have different design features as the voltage, capacity and frequency of operation is different from that of the EHV circuit-breakers. The part of the circuit-breaker connected in one phase is called 'Pole of the circuit-breaker'. A circuit-breaker for power systems is called 'Triple pole circuit breaker'. In single phase traction systems, single pole circuit breakers are employed.

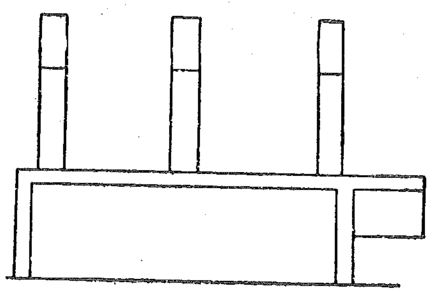


Fig. 2.2. Structural form of a triple outdoor circuit-breaker with one iterrupter per pole.

TABLE 2.2. Present Trends in Choice of Circuit-Breakers

Rated Voltage	*Preferred type*	*Remarks*
Below 1 kV (low voltage)	— Air break Circuit-breaker	— Metal-enclosed switchgear — Metal-enclosed control gear
3.6 kV to 12 kV	— Vacuum Circuit-breakers — SF_6 C.B.	— Metal-enclosed Switchgear, Indoor use with : — Vacuum Switchgear preferred — Single Pressure SF_6 preferred
36 kV	— Minimum Oil Circuit-Breaker — Vacuum C.B. SF_6 Circuit Breaker	Outdoor Type or in Kiosk MOCB becoming obsolete.
145 kV and 245 kV*	— Minimum Oil Circuit-Breaker out door — SF_6 Outdoor Puffer type	— SF_6 Circuit Breaker Preferred — MOCB becoming obsolete.
420 kV*	— SF_6 Outdoor Puffer type	— SF_6 Circuit-Breaker Preferred.

* Puffer type out-door SF_6 C.B. installed in India 1980-1981.
** Vacuum Switchgear introduced in India 1980-81.
* Vacuum contactors introduced in India 1980.

† Capacitor Switching VCB or SF_6
Motor Switching SF_6 or VCB with RC
Suppressors Arc Furnace Duty. VCB/SF_6/ABCB
Repeated operations VCB/SF_6

Motor Switching SF_6 or VCB with RC Suppressors

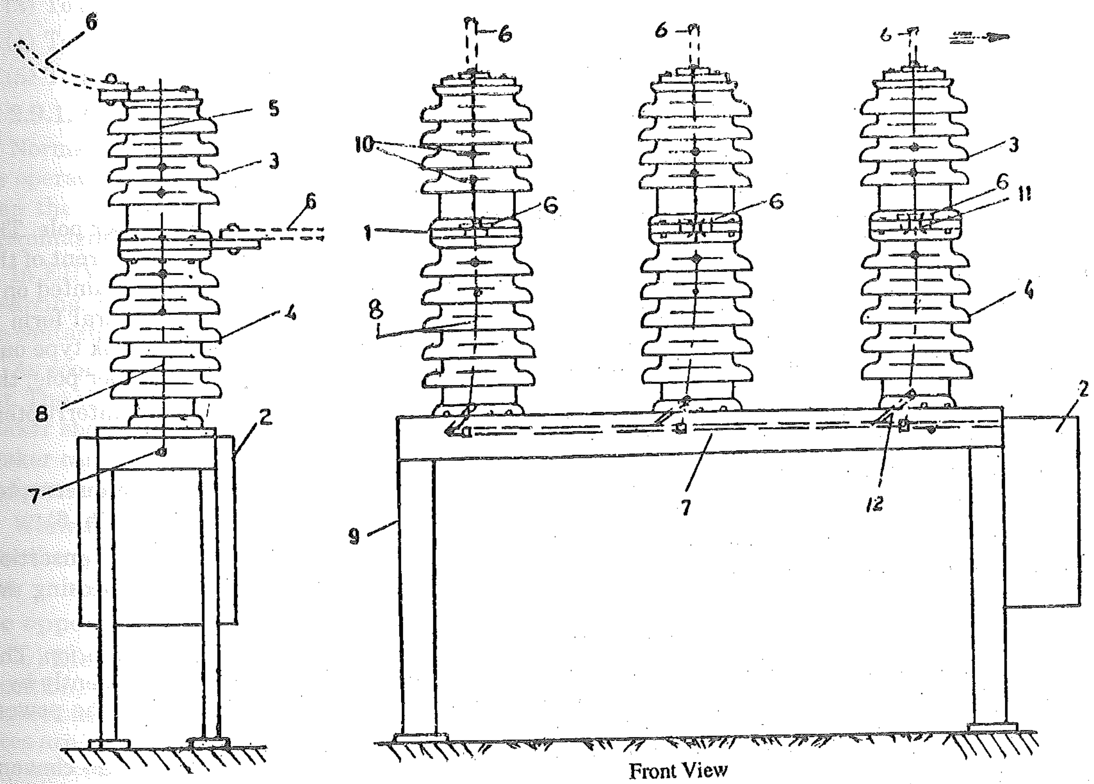
In Fig. 2.3 we see three identical poles of a circuit breaker assembled on a common frame. The distance between the poles is determined by the voltage between their conducting parts. The current carrying parts are supported by dielectric materials. The current is interrupted in closed chamber known as arc extinction chamber (Fig. 2.3, item 3) or interrupter.

The contacts (10) are generally in pairs of fixed contact and moving contact. The moving contact is moved mechanically. To achieve this operation of closing and opening, an *Operating Mechanism* is necessary. The function of operating mechanism is to open and close the contact when desired.

The operating mechanism may be common for the three poles or may be separate one for each pole. In addition to the operating mechanism, there is *Control Cabinet* or what is known as *Switch Cubicle.* The various control interlocking, indicating connections are through this control cabinet placed near the breaker.

Thus a complete three-phase circuit-phase circuit breaker consists of the following sub-assemblies.

— Three poles
— control cabinet
— operating mechanism support structure
— auxiliaries



1. Circuit-breaker pole
2. Operating mechanism
3. Interrupter
4. Support porcelain
5. Conductor
6. Terminals
7. Operating rod
8. Insulating operating rod
9. Frame
10. Contacts
11. Transfer contacts between moving contacts and terminal.
12. Linkage

Fig. 2.3. Diagram illustrating the assembly of an outdoor circuit-breaker.

2.8. STRUCTURAL FORM OF CIRCUIT-BREAKERS

The structural form of a circuit-breaker depends on its type, rated voltage type of design, type of operating mechanism etc.

In indoor, metal clad switchgear, the three poles of the circuit-breaker are mounted on a withdrawable truck. Such configuration is commonly used for rated voltages unto 24 kV (Ref. Ch. 15).

For 36 kV and above, outdoor circuit-breaker are preferred. The structural form of outdoor circuit-breaker depends of rated voltage, number of interrupters of per pole and type of operating mechanism. Circuit-breakers of rated voltages upto and 145 kV generally have a single interrupter per pole (Ref. Fig. 2.3) In such a structural form, the interrupter porcelain and support porcelain should withstand the power-frequency and impulse test voltages internally and externally (Ref. Ch. 12).

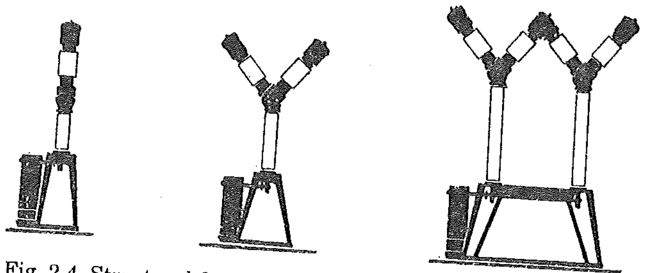


Fig. 2.4. Structural from of 145 kV, 245 kV and 420 kV C.B. Pole.

245 kV circuit-breakers have two or more identical interrupter units (elements) per pole. The number of interrupters per pole depends upon the rated voltage and rated breaking current of the circuit-breaker. Such circuit-breaker pole comprises identical twintinterrupter units mounted on a single support porcelain column in T or Y formation (Ref. Fig. 2.4). Such a structural form is preferred in outdoor minimum oil circuit breakers, air blast circuit-breaker and live tank type outdoor SF_6 circuit-breakers. While MOCBs and ABCDs require two to six interrupters per pole; the SF_6 circuit-breakers are with one or two interrupters per pole for 245 kV and with two interrupters per pole for 420 kV. The SF_6 breakers are therefore more economical.

In multi-break type construction *voltage-grading capacitor* is connected across each interrupter for equalizing the voltage shared by the interrupter during interruption process (Ref. Ch. 6).

Pre-closing resistors are also connected in parallel whenever necessary. The pre-insertion resistors (Preclosing resistors) are necessary to limit over-voltages occurring during closing unloaded transmission lines (Ref. Ch. 18).

Circuit-breakers for rated voltage above 245 kV generally have *independent pole operation.* The operating mechanism of each pole is independent and each pole can be tripped independently by a separate relay. Independent pole operation is desirable for improving the stability of the power-system (Ref. Sec 44.8).

Structural form of EHV metal-clad SF_6 insulated switchgear is quite different than conventional equipment discussed above (Ref. Ch. 7).

2.9. OPERATING MECHANISMS

Circuit-breakers have two working positions-open and close. During the closing operation, the circuit-breaker contacts close against opposing forces. During the opening operation, the closed contacts are separated as early as possible. Operating mechanisms are provided to achieve the opening and closing operations. Operating mechanisms are also necessary for isolator. The circuit breaker operating mechanisms must be capable of dealing with large forces at high speeds with complete reliability even if the circuit breaker has remained idle for a prolonged duration.

The operating should be fast, in order to reduce circuit-breaker time. The operating time between instant of receiving trip signal and final contact separation is of the order of 0.03 second, *i.e.* 1.5 cycles in modern EHV circuits-breakers. In slow circuit-breakers used in distribution system time can be about 3 cycles.

While closing, the contact closure should be fast, sure without hesitation, with adequate contact pressure at the end of contact travel. If these conditions are not satisfied, contact welding can result.

The operating mechanisms should be capable of giving the specified duty of the breaker (sequence of opening and closing as specified in standard specification). The breaker should also pass the operational tests which ascertain the capability of the operating mechanism. The interlocks are provided between breaker, isolator and earthing switch, so as to avoid wrong operation and to assure operation in a correct sequence. The functions of the operating mechanisms can be summarised as follows:

(1) To provide means whereby the circuit-breaker can be closed rapidly without hesitation at all currents from zero to rated making current capacity.

(2) To hold the circuit-breaker in closed position by toggles or latches till tripping signal is received.

(3) To allow the circuit-breaker to open without delay immediately on receiving tripping signal.

(4) To perform the auto reclosure cycle.

(5) To perform the related functions such as indication control.

2.9.1. Closing Operation (C)

Normally, closing the circuit-breaker contacts during normal load does not cause any difficulty. The operating Mechanism has to overcome friction and accelerate the moving masses. However, when the circuit-breaker has to close against a short circuit, additional thermal stresses and electromagnetic stresses are involved.

In EHV circuit-breakers, the arc is established prior to final contact touch. This is known as pre-arcing. Pre-arcing causes higher temperature stresses and pressure due to vaporisation of oil. The contacts should close with sufficient speed to minimise the prearcing.

As soon as the contacts close on an existing short-circuit, breaker is subjected to making current. The electromagnetic forces set-up by the making current tend to repel the contacts. The circuit breaker should have rated making capacity, *i.e.* the highest peak current against which the circuit breaker can be closed at a given voltage. The making capacity of the circuit-breaker depends upon the force and speed with which the closing operation is carried out.

While closing the circuit-breaker, the operating mechanism should have enough power to overcome the opposing forces and accelerate the moving contact assembly rapidly within specified short time.

The opposing forces during closing operation

(*a*) **Electromagnetic forces between contacts.** When the contacts touch during the closing operation, electromagnetic forces appear at the instant of contact touch, their magnitude being proportional to square of the current and the direction being opposite to the direction closing. These forces are large if the breaker is closing on existing short circuit. Breaker should be capable of closing on short circuit.

(*b*) **Action of operating spring.** The moving contacts of circuit-breakers are opened by spring pressure. While closing these spring oppose the closure.

(*c*) **Inertia of movable subassembly.** The movable parts are contacts their holders tension rods, operating links of operating mechanisms, etc. The mass of these sub-assemblies is quite large in EHV circuit-breakers. And their inertia tries to oppose rapid acceleration. In modern EHV circuit-breakers, these parts are made as light as possible.

(*d*) **Opposing forces due to medium such as oil, SF_6 gas.** The movable sub-assembly has to move in dielectric medium which is, in some cases, compressed air/gas/oil at high pressure and density.

The total forces of the operating mechanism should be more than the sum of the above mentioned opposing forces.

(*e*) **Friction.** Static and dynamic.

2.9.2. Opening Operation (O)

The opening operation is significant in the fault-clearing process. As the trip coil is energized the opening operation is initiated. The energy required for the opening operation is obtained from one of the following methods :

— Opening springs charged during the closing operation
— High pressure hydraulic oil stored in accumulators
— High pressure compressed air stored in auxiliary air receivers.

The functional requirements of the opening mechanism are as follows:

(1) To accelerate the moving masses including contacts and linkages rapidly to achieve desired opening characteristic (Fig. 2.6).

(2) To achieve desired speed of contact at contact separation and during the opening stroke (3 to 7 m/s).

(3) To damp the speed at the end of the travel by dampers.

The forces and energy should be adequate to overcome the following:

Opposing forces during opening operating

(*a*) **Electromagnetic forces due to contact-grip.** The current transfer from fixed finger-contacts to movable contact is illustrated in Sec. 8.9. The finger contacts are spring-loaded and their grip oppose the movement of moving contact. During the short-circuit condition, the electromagnetic forces tend to increase the grip of the finger-contact assembly. The forces of contact grip increases in proportion to square of current. Hence it is significant during higher short-circuit currents.

(*b*) **Friction.** The various operating links, bearing surfaces mating surfaces between movable and fixed parts, etc. offer static friction. The frictional component depends upon the coefficient of friction, smoothness of mating surfaces, configuration of moving parts etc. High friction can reduce the initial speed of moving contact which may result in disastrous consequence of failure of the circuit-breaker to quench the arc.

(*c*) Inertia of movable parts. Energy in the operating mechanism is utilised in accelerating the movable sub-assemblies to required speed.

(*d*) **Opposing forces due to quenching medium.** The quenching medium (compressed air, dielectric oil SF_6 gas) itself may offer substantial opposing forces to the movement.

The operating mechanisms should be capable of overcoming these opposing forces and should achieve desired opening characteristic of contact travel during normal and short-circuit opening operations. (Refer Note at the end of this Chapter)

2.9.3. Closing followed by Opening Operating (CO)

The rated operating sequence of the circuit-breaker (Sec. 3.19.8) demands the operation 'CO'. The operating mechanism should have enough stored energy and capability to perform CO operation and rated operating sequence under short-circuit condition.

2.9.4. Types of Mechanisms

The operating mechanisms in circuit-breakers are either 'dependable' or 'stored energy type'. Dependent operating mechanisms depend on continuity of power supply or manual forces during closing. They are accordingly called as :

— dependable manual operating mechanisms
— dependable power mechanisms.

The stored energy type operating mechanisms are called independent operating mechanisms as they are independent of continuity of power supply or the skill of the operator. In such mechanisms the energy required for closing in stored in a charged spring or in compressed gas-hydraulic oil.

Stored energy type independent automatic operating mechanisms are used in all high voltage circuit-breakers above 200 MVA. These can be classified as follows :

— Spring opened, spring closed Mechanism.
— Solenoid closed, spring opened Mechanism
— Hydraulic Mechanisms
— Pneumatic Mechanisms etc.

(*a*) **Spring Opened Spring closed Mechanism.** In such a mechanism the opening and closing operations are achieved by means of separate springs.

The closing spring is of higher energy level and is charged by motor driven gear. When closing signals is given to the closing coil, the closing spring energy is utilized in closing the moving contacts and also for charging the opening springs. During the opening operation, the opening signal is given to trip-coil. The movable system is unlatched and the energy of the opening spring is released to obtain the opening. The closing spring is automatically charged after each closing operation. Hence energy is always available for reclosing the breaker. The oil-dashpots are provided for damping the forces at the beginning of opening and closing strokes. Springs have maximum force at the beginning of travel and the force reduces at the end of the travel. This is disadvantageous in closing operation. Both opening and closing operations are initiated by high speed, electromagnetic operated latches.

(*b*) **Pneumatically-closed spring-opened Mechanism.** Pneumatically closed spring-tripped mechanism are used for extra-high voltage minimum oil circuit breakers and SF_6 circuit-breakers. In such mechanisms, the circuit breakers is closed by means of pneumatic cylinder and piston. The compressed air required for the closing operation is obtained from a local air-receiver mounted inside the mechanism cubicle. During the closing stroke, the tripping springs are charged. The tripping spring is released by a latch operated by high speed electromagnetic energized by the trip coil. The closing operation is initiated by operation of a solenoid operated pneumatic value, which admits the compressed air into pneumatic cylinder. Damping is provided in pneumatic cylinder.

(*c*) **Solenoid-closed Spring-opened Mechanism.** In such mechanism the closing operation is obtained by energising a solenoid by direct current. When direct current is passed through the solenoid, the plunger is attracted. The plunger sets into motion the link mechanism resulting in closing of the breaker. The opening springs are charged during the closing operation. Solenoid has maximum force of attraction when plunger is fully inserted and the air-gap is minimum. This is advantageous in closing operation.

The solenoid requires d.c., supply which it takes from battery or rectifier. The solenoid is supplied at 110 or 220 V d.c. The current taken by solenoid is relatively high. Solenoid mechanism can be suitable for auto-reclosing.

Solenoid operating mechanism is a separate unit mounted on the front of the circuit-breaker. When current is passed through the solenoid it attracts the plunger which in turn sets into motion the link mechanisms resulting in closing of breaker.

When the breaker is closed, it is held in latched or toggled position, When the tripping signal is received, the latch is released and the breaker opens by spring action. Generally the links have three positions—tripped, reset, closed.

Solenoid closing mechanisms are used with low voltage and medium voltage circuit-breakers. On EHV circuit-breakers, the power requirement of solenoid mechanism tends to be too large (above 50 kW in some cases). Hence they are not preferable.

(*d*) **Pneumatic Operating Mechanism.** Pneumatic operating mechanisms are preferred in stations where compressed air supply is available *i.e.* where air blast circuit-breakers are installed.

Air blast circuit-breakers are invariably provided with pneumatic operating mechanisms. The operating rod is linked with the piston in pneumatic cylinder in the control cubicle of the operating mechanisms.

Compressed air at thigh pressure is used for closing. High pressure air is stored in the air receiver of the breaker. The air comes in the reservoir from the compressed air system. While closing the air at high pressure (18-30 kgf/cm^2) is admitted in the pneumatic cylinder. The closing piston is pushed by compressed air. Thereby the levers move the closing operation is obtained. The automatic operations are achieved by means of solenoid operated pneumatic valves.

In SF_6 circuit-breakers spring assisted pneumatic mechanisms are preferred for opening and closing.

In air blast circuit-breakers the high pressure air is admitted in arc extinction chambers. The moving contacts are pushed against spring pressure (Details in Ch. 6).

Pneumatic operating mechanisms require the auxiliary set up for the supply of high pressure air.

In some hybrid-operating mechanisms, the pneumatic pressure is utilized to charge the closing spring. Then the stored energy of the spring is utilized for closing the breaker. Such operating mechanisms are called pneumo-spring mechanisms.

(*e*) **Hydraulic mechanisms.** The hydraulic system comprises the following essential components:

— motor driven hydraulic pump, accumulators
— Hydraulic valves and piping
— Oil tank
— Hydraulic cylinder, piston, etc.

The oil is maintained high pressure in the accumulators (300 to 350 kgf/cm^2). The piston can be moved with high pressure by opening of hydraulic valves and letting in the hydraulic oil from the accumulator into the cylinder. This movement is utilized to operate the links so as to close the circuit-breaker contacts.

During opening, the high pressure oil acts on upper area of piston and opening stroke is obtained.

2.10. INTERLOCKS, INDICATION AND AUXILIARY SWITCH. (Ref. Sec. 26.3)

Interlocking devices are those which make to operation of the switching device dependent upon the position or operation of other equipment. Interlocks are provided as a safety measure against erroneous operation of a switching device. The interlocks are of the following forms: Electrical Interlock, Mechanical Interlock.

Electrical interlock can be used between remote equipment, mechanical interlock can be provided for the operating mechanisms of the two adjacent equipments. The electrical interlock comprises coil and bolt. When the coil is energized, the bolt is drawn by magnetic attraction and the interlocking is achieved. Interlocks are provided between circuit-breaker, isolator and earthing switch to ensure the following sequence :

While opening :
— First to open: Circuit-breaker — Next to open: Isolator
— Then the earthing switch (if any) to close

While closing :
— Open earthing switch — Close isolator
— Then close circuit-breaker.

This sequence must be followed because Isolators are no load disconnecting devices. They do not have breaking capacity, nor do they have making capacity. Hence breaker performs the opening and closing duty.

Indicator or indicating device indicates whether the switching device is in 'open' or 'closed' position. Such indication is available on the glass-window on the control cabinet near the breaker, in form of a flag marked open close. One breaker panel, the indication is obtained by means of lamps. Thus, from the control room, the operator can know the position of circuit-breakers and isolators. (Breaker Panel in installed in control room).

Auxiliary switches have standard number of pairs of contacts (6, 8, 12). Auxiliary switch has two positions 'open' and 'close' corresponding to the position of the circuit-breaker. In each position, some auxiliary circuits are opened and some are closed. The auxiliary circuits serve several purposes such as:

(1) **Indication.** Breaker open or closed by lamps, near circuit-breaker and at a remote place.

(2) **Electrical Interlocks.** The breaker is interlocked electrically with isolators. The connections to solenoids in operating mechanisms are made through the auxiliary switch.

(3) Connections for relaying, auxiliary circuits of operating mechanisms.

The various terminals are connected in a terminal blocks in the operating cubical.

2.11. CIRCUIT-BREAKER TIME (TOTAL BREAK TIME) (Ref. Sec. 3.19.23)

Fault clearing time is the sum of relay time and circuit-breaker time. Circuit-breaker time is also called total break time.

The rapid fault clearing of extra-high-voltages transmission lines improves the power system stability. Hence faster relaying and fast circuit-breakers are preferred for extra-high-voltage transmission lines, the circuit-breaker time being of the order of 2.5 cycles, 2 cycles.

For distribution system such a fast clearing is not necessary. Discrimination is obtained by graded time-lag. Hence Slower Circuit breakers, 3 to 5 cycles are used.

Remember the Time Events :

[Fault clearing Time]	=	[Relay Time]	+	[Circuit-breaker Time]
[Relay Time]	=	[Instant to fault]	to	[Closure of Trip Circuit]
[Circuit-Breaker Time]	=	[Closure of Trip Circuit]	to	[Final Arc Extinction]
	=	[Opening Time	+	Arcing Time]

Relay time is the time elapsed between the instant of occurrence of fault and instant of closure of relay contacts *i.e.* closure of trip circuit.

Circuit-breaker time is the time elapsed between the instant of closure ot trip circuit and the instant of final current zero. Circuit-breaker time is the sum of time required for operating mechanism to open the contacts and the arcing time. Total break time is equal to the sum of opening time and the arcing time.

Thus the fault clearing time is elapsed time between the instant of occurrence of fault and the instant of final arc interruption.

The circuit-breaker time is of the order of a few cycles. One cycle equals 1/50 seconds in 50 cycles per second system. Circuit-breaker time of EHV circuit-breaker of the order of 2.5 cycles. Circuit-breakers of time more than 5 cycles can be considered as slow.

2.12. AUTO RECLOSURE (Ref. Sec. 44.5 and 44.132)

Many faults on overhead transmission lines are transient in nature. Statistical evidence shows that about 90% of faults are used by lightning, birds, vines, tree branches etc. These conditions result in arcing faults and the arc in the fault can be extinguished by de-energizing the line by simultaneous opening of circuit-breakers on both ends of the line or on one end of the line. Since the cause of transient faults mentioned above disappears after a short time the circuit-breakers can be reclosed as soon as the arc in fault has been extinguished and the path has regained its dielectric strength. Reclosing of lines restores the supply continuity of service is the major advantage of Auto-enclosure. If the fault is transient one the normal condition is restored by auto reclosure.

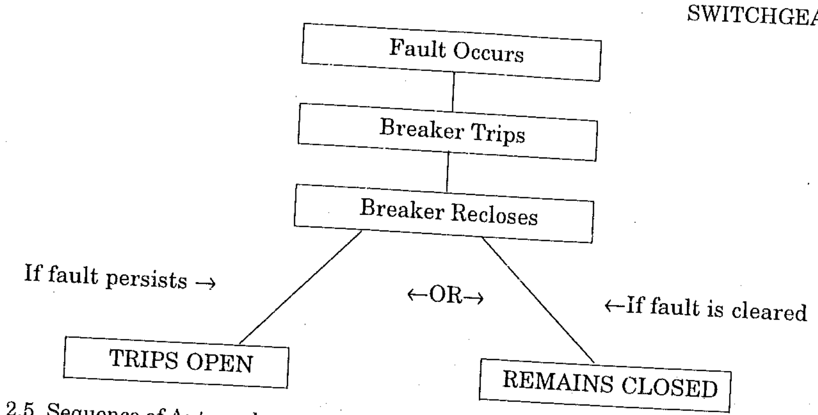


Fig. 2.5. Sequence of Auto reclosure for EHV, bulk of power transmission lines. Single Shot Scheme.

High speed tripping and high speed reclosing improves the stability of power system*. Henc the circuit-breakers and relaying on EHV lines are provided with auto reclosing feature. Tests o high voltage systems have shown that a reclosure in 12 cycles (0.24 sec) is practical the perio depending upon the time necessary to dissipate the ionised air of arc path.

The Auto-reclosing of EHV lines is high speed and single shot, *i.e,*. only one reclosing is at tempted.

2.13. AUTO RECLOSURE OF EHV CIRCUIT BREAKERS FOR TRANSMISSION LINES

The timing of EHV Auto-reclosure is based on the following requirements.........(Ref. Sec. 44.12

— It is a single-shot Reclosure.

— the arc in the fault should de-ionise before allowing reclosure. Hence certain 'Dead Time' of the order of 0.2 seconds is provided between opening and reclosing of C.B.

— the operating mechanisms of c.b. to open and to close as per desired operating sequence.

Looking Fig. 2.6 the following sequence can be observed:

Table 2.2

(Refers to Fig. 2.6) (Ref. Sec. 3.19.23)

Sequence	*Time in 1/100 Second*	*Operation*	*Remarks*
1	0	Fault occurs	Circuit-breaker closed. Protective gear starts operating.
2	0-4	Relay time	Fast relaying
3	4	Trip circuit closed	Operating mechanism starts to open.
4	4-9	Opening time of breaker	
5	9-12	Total break time	Breaker is of 4 cycles
6	12-36	Dead time	12 cycles for deionization. CB remains open.
7	27	Contacts start closing	
8	36	Contact touch for reclose	
9	40	Circuit-breaker reclosed	Will be opened again if fault persists and will lock-open.
10	Single shot is complete, the circuit-breaker will remain closed, if fault has vanished CB will open again if fault persists and will remain locked-open.		

* Rapid Auto-reclosing: For weakly interconnected systems, Delayed Auto-reclosing: a for strongly interconnected systems. (Ref. Sec. 44.12)

— C.B.'s at both ends of the line should reclose simultaneously.

— Deionization time for arc space in fault on overs-head line depends on several aspects such as magnitude of fault current, service voltage, length of line wind condition, spacing of conductors etc. Generally the time allowed is based on rated voltage of line and is as follows:

— The circuit-breakers should be capable of withstanding the electrodynamic stress in case they are reclosing on an existing short circuit. The pressure in the reservoir generally reduces after the first opening, thereby there is a reduction in breaking capacity for the subsequent opening. This aspect should be taken care of while designing the circuit-breakers suitable for auto-reclosure.

Voltage of Transmission line (kV)	*Rated voltage of C.B. (kV)*	*Minimum Deionization time necessary, Cycles*
66	72.5	5
132	145	9
220	245	14
400	420	18

2.14. AUTO RECLOSURE FOR DISTRIBUTION LINES (upto 33kV)

In rural distribution overhead lines are used. The spacing between conductors is relatively close. The disturbance on such lines are generally trasient, as described earlier. Auto reclosure is therefore, suitable in improving the continuity of service. The usual procedure was to reclose circuit-breaker three times between 15 to 120 seconds.

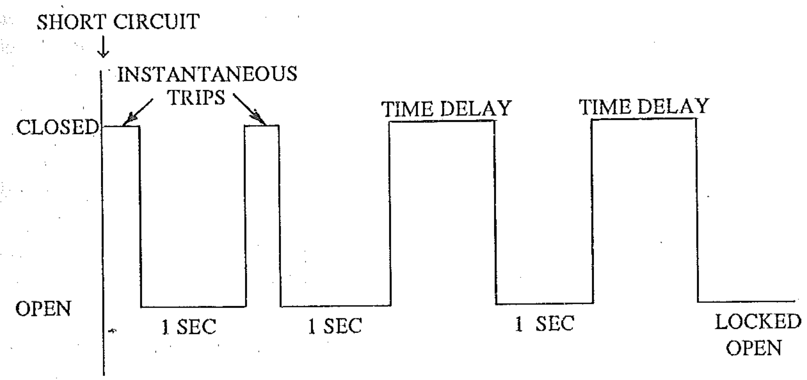


Fig. 2.7. Auto reclosure cycle of a 12 kV c.b. for rural distribution.

If the breaker trips after the third reclosure, it opens and remains open. The attendant thereby knows that the fault is permanent and sends electricians to locate and correct the fault. The auto reclosure cycle is illustrated in Fig. 2.7, but the sequence may vary in other cases. This practice is no more favoured in modern distribution systems.

2.15. WEIGHT OPERATED RECLOSING, POLE MOUNTED CIRCUIT-BREAKERS

Such circuit-breakers were used in rural distribution. An endless chain passes over a pulley on the end of an operating shaft. The operating shaft is brought out through the side of the breaker top plane. A weight is attached to the chain. The energy required to reclose the breaker is derived from the weight falling due to gravity. The timing mechanism controls the open-circuit time (about 30 sec.)

2.16. TRIP-FREE FEATURE

Suppose the breaker has been instructed to close by manual instruction by pushing of push button. The operating mechanism will start operating for closing operation. Meanwhile a fault has taken place and a relay close the trip circuit of the breaker. The Trip-Free mechanisms, permits the circuit-breaker to be tripped by the protective relay even if it is under the process of closing. This feature is called *Trip Free* feature. Another feature of operating mechanisms is to prevent 'Pumping', *i.e.* alternate tripping and closing if the closing button is held closed during a fault.

In oil circuit-breakers and puffer type SF_6 circuit-breakers, the contacts should be allowed to touch during the end of the closing stroke before the start of the opening operation.

2.17. MATERIALS

The materials are important in switchgear manufacturing. Normally all the incoming materials are tested in the factory before acceptance. The manufacturer maintains with him all the necessary standards of material specifications.

Currents Carrying Parts

These include contacts, contact stems, flanges bus-bars, bushing-conductors connectors etc. The design of conducting parts is based on the following requirements:

— temperature rise during normal continuous current.

— temperature stresses during short-time current. (rated duration of short-circuits)

— mechanical stress during opening and closing operation.

— mechanical stresses due to electromagnetic forces under short-circuit conditions.

Insulating Parts

These include interrupter-enclosures, insulating supports for interrupters, supports to bus-bars insulating pull-rods connecting the operating mechanism to the moving contacts, insulating tubes enclosing the arc-control devices etc.

2.18. DESIGN AND DEVELOPMENT

The development of a new circuit-breaker comprises the following major activities (Ref. Sec. 12.3).

(1) Research. The research on arc quenching techniques, various thermal, electrical, mechanical stresses under various switching conditions, design principle for arc quenching etc. This is carried out in research laboratories.

Table 2.3 Material Used in Circuit-Breakers and Metal Enclosed Switchgear, Controlgear

	Material	*Applications*	*Remarks*
1.	Porcelain	Enclosures for Interrupter support Procelain, support for bus-bars insulating tubes solid rods etc.	Compression strength 6000 kg/cm^2. Tensile Strength 3000 kg/cm^2. Ceramic material made by firing clay, glazing and firing again. Suitable for outdoor use.
2.	Epoxy Resin	Support Insulators for indoor applications, enclosures covers encapsulation etc.	Used in solid form. Obtained by maxing with suitable hardener and curing a suitable temperature, suitable fillers used. Not suitable for outdoor use.
3.	Glass fibre reinforced synthetic resin	Insulating drive rods, insulating tubes for interrupted	High tensile strength, withstand pressure, dielectric strength.
4.	Polytetra fluroethelene PTFE	Nozzles for SF_6 Breakers, bearings, Piston rings etc.	Low friction; arc resistant; can be moulded/machined. Pure PTFE is insulating used with various filters.
5.	Electrolytic Copper (99.9% purity)	Bus-bars Main contacts conducting parts, terminals	Ref. Sec. 17.16
6.	Eletrical grade aluminium	Busbar, conducting parts, casting, terminals Enclosures of SF_6 GIS, Enclosures of busbars Eclosures of busducts	Ref. Sec. 17.16
7.	Tungsten Copper	Arcing contacts	80% Tungsten, 20% copper, sintered material
8.	Stainless Steel	Enclosures of SF_6 GIS parts enclosed circuits	
9.	Copper-bismuth, Copper-Chromium, Copper-berrylium	Main Contacts of vacuum interrupters, Contactors	High conductivity, low welding-tendency. Ref. Sec. 9.9.5

(2) **Design and development of Prototypes.** The structural configuration (Sec. 2.8) is decided first. Then the various sub-assemblies are designed and finally the complete breaker is designed. Full scale prototypes are manufactured.

(3) **Development Testing.** Various development tests (Sec. 10.1) are carried-out on sub-assemblies poles, mechanism and complete breaker.

(4) **Type Tests for Certifications** (Sec 10.1) These are exhaustive test as per standards.

(5) **Actual Installation** in system for observing performance.

Summary

Circuit breakers are classified on the basis of the arc quenching medium as: Air break; bulk-oil; Minimum oil; Air blast; vacuum ; SF_6. While various types are in service; the trends in new installation is in favour of;

Low voltage (upto 1000 V): Air-Break CB and Contractors

Medium Voltage (upto 33 kV): VCB and SF_6 CB

High Voltage (33 kV and above): SF_6 and SF_6 insulated GIS.

QUESTIONS

1. With the help of a neat sketch, describe the configuration of an outdoor, triple pole circuit beaker for 36 kV application. Name the parts and explain the operation of the circuit breaker during fault clearing.
2. Explain the functions of operating mechanism of a circuit breaker and describe the motor Charged Spring Mechanism.
3. Describe a trip circuit and the fault clearing process.
4. Explain the purpose of Auto Reclosing of an EHV Circuit Breaker controlling an over head transmission line. State the sequential events in a single shot auto reclosing scheme.
5. Explain the functions of isolator, earthing switch and circuit breaker. State the sequence during opening and closing of circuits. State the interlocks necessary to prevent accidents.

3

Fundamentals of Fault Clearing, Switching Phenomena and Circuit-Breaker Ratings

Transient phenomena during fault clearing—Shortcircuit current—Transient, Sub-trasient and Steady-State—Current and voltage variation during arc extinction process—Transient Recovery voltage—Switching phenomena—Circuit-breaker ratings.

3.1. INTRODUCTION

The following phenomena can be observed during the fault clearing process :

1. As the fault occurs, the current increases to a high value during the first half cycle of the wave and thereafter the amplitude of the wave goes on reducing as the waveform passes through the sub-transient, transient and steady state. The waveform of the current is asymmetrical about the normal zero axis.

2. The voltages across the circuit-breaker pole after the final arc extinction (called the transient recovery voltage) has a relatively high amplitude and rate of rise. The voltage has a high frequency transient component superimposed on a power frequency component.

In this chapter the above mentioned phenomena have been studied with reference to the behaviour of circuit-breaker. For the purpose of analysis, simple RLC networks have been considered. The generator has been represented by an e.m.f source. The equations of voltage and current have been solved by simple rules of differential calculus.

The analysis of short-circuit current and transient recovery voltage is followed by *Circuit-Breaker Ratings* (Sec. 3.19)

3. Overvoltages can be generated while closing circuit-breaker on capacitor banks or loaded transmission lines. These are minimised by pre-closing resistors and surge suppressors.

3.2. NETWORK PARAMETERS : R, L, C

An electrical network comprises the following network parameters:

— Inductance — Capacitance — Resistance.

The resistance can be neglected as a first approximation.

(*i*) **Inductance.** Inductance is defined as

$$L = \frac{d\Lambda}{di} \text{ henry} \qquad \text{...(3.1)}$$

where L = Inductance of circuit, henry.

A = Flux linkage due to current i, weber turns

i = current in the circuit, amp.

The e.m.f. induced in an inductor is given by,

$$e = \frac{d\Lambda}{di} = L\frac{di}{dt} \text{ volts} \qquad \text{...(3.2)}$$

Energy in inductance L henry at the instant when the current in it is i amp. is given by,

$$W_m = 1/2Li^2 \text{ joules} \qquad \text{...(3.3)}$$

(1 joule = 1 watt second)

In an inductive circuit current cannot change instantaneously. Hence when the *e.m.f* is applied at $t = 0$. The current is zero at the instant of closing the switch. Also we know that the current lags behind applied voltage by 90° in the inductance.

Considering sinusoidal voltage applied to an inductance, the current lags by 90°, therefore, the voltage of the circuit has maximum instantaneous value at the current zero.

While interrupting the current flowing through an inductive circuit such as a transformer on no load, a transformer loaded by an inductor, etc. the circuit-breaker should interrupt the arc at natural current zero of the altenating current wave. If the arc extinction takes place at the natural current zero, the energy in the inductance ($1/2Li^2$) is zero. However, if the arc is suddenly interrupted before the natural current zero, at the instantaneous value of current, say i amperes, the energy $1/2Li^2$ is suddenly interrupted by the chopping of current to an artificial zero value. Due to such a phenomenon. The interrupting of low magnetising currents of transformers, reactors need a particular attention. The circuit-breaker should be capable of interrupting such currents without getting damaged or without giving rise to over voltage above the permissible limits.

(*ii*) **Capacitance.** The well-known definition of the capacitor is: "Two or more conductors separated by dielectric (insulating) medium." The capacitance C is given by

$$C = \frac{dq}{dv} \text{ farads} \qquad \text{...(3.4)}$$

where C = capacitance farads ; q = charge, coulombs ; v = voltage, volts.

From the above definition, it is understandable that transmission lines, bushing, circuit-breakers etc. have inherent capacitance between phase and ground. In some cases the capacitance may be negligible. In h.v. circuit it becomes important and may not be negligible. In circuit-breaking phenomenon, capacitance plays an important role. The voltage across capacitor is given by

$$dv = \frac{dq}{C} \text{ volts}$$

$$v = \frac{1}{C}\int dq = \frac{1}{C}\int idt$$

Energy in a capacitor is in the form of electric field and is given by

$$W_c = \frac{1}{2}Cv^2 \text{ joules} \qquad \text{...(3.5)}$$

where C is in farads

v is in volts, q is the charge in coulombs.

There exists a distributed capacitance between conductors and between conductor and ground in case of transmission lines. The flow of alternating current in the transmission line is associated with alternate charging and discharging of this capacitance. The currents taken by the capacitance for charging are called charging currents. The charging current flow in transmission line, even if the receiving end is open circuited. The voltage across a capacitor cannot change instantaneously.

While closing a circuit-breaker on a predominantly capacitive circuit like a capacitor bank, the current flowing in the capacitance is given by

$$i = C\frac{dv}{dt}$$

where i = Instantaneous value of current amperes

C = Capacitance farads

dv/dt = Rate of change of voltage, volts/sec.

The current inrush during the closing of capacitive circuit can occur during pre-arcing between the circuit-breaker contacts. The following duties can produce severe stresses on the circuit-breaker:

— Paralleling of two capacitor banks
— Closing and opening capacitor banks.
— Closing and opening unloaded transmission lines on no load

3.3. VOLTAGE EQUATION OF AN RLC SERIES CIRCUIT

The voltage equation of an *RLC* series circuit is given by

$$e = L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \text{ volts} \qquad \text{...(3.6)}$$

where e = impressed voltage

$L\frac{di}{dt}$ = voltage across inductor

Ri = voltage across resistor

$\frac{1}{C}\int idt$ = voltage cross capacitor.

For an alternating *e.m.f.* the induced voltage e is given by

$$e = E_m \sin(\omega t + \theta) \qquad \text{...(3.7)}$$

where, $E_m = \sqrt{2}$ Erms and $\omega = 2\pi f$. Angle θ depends on magnitude of e at $t = 0$. If e is Zero at $i = 0$, then $\theta = 0$ if $e = E_m$ at $t = 0$ then $\theta = \pi/2$.

3.4. SUDDEN SHORT CIRCUIT OF R.L. SERIES CIRCUIT

Let us see, what happens, when switch S of circuit shown in Fig. 3.1 is suddenly closed.

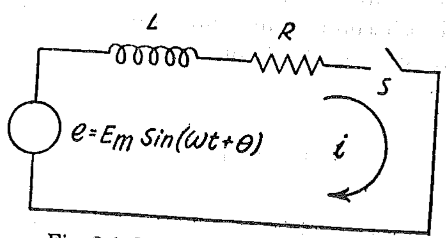


Fig. 3.1. *RL* series circuit under study.

Writing as equation for current i on the basis described in section 3.3,

$$L\frac{di}{dt} + Ri = e = E_m \sin(\omega t + \theta) \qquad \text{...(3.8)}$$

We shall solve this equation to obtain an expression for current i.

Eq. (3.8) is a non-homogeneous differential equation of first order. The complete solution is the sum of complementary solution, *i.e.* and particular solution *ip i.e.*

$$i = i_c + i_p \qquad \text{...(3.9)}$$

Complementary Solution, i_c. The auxiliary equation is obtained by putting the right hand side Eq. (3.8) equal to zero,

i.e. $$L\frac{di}{dt} + Ri = 0$$

Rearranging the terms,

$$\frac{di}{i} + \frac{R}{L}dt = 0$$

Integrating, $$\log i + \frac{R}{L}t = k$$

i.e., $$\log i = -\frac{R}{L}t + k$$

where k is a constant of integration given by $k = \log_e A$, where A is some other constant. Further, we know that $\log_e e^x = x$ Hence

$$\log_e i = \log_e e^{(-R/L)t} + \log A$$

Taking anti-log $$i = A\, e^{(-R/L)t} \qquad \text{...(3.10)}$$

This is complementary solution of current i. It is an exponentially decaying component called *D.C. Component.* The magnitude of constant A depends on initial conditions. A may be zero, positive or negative depending upon magnitude of e at $t = 0$.

Particular solution of i **(**i_p**)** Take a trial solution

$$i = C\cos(\omega t + \theta) + D\sin(\omega t + \theta) \qquad \text{...(3.11)}$$

Such a trial solution is taken because the R.H.S. of Eq. (3.8) is of the form $E_m \sin(\omega t + \theta)$.

Obtain $\frac{di}{dt}$ and $\frac{di^2}{dt^2}$ of Eq. (3.11)

and subtitute in Eq. (3.8). Equate the coefficients of like terms from both the sides to get

$$C = -E_m \frac{\omega L}{R^2 + \omega^2 L^2} \qquad \text{...(3.12)}$$

$$D = E_m \frac{R}{R^2 + \omega^2 L^2} \qquad \text{...(3.13)}$$

Substituting these values of C and D in Eq. (3.8) we get

$$i = -\frac{\omega L}{R^2 + \omega^2 L^2} E_m \cos(\omega t + \theta) + \frac{R}{R^2 + \omega^2 L^2} E_m \sin(\omega t + \theta) \qquad \text{...(3.14)}$$

Let ϕ be the angle of impedance triangle

$$\phi = \tan^{-1}\frac{\omega L}{R}$$

$$\sin\phi = \frac{\omega L}{\sqrt{R^2 + \omega^2 L^2}}\,; \quad \cos\phi = \frac{R}{\sqrt{R^2 + \omega^2 L^2}}$$

Substituting $\sin\phi$ and $\cos\phi$ in Eq. (3.14),

$$i = \frac{-E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin\phi\cos(\omega t + \theta) + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \cos\phi\sin(\omega t + \theta).$$

The R.H.S. of the above Eq. is of the form

$$\sin(A - B) = \sin A\cos B - \cos A\sin B$$

$$\therefore \quad i = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(\omega t + \theta - \phi) \qquad \text{...(3.16)}$$

Eq. (3.16) is particular solution of Eq. (3.8). It is sinusoid called *A.C.* Component.

Complete solution

$$i = i_p + i_c$$

From Eqs. (3.10) and (3.16), we get

$$\boxed{i = Ae^{(-R/L)t} + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(\omega t + \theta - \phi)} \qquad \text{...(3.17)}$$

This is a complete solution of Eq. (3.8). Let us put the initial condition to evaluate A.

At $t = 0$; $i = 0$. Because the current in inductive circuit does not change instantaneously. Assuming R to be too small as compared with ωL;

$$\sqrt{R^2 + \omega^2 L^2} = \omega L$$

and

$$\omega = \tan^{-1}\frac{\omega L}{L} = 90°$$

Case 1. Switch closed at $e = 0$

Hence $\quad e = 0$ at $t = 0$

$\therefore \quad \theta = 0.$

Also $\quad i = 0$ at $t = 0.$

From Eq. (3.17)

$$0 = A + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}}\sin(-90°)$$

$$\therefore \quad A = +\frac{E}{\omega L}$$

This is maximum value of A, hence the d.c. component is maximum when switch is closed at voltage zero. This case is called *Doubling Effect.* Because peak value is $2E_m/\omega L$, at the peak of first current loop. There is as slight drop in the instantaneous value of the current from $t = 0$ to the $t = \frac{\pi}{2}$. Therefore, the peak value can be considered to be approximately $1.8E_m/\omega L$ instead of $2E_m/\omega L$.

Case II. Switch closed at $e = E_{max}$

$$e = E_{max} \text{ at } t = 0.$$

$$\theta = \pi/2$$

$i = 0$ at $t = 0$ we get

$$0 = A + E_m/\omega L \sin(\pi/2 - \pi/2).$$

$$A = 0$$

Hence A is zero, if switch is closed when $e = E_{max}$. Thereby the d.c. component is also zero.

From cases I and II we observe that the magnitude of initial value of d.c. component $Ae^{-(R/L)t}$ depends upon the moment of closure of switch, or voltage at the instant of occurrence of short circuit.

Let us interpret result of the solution.

When an *R-L* series circuit is closed with an alternating voltage source, the resulting current consists of two components, the d.c. component and a.c. component. The a.c. component is superimposed on the d.c. component. The magnitude of d.c. component depends upon the voltage at the instant of closing the switch. When the switch is closed at voltage zero, the d.c. component is maximum (Fig. 3.2). If the switch is closed at voltage maximum, d.c. component is zero and the waveform is symmetrical about the normal zero axis as shown in Fig. 3.3.

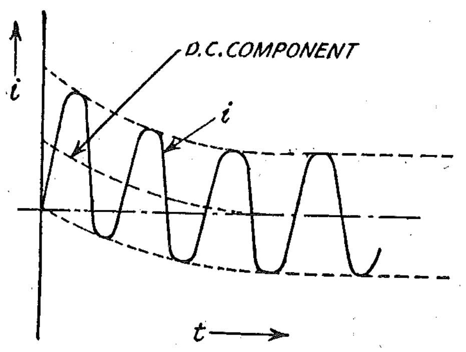


Fig. 3.2 Switch closed at voltage zero, d.c. component maximum.

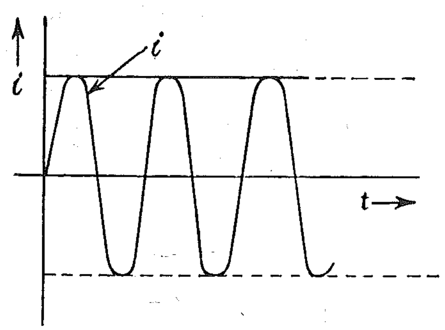


Fig. 3.3 Switch closed at voltage maximum, no d.c. component.

Example 3.1. A.C. transient R-L circuit. *A 50 Hz sinusoidal voltage of implitude 400 volts is applied to a series circuit of resistance 10 ohm and inductance of 0.1 H. Find an expression for the value of the current at any instant after the voltage is applied, assuming the voltage is zero at the instant of application. Calculate the value of the transient current 0.02 sec after switching on (P. Sm.)*

Solution. Refer to the derivation in section 3.2

Given :

$$R = 10 \text{ ohm}$$

$$L = 0.1 \text{ henry}$$

$$f = 50 \text{ Hz}$$

$$2\pi f = 314$$

$$\sqrt{R^2 + \omega^2 L^2} = \sqrt{10^2 + (31.4)^2} = 33 \text{ ohm}$$

$$\text{Angle } \phi = \tan^{-1}\omega L/R = \tan^{-1} 31.4/10$$

From the mathematical table, we get

$$\phi = 73.35° = 1.26 \text{ radians}$$

$$e = E_m \sin(\omega t + \theta)$$

at $\quad t = 0, e = 0$

since the switch is closed at voltage zero.

Hence $\quad \theta = 0$

The equation for R-L circuit current is

$$L\frac{di}{dt} + Ri = e = E_m \sin(\omega t + \theta).$$

The solution (Eq. 3.17) is $i = Ae^{-(R/L)t} + \dfrac{E_m}{\sqrt{R^2 + \omega^2 L^2}}\sin(\omega t + \theta + \phi)$

Putting the value of i at $t = 0$ and other given quantities

$$0 = A(e^0) + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}}\sin(0 + 0 - 72.35°)$$

i.e.

$$A = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}}\sin 72.35 = \frac{400}{34}(0.953) = 12.1\ (0.953)$$

Hence $\quad i = 12.1(0.953e^{-100t} + \sin(314t - 1.26)].$

Angle in the bracket is given radians. This is the required expression for current. **Ans.**

The magnitude of (d.c. component)

at $t = 0.02$ second is given by

$$i_{dc} = A^{e-(R/L)t} = 12.1 \times 0.953e^{-100 \times 0.2} = 1.56A. \quad \textbf{Ans.}$$

Example 3.2. *A 50-cycle alternating voltage is applied to an R-L series circuit by closing a switch. The resistance is 10 ohm. Inductance is 0.1 Henry. The r.m.s. value of applied voltage is 100 volts.*

(*a*) *Find the value of d.c. component of current upon closing the switch if instantaneous value of voltage is 50 at that time*

(*b*) *What value of instantaneous voltage will produce a maximum d.c. component of current upon closing the switch ?*

(*c*) *What is the instantaneous value of voltage which will result in the absence of any d.c. component upon closing the switch ?*

(*d*) *If the switch is closed when instantaneous voltage is zero, find the instantaneous current 0.5, 1.5, 5.5 cycles later.*

Solution. Let us calculate the quantities for Eq. (3.17) *i.e.*

$$i = Ae^{-(R/L)t} + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(\omega t + \theta + \phi)$$

$$R = 10\Omega$$

$$L = 0.1 \text{ H}$$

$$e^{-(R/L)t} = e^{-100t}$$

$$\sqrt{R^2 + \omega^2 L^2} = \sqrt{10^2 + (0.4)^2} = 33 \text{ ohm}$$

$$\phi = \tan^{-1}\frac{\omega L}{R} = \tan^{-1}\frac{31.4}{10} = 72.35°$$

$$2\pi \text{ radians} = 360°$$

$$72.35° = 1.26 \text{ radians}$$

$$E_{rms} = 100 \text{ V}$$

$$E_{max} = \sqrt{2}E_{rms} = \sqrt{2} \times 100 = 141.3$$

$$i. = e^{-100t} + \frac{141.3}{33}\sin(314t + \theta - 1.26)$$

$$i = Ae^{-100t} + 4.3 \sin(314t + \theta - 1.26) \quad ...(i)$$

This is the equation of current in the circuit.

(*a*) Switch closed at $t = 0$, when $e = 0$ and in an inductive circuit, current does not change instantaneously. Therefore,

$$i = 0 \text{ at } t = 0$$

∴ From Eq. (1), we get

$$0 = A + 4.3 \sin(-1.26)$$

$$A = 4.3 \sin 1.26 \text{ (Note 1.26 is angle in radians)}$$

$$= 4.3 \times 0.953 = 4.1$$

∴ D.C. component at $t = 0$ is given by

$$Ae^{-(R/L)t} = 4.1e^{-100t} = 4.1e^0 = 4.1 \text{ amp}$$

(*b*) The maximum d.c. component will be produced if instantaneous value of applied voltage is zero at the instant of closing the switch.

(*c*) The d.c. component will vanish if $e = E_{max}$, *i.e.* $\sqrt{2} \times 100 = 131.3$ V (instantaneous) at the instant of closing the switch.

(*d*) Like Problem 3.1,

$$0.5 \text{ cycles} = 0.5 \times 0.02 \text{ second}$$

$$1.5 \text{ cycles} = 0.03 \text{ second}$$

$$5.5 \text{ cycles} = 0.11 \text{ second}$$

Substitute in Eq. (1) taking A = 4.1 from part (*a*).

3.5. SUB-TRANSIENT, TRANSIENT AND STEADY STATE

The analysis of sudden short-circuit of an R-L series circuit (section 3.4) will now be applied to three-phase short-circuit of an alternator. An alternator has stator windings having certain resistance and reactance. If we neglect the armature reaction and variation in field current, the current flowing in an altenator phase during the short-circuit has waveform similar to that of an *R-L* circuit short-circuit current wavaform given in Figs. 3.2 and 3.3. However, in the alternator, the waveform is modified by armature reaction. An oscillogram of three-phase currents is shown in Fig. 3.4.

When the alternator is short-circuited, the currents in all the three phases rise rapidly to a high value (10 to 25 times full load current), during the first quarter cycle. The flux crossing the airgap is large during a first couple of cycles. The reactance during these first two or three (there

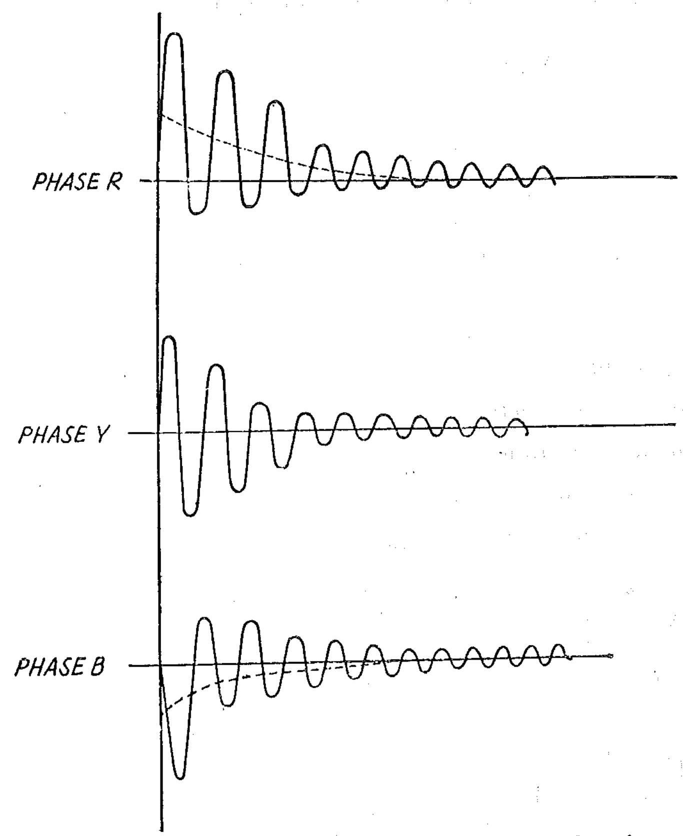


Fig. 3.4 Waveforms of currents in 3-phase short circuit of an alternator.

is no definite number, it depends on the machine) cycles is least and the short circuit current is high. This reactance is called *sub-transient reactance* and is denoted by X''. The first few cycles come under *sub-transient state.*

After a first few cycles the decrement in the r.m.s. value of short circuit current is less rapid than the decrement during the first few cycles. This state is called the *Transient* State the reactance in this state is called transient reactance X'. The circuit-breaker contacts separate in the transient state.

Finally the transient dies out and the current reaches a steady sinusoidal state called the *Steady State*. The reactance in this state is called steady state reactance Xd. The Xd is called direct axis synchronous reactance.

Since the short circuit current of the alternator lags behind the voltage by 90°, the reactances involved are direct axis reactance.

Consider Fig. 3.4; the d.c. components in the three phases are different; hence the wave-forms of the three phases are not identical. If voltage of phase, say, Y, is maximum at the instant of short circuit, d.c. component of short circuit current is zero. Hence the waveform is symmetrical as shown in Fig. 3.5.

Referring to Fig. 3.5 draw an envelope enclosing the waveform.

Extend the portions of the envelopes as shown in the figure. NM is extrended to meet the zero time ordinate at point, A. ML is extended to meet the ordinate at B and LC meets the ordinate of zero time at C. Measure OC, OB and OA.

NM is a portion of envelope in steady state LM is a portion of envelope in trasient state LC is a portion of the envelope is sub-trasient state and LC is the portion of the envelope in sub-transient state.

The currents and reactance are given by the following expressions :

$$I = \frac{OA}{\sqrt{2}} = \frac{E_a}{X_d} \quad ...(3.20)$$

$$I' = \frac{OB}{\sqrt{2}} = \frac{E_a}{X_{d'}} \quad ...(3.21)$$

$$I'' = \frac{OC}{\sqrt{2}} = \frac{E_a}{X_{d''}} \quad ...(3.22)$$

where I = Steady state current, r.m.s. value

I' = Transient current r.m.s. value

I'' = Sub-transient current, r.m.s. value

E_a = Induced e.m.f. per phase

X_d = Direct axis synchronous reactance

$X_{d'}$ = Direct axis transient reactance

$X_{d''}$ = Direct axis sub-transient reactance

OA, OB and OC are intercepts shown in Fig. 3.5.

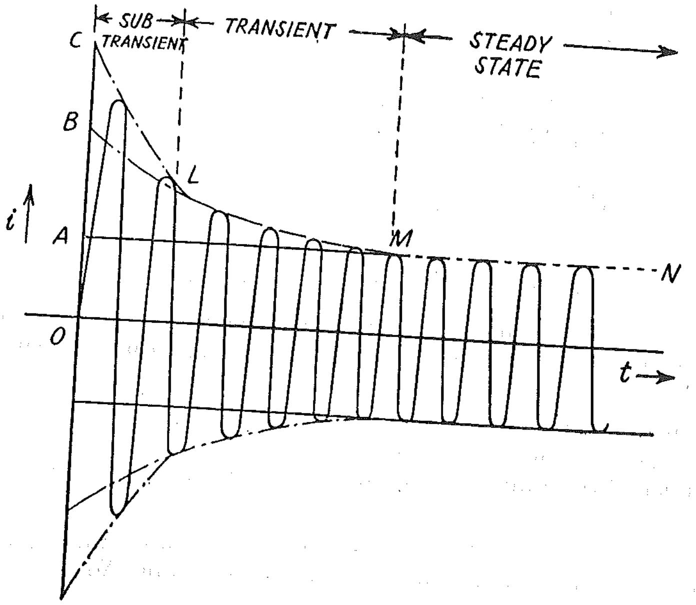


Fig. 3.5 Oscillogram of current is the phase having zero d.c. component.

As the short circuit occurs, the short-circuit current attains high value. The circuit-breaker contacts start separating after the operation of the protective relay. The contacts of the circuit-breaker separate during 'trasient state.' The r.m.s. value of the current at the instant of the contact separation is called the *breaking current* of the circuit breaker and is expressed in kA.

If a circuit-breaker closes on existing fault, the current would increase to a high value during the first, half cycle as shown is Figs. 3.2 and 3.3. The highest peak value of the current is reached during the peak of the first current loop. "This peak value is called *making current* of the circrcuit-breaker and is expressed in kA." The terms 'breaking current' and 'making current' have been discussed in details in section 3.19.

Though the short-circuit current varies continuously during the sub-transient and trasient states, the representative values can be calculated from the equations 3.20, 3.21, and 3.22. The

subtransient, transient and steady-state reactances can be determined experimentally by conducting short circuit test.

It is clear from Eqs. (3.20) to (3.22) that while calculating subtransient, transient and steady state currents; the respective reactances should be considered. The examples of short-circuit current are given in Section II of the book.

3.6. CURRENT INTERRUPTION IN A.C. CIRCUIT-BREAKERS

The waveform of the current and the voltage during the arc interruption process will be studied in this section. This description applies to the circuit-breakers employing the principle of zero-point interruption. Every a.c. circuit-breaker generally adopts the zero-point interruption technique.

Consider a circuit-breaker connected to a generator on no load at rated terminal voltage. The circuit-breaker is in open position and the other side of circuit-breaker is short circuited (Fig. 3.6).

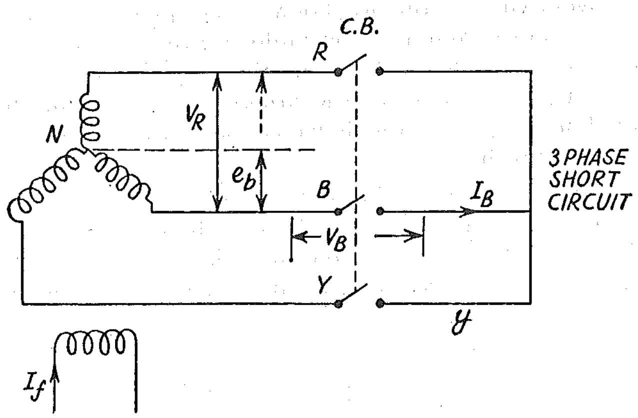


Fig. 3.6 Sudden-3 phase-short circuit of an alternator.

Let the circuit-breaker be closed at the instant when voltage of terminal B w.r.t neutral is zero. In such a case the short circuit current in phase B will have maximum d.c. component and the waveform of current I_b will be unsymmetrical about normal zero axis as shown in Fig. 3.7. The figure shows the typical waveform of short circuit current in a phase having maximum d.c. component. The generator is on no load before $t = 0$. Hence the current is zero before $t = 0$. At $t = 0$, the short circuit is applied and the current increases to a high value during the first quarter cycle. The peak of the first major current loop (shown hatched) is OM and this is the maximum instantaneous value of current during the short-circuit the instantaneous peak value of the first major current loop is called the *Making current.*. In the figure the making current is OM. It is expressed in kA peak.

Let us come to this making current after covering the remaining process (Sec. 3.19.6).

The circuit-breaker contacts separate after a few cycles since the relay and the operating mechanism takes atleast a couple of cycles. Let us assume that the circuit-breaker contacts separate at $t = T_1$ The r.m.s. value of short circuit at the instant of contact separation is termed as *Breaking current.*

After the separation of contacts of the circuit-breaker, an arc is drawn between the contacts. The arc current varies sinusoidally for a few cycles. At $t = T_2$ a particular current zero, the dielectric strength of arc space builds up sufficiently so as to prevent the continuation of arc. At the current zero, this arc is extinguished and is interrupted.

Meanwhile what is happening to the voltage between contacts ? This voltage is recorded in Fig. 3.7. Before $t = 0$, the contacts are closed and the voltage between them is zero. After the separation of the contact ($t = T_1$), the voltage across contact increases. In fact this voltage in the voltage drop across the arc during the arcing period. The voltage across arc is in phase with current since the arc is resistive. The peculiar waveform shape is a result of voltampere characteristic of arc-discharge to be studied later. During subsequent half cycles, the voltages across contact increases due to increased arc resistance. Finally at $t = T_2$ when arc gets extinguished a high frequency voltage transient appears across the contacts which is superimposed on power frequency system voltage. This high frequency transient voltage tries to restrike the arc. Hence it is called Restriking Valtages or Transient Recovery voltage (TRV). The restriking voltage is transient voltage appearing across breaker pole after final current zero. The power frequency system voltage appearing between the poles after arc extinction is called *Recovery voltage.* The transient recovery voltage or restriking voltage has a profound effect on circuit-breaker behaviour. The current that would flow in the circuit if the circuit-breakers were replaced by solid conductor is called prospective current.

The transient recovery voltage (TRV) appearing across the circuit-breaker pole immediately after the final arc interruption causes a high dielectric stress between the circuit-breaker contacts. If the dielectric strength of the medium between the contacts does not build up faster than the rate of rise of the trasient recovery voltage, the breakdown takes place causing re-establishment of the arc. If the dielectric strength of the contact-space builds up very rapidly so that it is more than the rate of rise of transient recovery voltage the circuit-breaker interrupts the current successfully. The rate of rise of TRV, generally depends on the circuit parameters and the type of the switching duty involved. The rate of building up of the dielectric strength depends upon the effective design of the interrupter and the circuit-breaker.

While switching capacitive currents, the high voltage appearing across the contact gap can cause reignition of the arc after initial arc extinction. If the contact space breaks down within a period of one-fourth of a cycle (0.02×0.25) second from initial arc extinction, the phenomenon is called *Reignition.* If the breakdown occurs after one-fourth of a cycle, the phenomena is called *Restrike.* (Ref. sec. 3.20)

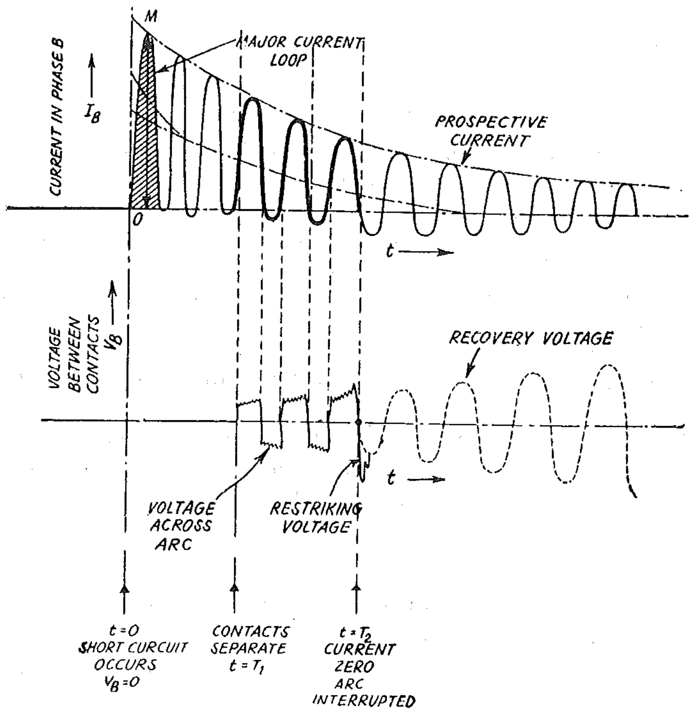


Fig. 3.7. Oscillogram of current and voltage during fault-clearing.

3.7. TRANSIENT RECOVERY VOLTAGE (TRV)

In altenating current circuit-breaker, the current interruption takes place invariably at the natural zero of the current wave.

After a current zero, the arc gets extinguished if the rate of rise of transient recovery voltage between the contacts less than the rate of gain of the dielectric strength. The voltage appearing between the breaker contacts at the moment of final current zero has a profound influence on the arc extinction process. The voltage appearing across contacts after current zero is a trasient voltage of higher natural frequency (restriking voltage). superimposed on the power frequency system voltage (recovery voltage). The trasient component vanishes after a short time of the order of less than 0.1 mill-sec and the normal frequency system voltage is established voltage. After current zero the voltage appearing across the contacts is composed of transient restriking voltage and power frequency recovery voltage.

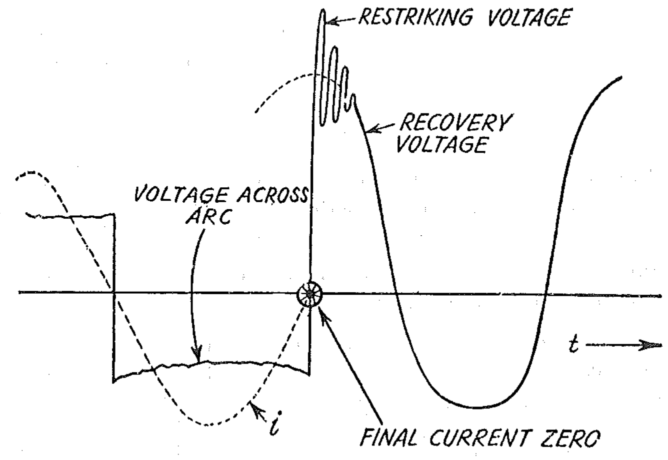


Fig. 3.8 (*a*) Voltages after final current zero (TRV) (Simplified). (Ref. Fig. 3.8*b*)

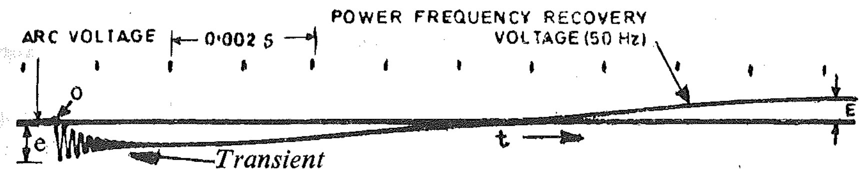


Fig. 3.8 (*b*) Shape of TRV waveform as seen from Cathode-ray oscillographic record.

"Recovery voltage is the voltage which appears across the terminals of a pole of a circuit-breaker after the breaking of current. It refers to the breaker-pole first to clear."

The transient recovery (TRV) or Restriking Voltage is the recovery voltage during the time in which it has a significant transient character. TRV lasts for a few tens or hundreds of microseconds. (Ref. Fig. 3.8*b*)

— It may be oscillatory or non-oscillatory or a combination, depending upon the characteristics of the circuit and the circuit-breaker.

— It is the voltage across the first pole to clear, the same is generally higher than across the two poles which clear later.

Power Frequency Recovery Voltage is the recovery voltage of power frequency (50 Hz.) appearing after the transient voltage has been subsided.

The transient Recovery Voltage refers to the voltage across the pole immediatley after arc extinction. Such voltage has a power-frequency component plus an oscillatory trasient component. The oscillatory trasient component due to the inductance and capacitance in the circuit. The power frequency component is due to the system voltage (Ref. Fig. 3.8). The transient oscillatory component subsides after a few micro-seconds and the power frequency component continuous. The frequency of transient component is given by

$$f_n = \frac{1}{2\pi\sqrt{LC}} Hz$$

where f_n = frequency of transient recovery voltage, Hz

L = equivalent industance, hency.

C = equivalent capacitance, farad.

In actual systems the waveform of the transient recovery voltage has several component frequencies ranging from a few hertz to several thousand hertz, depending upon the values of the circuit parameters.

3.7.1. Effect of natural frequency of TRV

Fig. 3.9 illustrates the slopes of tangents to three TRV waveforms of different frequencies (f_n, f_{2n}, f_{4n}). With increase in the natural frequency, the rate of rise of TRV at current zero increases.

The rate of rise of trasient recovery voltage across circuit-breaker pole causes voltage stress on the contact-gap tending to continue the arc. With higher frequency (say f_{4n}), relatively less time is available for the building of dielectric strength of the contact gap. Hence higher frequency is associated with greater stresses.

The breaking capacity of a circuit-breaker (r.m.s. value of current, which the circuit-breaker can interrupt) is related with the rate if rise TRV, and, therefore, natural frequency of TRV. The breaking capacity reduces with increase in natural frequency (Ref. Sec. 3.10. Eq. 3.26).

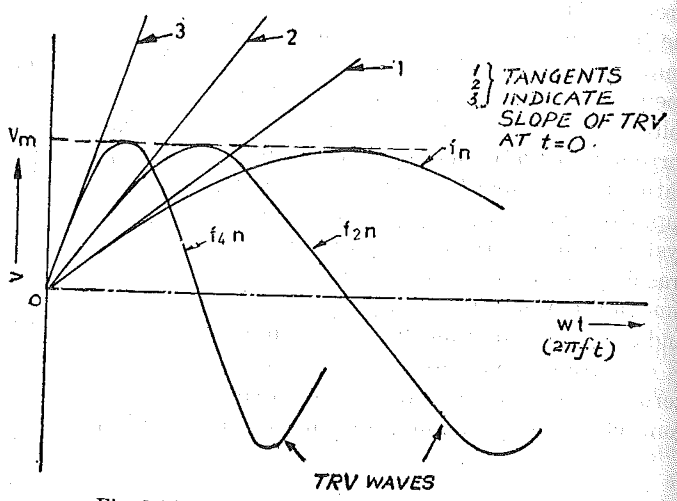


Fig. 3.9 Effect of frequency of TRV on the RRRV.

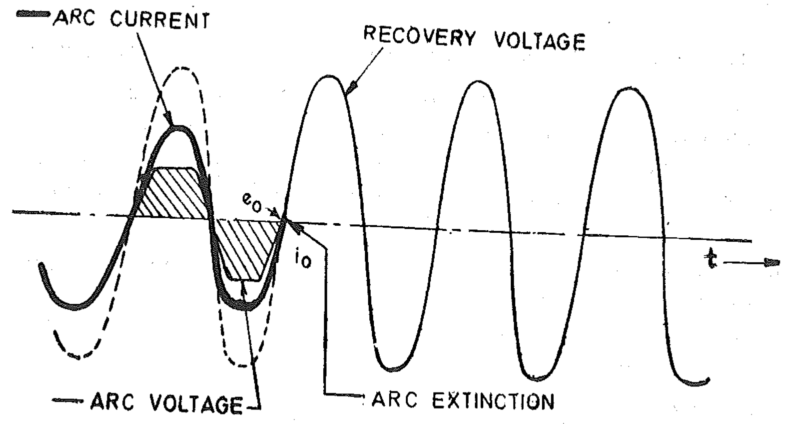


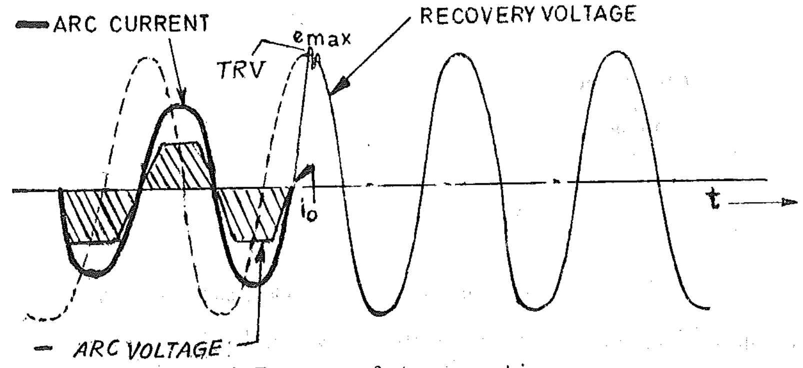
Fig. 3.10. (a) Unity power factor: e_0 at i_0.

3.7.2. Effect of Power-Factor on TRV

The voltage appearing across the circuit-breaker pole at the instant of final current zero is influenced by the power-factor of the current. (Fig. 3.10). The arc gets extinguished at current zero. The power-frequency voltage appears across the circuit-breaker pole. The instantaneous value of the voltage at the instant of current zero depends upon the phase angle between current and voltage. For unity power-factor loads, the voltage and current are in phase and both are zero at the same instant. For zero power-factor currents, the peak of the voltage (E_{max}) is impressed on the circuit-breaker pole at the instant of current zero. Such sudden application of voltage give rise to severe transient and has a high rate of rise of TRV. Hence interrupting currents of low power-factor is a difficult switching duty.

3.7.3. Effect of Reactance-drop on power-frequency Recovery Voltage

Suppose V_1 is voltage at the location of the circuit-breaker berfore fault. During the fault the increased current cause an increase in the voltage drop in the reactance. As a result the voltage appearing at the location of the fault, immediatly after fault clearance say V_2 is slightly less than V_1. It takes some time for the system voltage to regain the original value V_1. Hence the power frequency recovery voltage is slightly less than the normal power frequency system voltage.



(b) Zero power-factor : e_{max} at i_0.

Fig. 3.10 Effect of power factor on instantaneous value of voltage at current zero.

3.7.4. Effect of Armature Reaction on Recovery Voltage

The short-circuit currents are at lagging power factor and, therefore, have a demagnetising armature reaction in altenators. As a result, the induced e.m.f. of alternators reduces during short-circuit currents. The e.m.f. requires some time to regain its original value. Hence the power frequency component of recovery voltage is slightly less than the normal value of system voltage.

3.7.5. Effect of the First-Pole-to-Clear

Refer to Fig 3.11 illustrating a three phase fault not involving the earth. The voltage across the circuit-breaker pole, first to clear is 1.5 times the phase voltage. In three-phase a.c. circuit-breakers, arc extinction in the three poles is not simultaneous as currents in three phases are mutually 120° out-of-phase. Hence, the power-frequency recovery voltage of the phase in which the arc gets extinguished first, is about 1.5 times the phase voltage. In practice the recovery voltage of the pole, first-to-extinguish the arc is of the order of 1.2 to 1.5 times. If the neutral is grounded through reactor and if the fault involves earth, the recovery voltage at the location of the circuit-breaker is influenced by the equivalent system reactance and can be calculated by the method of symmetrical components.

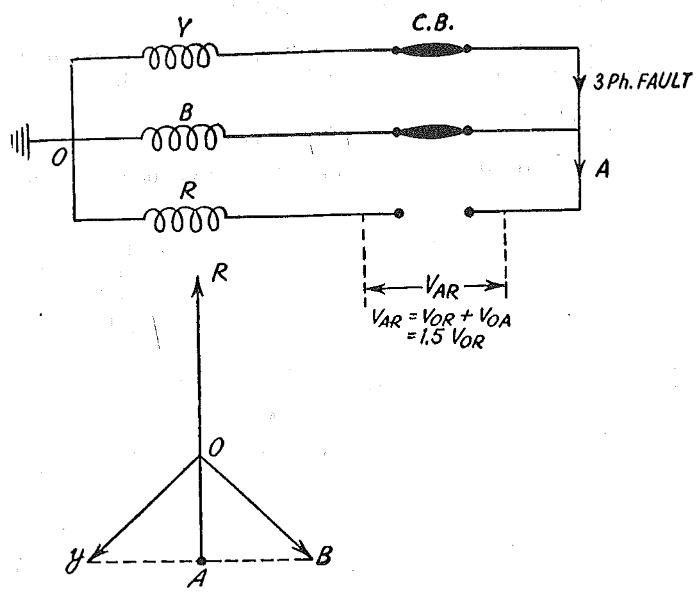


Fig. 3.11. Voltage across the phase, first-to-open.

3.7.6. The First-Pole-to-Clear Factor

To consider, the effect of the first-pole-clear on the power frequency component of the recovery voltage, the following factor has been defined in the standards on high voltage a.c. circuit breakers.

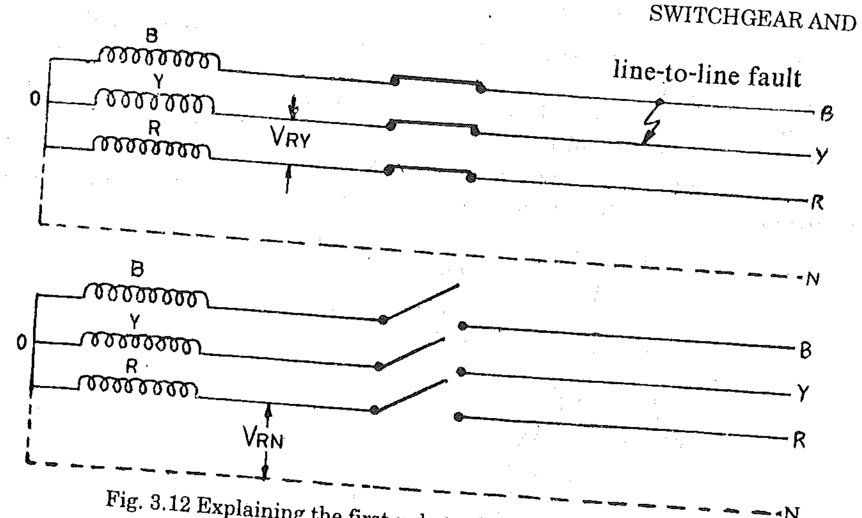


Fig. 3.12 Explaining the first-pole-to clear factor (V_{RY}/V_{RN})..

The first pole to clear factor $= \dfrac{\text{R.m.s. voltage between healthy phase \& faulty phase}}{\text{Phase to netural voltage with fault removed}}$

at the location of the circuit-breaker during a phase-to-phase fault.

Ref. Fig. 3.12, first-pole-to-clear factor is the ratio of the

$$\frac{\text{Voltage between healthy and faulty phase } (V_{RY})}{\text{Normal phase voltage } (V_{RN})}$$

at the location of the circuit-breaker for a phase-to-phase fault (Fig. 3.12).

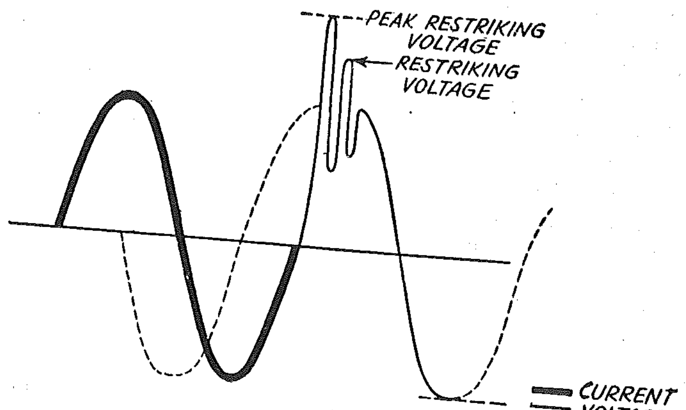
3.8. SINGLE FREQUENCY TRANSIENT

The single frequency restriking voltage transient is produced in the circuit illustrated in Fig. 3.13 (*b*). The frequency of oscillation is given by the natural frequency of the circuit.

i.e.

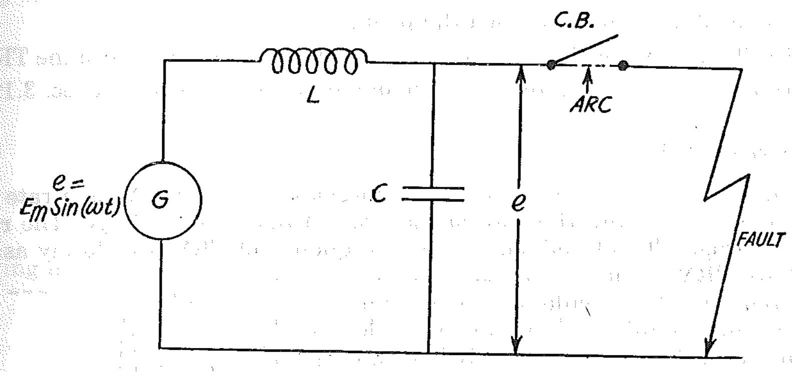
$$f_n = \frac{1}{2\pi\sqrt{LC}}\ Hz$$

where L = Inductance, henry ; C = Capacitance, farads.



(*a*)

These frequencies are of the order of 10 to 10,000 Hz depending upon the value of L and C. The actual power system is composed of distributed capacitance and inductance. The circuit configuration is also complex. The TRV for such circuits can have several component frequencies ranging from a few Hertz to several kilohertz. A typical single frequency transient is illustrated in Fig.



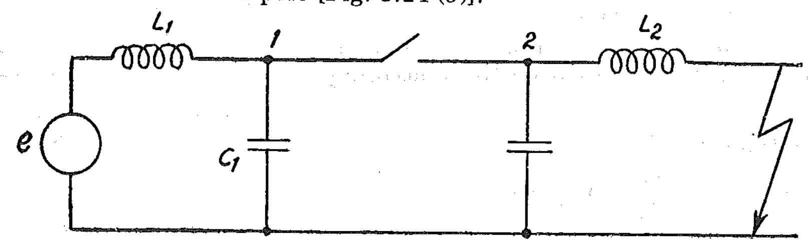
(*b*) Single frequency transient.

Fig. 3.13. Explaining single frequency transient of TRV.

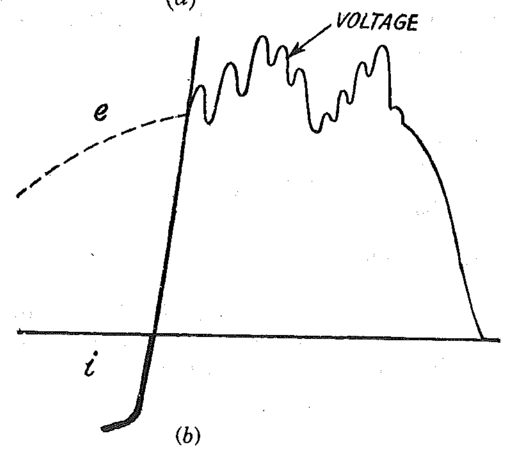
3.13 (*a*). Such a transient is obtained while opening on a terminal fault. In such cases the reactance between the fault and the circuit-breaker is negligible.

3.9. DOUBLE FREQUENCY TRANSIENTS

The circuit may have L and C on both sides of the circuit-breaker as shown in Fig. 3.14. Before clearing the fault, both the terminals, 1 and 2 are at the same potential. After arc extinction both the circuits oscillate at their own natural frequencies and a composite double frequency transient appears across the circuit breaker pole [Fig. 3.14 (*b*)].



(*a*)



(*b*)

Fig. 3.14. Double frequency transient of TRV.

In general the frequencies and waveform, rate of rise and peak value of the TRV depends upon several aspects such as

— net work configuration — type of fault — type of neutral earthing.

The TRV wave can be defined by various methods such as

— specifying the peak and time to reach the peak.

— specifying the TRV wave by defining the segment of lines which enclose the TRV waveform.

The latter method has been now universally adopted and is described in sec. 3.19.9.

3.10. RATE OF RISE OF TRV

The rate of rise of restriking voltage usually abbreviated by R.R.R.V. is a rate expressed in volts per micro-second, represents the rate of increase in restriking voltage. The rate of rise of Trasient Recovery Voltage. (TRV) and the natural frequency of TRV are closely associated. The rate of the rise of TRV depends on the system parameters. The circuit breaker should be capable of interrupting its rated short-circuit breaking current under the specified conditions of TRV. Hence the follwing characteristics of TRV are significant:

— Peak of TRV, time to reach the peak. Hence the rate of rise of TRV

— frequency of TRV

— Initial rate of rise

The term rate of rise of restriking voltage is explained as follows :

If e is restriking voltage volts

$$\text{R.R.R.V.} = \frac{de}{dt} \text{ volts}/\mu \text{ sec.}$$

where t is in μ seconds, e is in volts.

The peak restriking voltage is defined as the maximum instantaneous value attained by the restriking voltage (e_m).

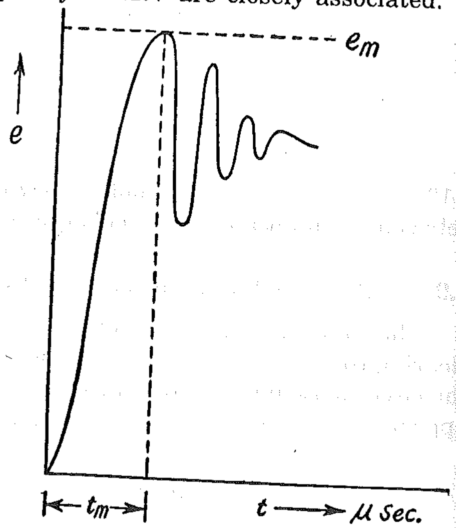


Fig. 3.15. Measurement of single frequency transient.

Referring to Fig. 3.15, R.R.R.V is given by

$$\text{R.R.R.V.} = \frac{e_m}{t_m} \text{ ...V}/\mu \text{ sec.}$$

where e_m = peak restriking voltage, volts

t_m = time between voltages zero and peak restriking voltage in μ sec

E_m = peak recovery voltage.

$$\text{Amplitude factor} = \frac{e_m}{E_m}$$

$$\text{Natural frequency} = \frac{10^3}{2t_m} \text{ kilo cycles/second} \qquad \text{...(3.18)}$$

Since $f = \dfrac{1}{2t_m}$ for any sinusoidal waveform.

Derivation of Restriking Voltage. Consider the circuit shown in Fig. 3.13 when current reaches zero at final arc extinction, a voltage e is suddenly impressed across capacitor and therefore, across the $c.b.$ contacts. The current i which would flow to the fault is not injected in the capacitor and inductor. Thus

$$i = i_L + i_c$$

$$i = \frac{1}{L}\int e\,dt + C\frac{de}{dt}$$

$$\therefore \quad \frac{di}{dt} = \frac{e}{L} + C\frac{d^2e}{dt^2}$$

Assuming zero time at zero currents when $t = 0$, and further

$$e = E \cos \omega t$$

$$i = \frac{E_m}{\omega L} \sin \omega t \text{ before opening of c.b.}$$

$$\frac{di}{dt} = \frac{E_m}{\omega L} \times \omega \cos \omega t$$

$$t = 0; \left|\frac{di}{dt}\right| = \frac{E_m}{L}$$

Substituting in Eq. (3.18), we get

$$\frac{E_m}{L} = \frac{e}{L} + C\frac{d^2e}{dt^2} \qquad \text{...(3.19)}$$

The solution of this standard equation is

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right) \qquad \text{...(3.20)}$$

This is an expression for restriking voltage in which

E_m = Peak value of recovery voltage, phase to neutral volts

t = Time in seconds

L = Inductance in henrys

C = Capacitance, farads

e = Restriking voltage, volts.

Note. Rate of rise of restriking voltage

$$= \frac{de}{dt}$$

$$= \frac{E_m}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}} \qquad \text{...(3.21)}$$

R.R.R.V. is maximum when it derivative is zero (from maxima theorem of differential calculus) .

$$\frac{de}{dt} \text{ is maximum when } \frac{d^2e}{dt^2} = 0$$

i.e. $$\frac{E_m}{LC}\cos\frac{t}{\sqrt{LC}} = 0$$

or when $$\frac{t}{\sqrt{LC}} = \frac{\pi}{2}$$

i.e. $$t = \sqrt{LC}\,\frac{\pi}{2}$$

The maximum R.R.R.V. is the value of de/dt at

$$t = \sqrt{LC}\,\frac{\pi}{2}$$

i.e. $$\text{R.R.R.V.}_{max} = \frac{E_m}{\sqrt{LC}} \qquad \text{...(3.23)}$$

Further, peak restriking voltage occurs when e is maximum

i.e. when $\dfrac{de}{dt} = 0$

i.e. when $\dfrac{t}{\sqrt{LC}} = \pi$, *i.e.*, $t = \pi\sqrt{LC}$

and peaking restriking voltage is equal to

$$e = E_m(1 - \cos \pi) = 2E_m \qquad \text{...(3.24)}$$

SUMMARY OF EXPRESSIONS

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right) \quad ...(3.20)$$

$$\text{R.R.R.V.} = \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}} \quad ...(3.21)$$

$$e_{\max} = 2E_m \text{ at } \frac{t}{\sqrt{LC}} = \pi \quad ...(3.24)$$

$$\text{R.R.R.V.}_{max} = \frac{E_m}{\sqrt{LC}} \text{ at } t = \sqrt{LC}\,\frac{\pi}{2} \quad ...(3.22)$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} \quad ...(3.25)$$

It is observed from Eqs. 3.22 and 3.25 that

$$\text{R.R.R.V.}_{max} = 2\pi E_m f_n \quad ...(3.26)$$

The Maximum Rate of Rise of Restriking voltage is proportional to the natural frequency of the circuit.

This is an important conclusion. The circuit with high natural frequency give a high rate of TRV and produce severe dielectric stress on the contact space of the circuit-breaker.

Hence High $f_n \rightarrow$ High rate of rise of TRV

Examples on Restriking Voltage*

Example 3.3. *A 50-cycles, 3-phase alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to busbar through a circuit-breaker. The capacitance to earth between the alternator and the circuit-breaker is 0.003 μF per phase. The circuit breaker opens when r.m.s. value of current is 7500 A. Determine analytically the following :*

(a) Maximum rate of rise of restriking voltage.
(b) Time for maximum rate of sise of restriking voltage.
(c) Frequency of oscillations.
Neglect First-Pole-to-clear factor.

Solution. Frequency of oscillation is given by

$$f_n = \frac{1}{2\pi\sqrt{LC}} \text{ c/s}$$

where L in henry, C is in farads, f_n is in Hz.

$$\therefore \quad f_n = \frac{1}{2\pi\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}}$$

$$= \frac{1}{2\pi\sqrt{4.8\times10^{-12}}} = \frac{1}{2\,\pi\times2.2\times10^{-6}} = 72{,}400 \text{ c/s.}$$

The recovery voltage can be calculated from the known values of current I and ωL.

$$E = I\times\omega L = I\times 2\pi f\times L$$

$$= 7500\times314\times1.6\times10^{-3} = 3780 \text{ volts r.m.s.}$$

$$E_m = \sqrt{2}\times E_{rms} = 3780\times\sqrt{2} = 5340 \text{ volts}$$

Expression for restriking voltage

$$e = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right) = 5340\left(1-\cos\frac{t}{2.2\times10^{-6}}\right)$$

where e is in volts, t is in sec.

* In this derivation and in Examples on Restriking Voltage, First Pole to Clear Factor is neglected.

Maximum rate at rise of restriking voltage occurs when

$$\frac{d^2e}{dt^2} = 0$$

i.e. when $$t = \sqrt{LC}\,.\,\frac{\pi}{2} = 2.2\times\frac{\pi}{2} = 3.45 \ \mu\text{-sec.}$$

$$\text{Maximum R.R.R.V. is given by } = \frac{E_m}{\sqrt{LC}} = \frac{5340}{2.2} = 2420 \text{ volts}/\mu\text{-sec.}$$

[**Ans.** (*a*) 2420 V/μ-sec., (*b*) 3.45 μ-sec., (*c*) 72,400 c/s.]

Example 3.4. *A three phase altenator has the line voltage of 11 kV. The generator is connected to a circuit-breaker. The inductive reactance upto the circuit breaker is 5 ohm per phase. The distributed capacitance upto circuit-breaker between phase and neutral is 0.01 μF. Determine the following :*

Neglect First Pole to clear factor
(a) Peak restriking voltage across the c.b.
(b) Frequency of restriking voltage transient.
(c) Average rate of restriking voltage upto peak restriking voltage.
(d) Maximum R.R.R.V.

Solution. $$2\pi fL = 5\Omega$$

$$\therefore \quad L = \frac{5}{314} = 0.0159 \text{ H}$$

$$V_r = 11 \text{ kV}$$

$$V_{ph} = \frac{11}{\sqrt{3}} = 6.35 \text{ kV r.m.s.}$$

$$E_{\max} = \sqrt{2}\times6.35 = 9 \text{ kV.}$$

Expression for striking voltage

$$e = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right)$$

$$= 9\left(1-\cos\frac{t}{\sqrt{0.0159\times0.01\times10^{-6}}}\right)$$

$$= 9\left(1-\cos\frac{t}{12.6\times10^{-6}}\right)$$

Peak restriking voltage $= 2\times E_{\max} = 2\times9 = 18$ kV

Time for peak restriking voltage:

$$\frac{t}{\sqrt{LC}} = \pi$$

$$t = \sqrt{LC}\times\pi = 12.6\times\pi = 39.5 \ \mu\text{-sec.}$$

$$\text{Average rate of restriking voltage} = \frac{e_{\max}}{t_m} = \frac{18}{39.5} = 0.456 \text{ kV}/\mu\text{-sec.}$$

$$\text{Frequency oscillations} \quad f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\times12.6\times10^{-6}} = 12{,}637 \text{c/s}$$

$$\text{Max. R.R.R.V.} = \frac{E_m}{\sqrt{LC}} = \frac{9\times10^3}{126} = 714 V/\mu\text{-sec.}$$

Example 3.5. *In a system the r.m.s. voltage is 19.1 kV, L is 10 mH, C is 0.02 mF. Determine the average rate of rise of restriking voltage, when the circuit breaker opens.*

Solution. $$e = E_{max}\left(1 - \cos \frac{t}{\sqrt{LC}}\right)$$

Inserting the numerical values $e = \sqrt{2} \times 19.1\left(1 - \cos \frac{t}{\sqrt{10 \times 10^{-3} \times 0.02 \times 10^{-6}}}\right)$

$$= 27\left(1 - \cos \frac{t \times 10^5}{1.414}\right) \text{kV}$$

Time to reach maximum restriking voltage

$$t = \pi\sqrt{LC} = \pi \times 1.414 \times 10^{-5} \text{ sec.} = 44.4 \ \mu\text{-sec.}$$

$$e_{max} = 2E_m = 2 \times 27.0 = 54 \text{ kV}$$

Average rate of restriking voltage$= \frac{e_{max}}{t_m} = \frac{54{,}000}{44.4} = 1220 \text{ V}/\mu\text{-sec.}$

Example 3.6. *In a short-circuit test on a 3 pole, circuit-breaker power factor of fault was 0.4, the recovery voltage was 0.95 times full line value. The breaking current was symmetrical. The frequency of oscillation of restriking voltage was 15,000 c/s. Estimate the average rate of rise of restriking voltage. The neutral is grounded and fault involves earth. Neglect First Pole to clear factor.*

Solution. The maximum restriking voltage is given by $2E_{max}$, where E_{max} is the instantaneous value of power frequency voltage at the time of current zero.

Line to line voltage = 110 kV r.m.s.

Line to phase voltage $= \frac{110}{\sqrt{3}}$ kV r.m.s.

$$\text{Peal } E_{max} = \frac{110}{\sqrt{3}} \times 2 = 90 \text{ kV}$$

The power factor $= 0.4$

Hence p.f. angle $\theta = 66.4°$

$\sin\theta = 0.92$

Recovery voltage is 0.95 times peak value.

From equation instantaneous value of recovery voltage is $E = kE_{max}$

where $k = k_1 \times k_2 \times k_3$ (Ref. Sec. 3.7)

k_1 = multiplying factor due to power factor angle

$= \sin\theta = 0.92$

k_2 = multiplying factor due to system voltage = 0.95

k_3 = Factor depends on circuit conditions

= 1 in this case since the fault involves earth

$\therefore$ $k = k_1\, k_2\, k_3 = 0.92 \times 0.95 \times 1 = 0.875$

$\therefore$ $E = 0.875 \times 90 = 78.75$ kV (instantaneous)

The time to reach the first peak of restriking voltages can be estimated from Eq. (3.18).

$$f_n = \frac{10^3}{2 \times t_m}, \text{ where } f \text{ is in kc/sec.} \quad ...(3.19)$$

$$f_n = \frac{1}{2 \times t_m}, \text{ where } f \text{ is in c/s.}$$

$$t_m = \frac{1}{2f_n} \text{ sec.}$$

$$t_m = \frac{1}{2 \times 15{,}000} = 0.33 \times 10^{-4} \text{ sec.} = 0.33 \times 102 \ \mu\text{-sec.}$$

Average $\text{R.R.R.V.} = \frac{2E_{max}}{0.33 \times 10^2} = \frac{2 \times 78.75}{33} = 4.8 \text{ kV}/\mu\text{-sec.}$

Example 3.7. *In a short-circuit test on a circuit-breaker, the following readings obtained on a frequency transient:*

(a) time to reach the peak restriking voltage 70 μ-sec.

(b) the peak restriking voltage 100 kV.

Calculate the average rate of rise of restrking voltage and the natural frequency of the circuit.

Solution. Average rate of rise restriking voltage

$$= \frac{\text{Peak restriking voltage } (E_m)}{\text{Time to reach the peak } (t_m)} = \frac{100 \times 10^3}{70} = 1430 \text{ V}/\mu\text{-sec.}$$

Natural frequency f_n is given by

$$f_n = \frac{10^3}{2t_m} \text{ c/s}$$

$$f_n = \frac{10^3}{2 \times 70 \times 10^{-6}} = 7143 \text{ c/s.}$$

3.11. RESISTANCE SWITCHING, DAMPING OF TRV, OPENING RESISTORS

A deliberate connection of a resistance in parallel with the contact space (arc) is called *Resistance switching*. Resistance Switching is used in circuit-breakers having high post zero resistance of contact space (Air blast C.B.) Let us see the effect of such a resistance on the frequency of restriking voltage transient (Ref. Fig. 3.19).

Considering the current loop, we get

$$e = iR + L\frac{di}{dt} + \frac{1}{C}\int i_c dt \quad ...(3.26)$$

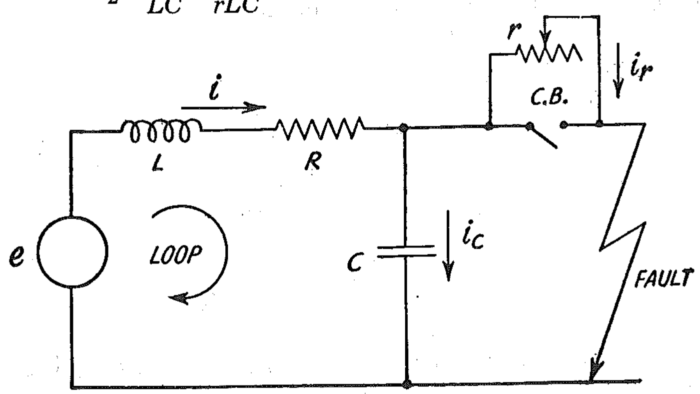
$$\frac{1}{C}\int i_c dt = i_r r$$

$$i = i_r + i_c, \; e = 0$$

$$\frac{d^2 i}{dt^2} + B_1 \frac{di_r}{dt} + B_2\, i_r = 0 \quad ...(3.27)$$

where $$B_1 = \frac{R}{L} + \frac{1}{rC} \quad ...(3.28)$$

$$B_2 = \frac{1}{LC} + \frac{R}{rLC} \quad ...(3.29)$$



(1) r is resistance connected in parallel with the *c.b.* (resistance switching opening resistance—ohm

(2) R series resistance of circuit per phase—ohm

(3) C capacitance between phase and earth per phase—farad

(4) L inductance per phase—henry ; i_r current in resistance switching ; i_c current in capacitor ; i total current

Fig. 3.19. Resistance switching.

The roots are complex and the frequency of transient is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4}\left(\frac{R}{L} - \frac{1}{rC}\right)^2}$$

and attenuation $p = \frac{1}{2}\left(\frac{R}{L} + \frac{1}{rC}\right)$

if $R \le L$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \left(\frac{1}{2rC}\right)^2} \qquad ...(3.30)$$

From Eq. 3.30, it is clear that if parallel resistance 2 across contacts is less than

$$\frac{1}{2}\sqrt{\frac{L}{C}}$$

the frequency reduces to zero as shown below

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2} \times \frac{4C}{L}}$$

$$= \frac{1}{2\pi}\sqrt{0} = 0 \text{ if } r < \frac{1}{2}\sqrt{\frac{L}{C}}$$

The value of resistance r at which the frequency of TRV becomes zero is called "Critical Damping Resistance'. The resistance connected in parallel with the circuit-breaker for opening operation is called 'Opening Resistance'.

The frequency of transient restriking voltage vanishes and the rate of rise of restriking is kept within the capability of the breaker. In the resistance switching resistance is connected in shunt with the arc (Fig. 3.19) so as to reduce the restriking voltage frequency. The resistance also diverts part of the arc current.

In the plain break oil circuit-breakers (tank type) the post zero resistance of the contact space is low. Hence resistance switching is not necessary. However, the resistance switching assists the circuit-breaker in interrupting the magnetising currents and capacitive currents.

The post-zero resistance of air-blast circuit-breaker is high. This may result in severe voltage transients due to current chopping (interruption of current before natural zero). Hence the resistance switching is adopted.

The magnitude of opening resistance for resistance switching is given by

$$r = \frac{1}{2}\sqrt{\frac{L}{C}}$$

Assuming $I_{sc} = \frac{E}{\omega L}$

$$L = \frac{E}{I_{sc}\,\omega}$$

$$\therefore \qquad r = \frac{1}{2}\sqrt{\frac{E}{I_{sc}\omega C}} = K\frac{1}{\sqrt{I_{sc}}}$$

Hence magnitude of resistance depends on the fault current.

Example 3.8. *In a system of 132 kV, the circuit phase to ground capacitance is 0.01 mF, the series inductance is 6H. Calculate the voltage appearing across the pole of a.c.b. if a magnetizing current of 10 amp. is interrupted (instantaneous). Calculate the Value of resistance to be used across contact space to eliminate the restriking voltage transient.*

Solution. L = 6H; C = 0.01 μF

$$\frac{1}{2}Li^2 = \frac{1}{2}Cv^2$$

$$v = i\sqrt{\frac{L}{C}}$$

$$= 10\sqrt{\frac{6}{0.01 \times 10^{-6}}} = 10\sqrt{6 \times 10^8}$$

$$v = 245{,}000 \text{ V}.$$

The magnitude of resistance r for resistance switching is given by

$$r = \frac{1}{2}\sqrt{\frac{L}{C}}$$

$$= 0.5\sqrt{6 \times 10^8} = 0.5 \times 2.45 \times 10^4$$

$$= 1.225 \times 10^4\ \Omega = 12.25\ \text{k}\Omega.$$

Hence the critical damping resistance = 12.25 kΩ.

3.12. INTERRUPTION OF LOW MAGNETIZING CURRENT, CURRENT CHOPPING

The necessity of interrupting small inductive current arises while disconnecting transformers on no-load. No-load currents of transformer, *i.e.* magnetizing currents are almost at zero power factor lag. The current is smaller than normal current rating of the breaker. The breaking of such a low current presents a sever duty on the circuit-breaker. (Sec. 15.23)

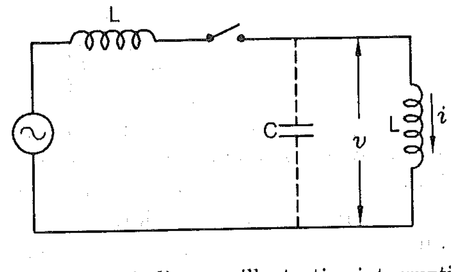


Fig. 3.20 Circuit diagram illustrating interruption of low inductive current.

When interrupting low inductive currents such as magnetizing currents of transformer, shunt reactor, the rapid deionization of contact space and blast effect may cause the current to be interrupted before its natural zero. This phenomenon of the interruption of current before its natural zero is called current chopping. As shown in example 3.6 the energy stores in inductance for value of current it is diverted to the capacitance at the moment of current interruption, i.e.

$$\frac{1}{2}Li^2 = \frac{1}{2}Cv^2 \text{ joules}$$

$$v = i\sqrt{\frac{L}{C}}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

Such a transient voltage having high RRRV appears across the contacts, unless the arc continues. If it restrikes a further, chop may occur or several chops may occur before the current is finally interrupted, circuit-breaker may fail to clear the fault.

If the restrike does not occur, the severe voltage appears across the c.b. contact and on the system.

Resistance switching is adopted to overcome the effect of over-voltages due to current

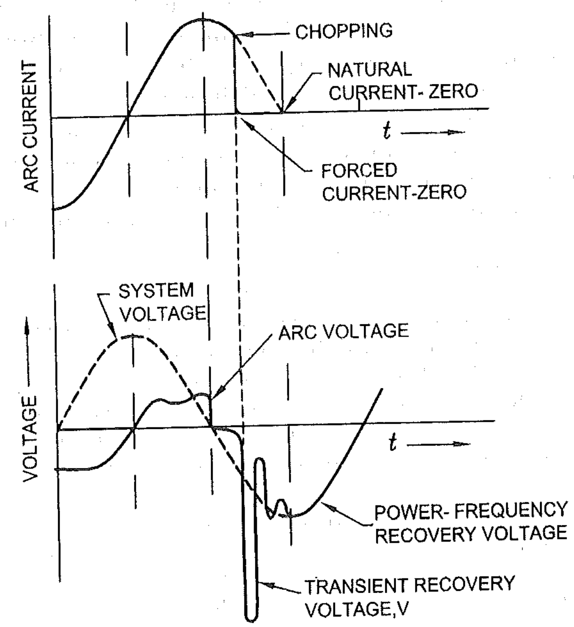


Fig. 3.21. Interruption of low magnetizing currents.

chopping. The value of resistance used for resistance switching is of the order of 15,000 ohms for switching off a 132 kV 45 MVA transformer.

The currents to be interrupted may be small, but interrupting such currents may result in very high voltages. For example consider disconnection of a 110 kV, 20 MVA tranformer.

$$\text{Rated current} = \frac{20 \times 10^6}{\sqrt{3} \times 110 \times 10^3} = 105 \text{ A.}$$

The magnetising current was 2 A.

$$X_0 = \frac{110 \times 10^3}{\sqrt{3} \times 2} = 31.7 \times 10^3 \text{ ohm}$$

$$L_0 = \frac{X_0}{2\pi f} = \frac{31.7 \times 10^3}{314} = 101 \text{ henry.}$$

Assuming current is interrupted at instantaneous value $\sqrt{2} \times 2 = 2.82$ A.

$$i^2 = (2.82)^2 = 8$$

The capacitance between phase and ground is found to be 5000 pF equating energies we get

$$\frac{1}{2} Li^2 = \frac{1}{2} Cv^2$$

$$v = i\sqrt{\frac{L}{C}} = 2.82\sqrt{\frac{101}{5000 \times 10^{-12}}} = 400 \text{ kV Peak}$$

Thus voltage of 400 kV appears across breaker pole. If the dielectric strength of the contact space is low or if resistance or capacitor is provided in shunt, the excessive voltage is discharged and therefore, does not appear on the system. Thus a circuit-breaker in which the dielectric strength of contact space grows at a slower rate, the problem of restriking voltage disturbance is less severe because the gap-breaks down and absorbs the magnetic energy in successive restrikes, circuit-breakers with internal extinguishing source such as oil circuit-breakers are, therefore suitable for such applications. On the contrary in air blast circuit-breakers, post arc dielectric strength is high, severe voltage transients can be expected. Hence resistance switching is adopted.

Another difficult duty for which the circuit-breakers should be desinged is breaking of inductive currents such as breaking of reactors or transformers loaded with reactors. Resistance switching is resorted to. Resistance switching comprises non-linear resistors which are brought into the circuit, parallel to the arc between contacts, during arc interruption. The current flows in the shunt resistor until it is interrupted by the resistor switch. In medium voltage systems upto 36 kV, RC surge absorbers with R = 100 ohms and $C = 0.1$ μF are connected phase to ground between the breaker and the inductive load. The surges are absorbed by the RC combination.

3.13. USE OF OPENING RESISTORS

'Opening resistors' also called 'switching resistors' are fitted parallel with main break in series with a resistance switch. The opening resistors come into the circuit prior to the opening of the main break (1) by closing of the resistors switch (II). The resistance switch (II) may be formed by the moving parts in the interrupter or striking of an arc depending upon the design of the circuit-breaker.

During the arc-interruption process in the main-break, the resistor switch (II) remains closed. The resistance switch (II) opens with a certain delay after the opening of the main break.

The magnitude of opening resistances depend upon the type of circuit-breaker and the switching duty involved.

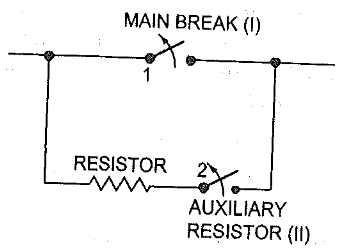


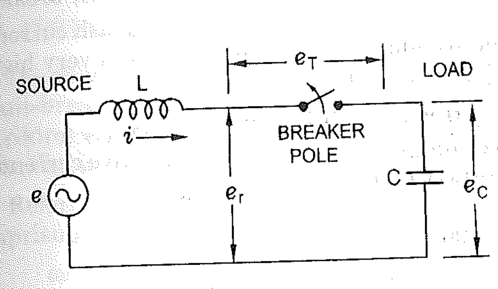
Fig. 3.22. Use of opening Resistor in Circuit-Breaker.

In air-blast circuit-breakers the problems or current chopping is generally more severe due to the fact that the blast is of same high pressure even if the breaking current is low. The opening resistors and the resistor switch are designed for values of currents of the order of 30% of the rated breaking current. The typical value of the opening resistors may be of the order of 300 to 500 ohms in case of 145 kV air-blast circuit-breakers. In oil-circuit-breakers the energy required for arc extinction is proportional to the current in the arc. Hence the opening resistors need not carry high value of current; the typical values being in the range of 5 to 10% of the rated breaking current (Ref., sec., 18.8 for Closing Resistors).

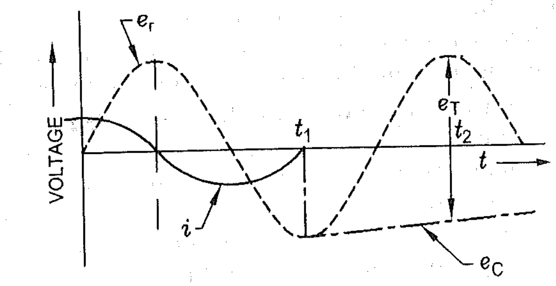
The SF_6 circuit breakers generally do not need opening resistors as the arc interruption generally takes place at natural current zero and the dielectric strength of the medium between the contacts builds up very rapidly.

3.13.1. Switching of Capacitor Banks (Ref. Sec. 15.26)

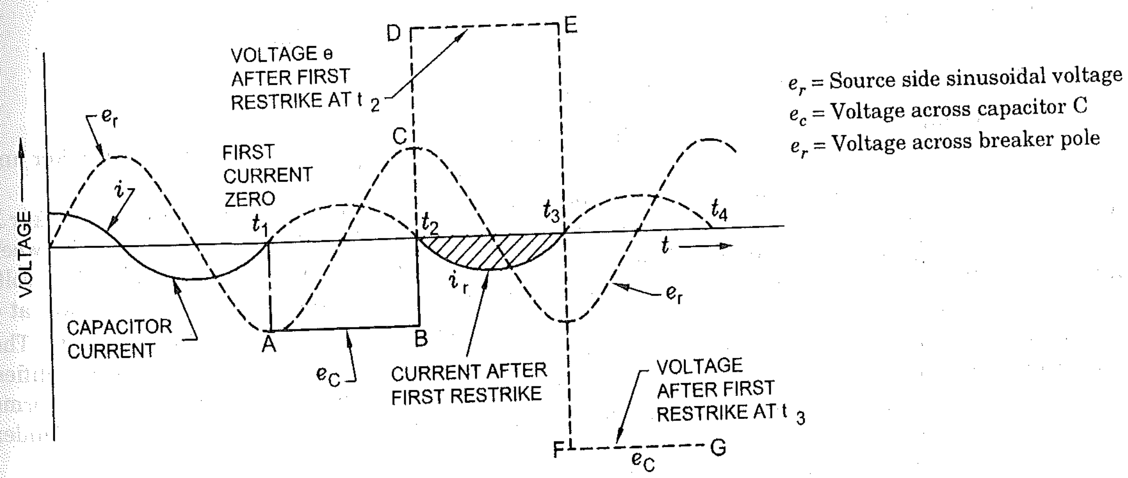
While opening capacitor banks the reginition and 'restriking' can occur in an interrupter (Ref. Sec. 3.6) Capacitor banks are connected in the network to provide reactive power at leading power factor. The voltage across a capacitor cannot change instantaneously. The currents supplied to the capacitor is generally of small order and the circuit-breaker can interrupt such currents invariably at the first current zero. Due to the 90° phase difference, the voltage across the Capacitor is at maximum value (e_c) at this instant (t_1) and the capacitor remains charged at this voltage (e_c). After



(a) Single phase Representation of star connected 3 ph. Capacitor Bank



(b) Waveform of Clean interruption without restrike (at t_1 current i is interrupted)



(c) Waveform for restrikes

Fig., 3.23 Switching of capacitive currents for opening operation.

half cycle (t_2) the recovery voltage of approximate magnitude of (e_{rmax}) appears across the circuit-breakers and the total voltage across the circuit-breaker is the sum of two voltages *i.e.*

$$e_{Tmax} = e_{rmax} + e_c$$

where e_{Tmax} = Maximum voltage across breaker

e_{rmax} = Max. value of power frequency recovery voltage

e_c = Voltage across capacitor.

Thus the recovery voltage of the order of $2E_{max}$, (where $E_{max} = \sqrt{2}\ E_{ph}$) appears across the circuit-breaker pole at the instant t_2, after 1/2 cycle of current zero. Therefore, a restrike is possible. If a restrike occurs, the LC circuit will oscillate at a frequency given by $f_n = 1/2\sqrt{LC}$. This current tries to maintain the arc. The voltage across the interrupter rises upto 4 p.u due to one restrike and upto 6 p.u. with second restrike. The energy ($1/2\ Cv^2$) to be dissipated during such arcs is quite large and the interrupters may get damaged in the process after a restrike. Hence, the circuit-breakers used for capacitors duty should be 'Restrike free'. It should have adequate rating for capacitive current switching.

While closing the circuit breaker of parallel capacitor banks, the pre-arcing between contacts can have damaging. The pre-arcing taken place before the contact touch. The frequecny of arc current is given by $f_n = 1/2\sqrt{LC}$. The energy in the arc is converted into heat. Every circuit-breaker has a limit of making capacity depending upon the frequency and magnitude of the inrush current. While paralleling one capacitor bank with another, the frequency of inrush currents is very high. Suitable reactor (L) should be provided in series. (Ref. Sec. 15.26)

3.13.2. Switching of Unloaded Transmission Lines and Unloaded Cables

Unloaded transmission lines and unloaded under ground power-cables take capacitive currents. The magnitude of capacitive currents encountered in practice are:

Unloaded lines: Charging currents : Up to 10 A

Underground cables : Charging currents: Up to 100 A

Capacitor Banks: Current up to 1400 A

During the opening operation, the restrike phenomenon is possible in above cases (described in Sec. 3.14.1)

The circuit-breaker used for a particular application should be capable of performing opening and closing operations without getting damaged and with overvoltages within specified limits. The circuit-breaker should have adequate rating and should be type tested for the relevant duty (Ref. Secs. V 3.19.20; 11.10)

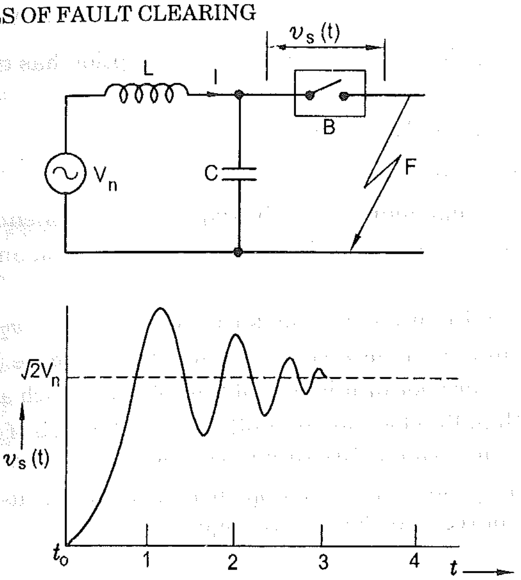
Vacuum CB, SF_6 CB and ABCBs are suitable for capacitors switching duty.

3.14. INTERRUPTING THE TERMINAL FAULTS

The Terminal Fault is defined as a fault occurring very near to terminal of circuit-breaker and that the reactance between the fault point and breaker is negligible.

Fig. 3.24 shows a single phase repesentation of a terminal fault condition. Consider breaker B closed and a short circuit F occurs very near the breaker terminal so that the impedance between the breaker and the fault is negligible. Under this condition the fault current I is governed by voltage of the source V_n and impedance of source ωL. The current I is interrupted by the breaker at a current zero. After the arc interruption, the voltage $Vs\ (t)$ appears across the breaker pole. The circuit being predominantly inductive, the power factor of current is low (0.1). The simplified waveform of transient recovery voltage is shown in Fig. 3.24. In practice quite complex waveforms are possible. The frequencies of TRV vary from several hundred to several thousand cycles under the condition of terminal short circuit.

As per IEC-56.2, the rated characteristics of a circuit-breaker include rated transient recovery voltage for terminal faults. The rated short-circuit breaking current is specified with references to the rated TRV for terminal faults.



B = Breaker
V_n = Voltage of source
L = Inductance on source side
F = Fault at terminal of B
$V_s\ (t)$ = Voltage across breaker
t = Time in microsec
C = Shunt capacitance on source side.

Simplified TRV form

Fig. 3.24 Conditions representing Terminal Fault (t in μs).

3.15. INTERRUPTING SHORT LINE FAULTS (Kilometric Fault)

The fault occurring between a distance of a few kilometers to a few tens kilometers from the circuit-breaker arc called short line faults. Such faults are characterised by high frequency of restriking voltage of the order of 10 to 100 kHz depending upon length of line and location of the fault. Fig. 3.25 represents a condition of a shortime fault and simplified TRV form.

Referring to Fig. 3.25 supply voltage cause short circuit current I to flow through the circuit comprising the following impedances :

ωL = impedance of source = $2\pi fL$

λ_1 = impedance of 1 km length of line

I = length of line between breaker and the fault, km

λ = impedance per km length of line.

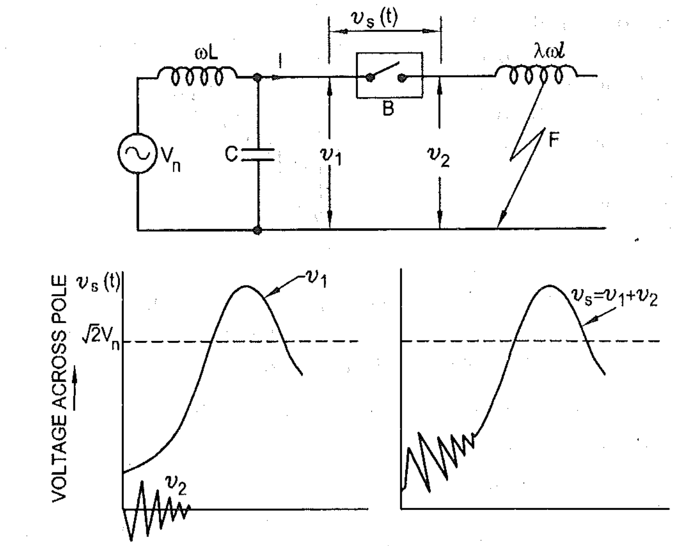


Fig. 3.25. Condition representing short-line fault (kilometric fault) (t in microsec).

The voltage appearing across breaker pole after final current interruption has two components v_1 and v_2. (Fig. 3.25)

- v_1 is the voltage at the terminal from supply side.
- v_2 is the voltage at the terminals from line side.

The voltage v_1 has power frequency component and high frequency component and reaches a peak value $\sqrt{2}V_n$ as illustrated in the figure. Whereas v_2 has saw-tooth waveform and drops to zero after a few microseconds.

The trasient recovery voltage v across the breaker pole is the sum of v_1 and v_2. The superimposed high frequency component due to line frequency F_L has a value $v_p/41$ where (v_p) is propagation velocity on the line and λ is the impedance per unit length of line. F_1 may reach a value between 10 to 100 kHz depending upon the length of line location of fault. The peak value of high frequency component is reached in a few microseconds. Hence the rate of rise of TRV is very high.

The resulting transient recovery voltage for short line appearing across circuit-breaker pole is the vector sum of the voltage from the source and the line voltage $V_S - V_L$.

3.16. PHASE OPPOSITION SWITCHING

When two systems are to be sychronised, it may happen that the breaker opens on non-synchronous condition. In Fig. 3.26, if V_1 and V_2 are not in sychronism during opening of breaker the likely waveform of transient recovery voltage is as shown in Fig. 3.27. Under certain conditions the voltage across pole may reach three times phase voltage or in extreme cases it may reach twice to line voltage.

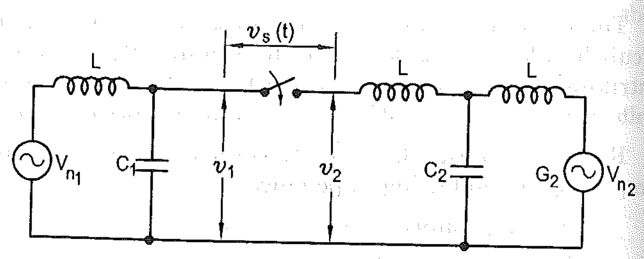


Fig. 3.26 Out-of phase switching.

The circuit-breakers used for synchronising, should be capable of opening satisfactory under non-synchronous condition. In such case the recovery voltage may be much higher than that for other short-circuit duties. The magnitude of recovery voltage depends upon the phase angle between the voltages on two sides of the circuit-breaker. The recovery voltage has a maximum value when the two voltages are 180° out of phase, given by :

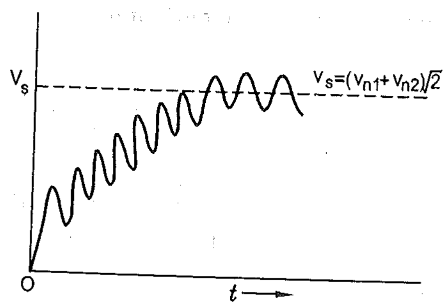


Fig. 3.27 Waveform of voltage across the breaker pole during out-of-shape opening (t in microsec.)

$$V_s = \sqrt{2}V_1 + \sqrt{2}V_2 = \sqrt{2}\,(V_1 + V_2)$$

where, V_s = Maximum value of power frequency recovery voltage

V_1 = Component from source side.

V_2 = Component from line side.

Summarising. The circuit-breaker should be capable of performing variety of switching duties. The current and voltage severities during these conditions are quite different. The studies on these switching conditions are simulated on

— Transient Network Analyzer — Analogue Computer

— Field testing — Short-circuit testing

To test the performance of circuit-breaker for various switching conditions, the tests are now recommended for high voltage circuit-breakers.

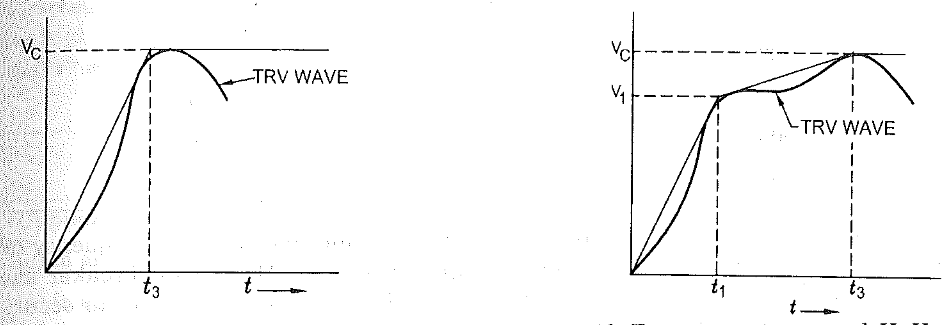
3.17. SPECIFYING THE TRV WAVE

The TRV waveform can be specified by various methods (Fig. 3.28) such as

— Specifying the peak value and time to reach the peak.

This methods was used earlier

— Specifying the parameters which determine the line segments enveloping the TRV wave (Fig. 3.28) (two parameter method and four-parameter method).



(*a*) Two-parameter method, V_C, t_3 (*b*) Four-parameter method, V_l, V_C, t_1, t

Fig. 3.28 Possible methods defining TRV waveform (t in μs).

3.18. RATED CHARACTERISTICS OF CIRCUIT-BREAKERS

The ratings of a circuit-breaker denote its capabilities under specified conditions of use and behaviour. The following paragraphs are generally based on the recommendations of IEC, Publication IEC-56: "High Voltage Alternating Current Circuit-Breakers" and IS-2516 : "Specifications of Alternating Current Circuit-Breakers."

The capabilities of a circuit-breaker of a particular type are proved by conducting type tests as per the recommendation of the standards.

The following rated characteristic (1-9) are generally specified for all high voltage a.c. circuit-breakers rated above 1000 V (For specifications of low voltage c.b.—Ref. Sec. 15.7).

3.18.1. Rated Voltage

The rated voltage of a circuit-breaker corresponds to the higher system voltage for which the circuit-breaker is intended. The standards values of rated voltages are given in Table 3.1. The rated voltage is expressed in $kV_{r.m.s.}$ and refer to phase to phase voltage for three-phase circuit. The earlier practice of specifying the rated voltage of a circuit-breaker as nominal system voltage is no more followed.

3.18.2. Rated Insulation level

The rated insulation level of a circuit-breaker refers to the power frequency withstand voltage and impulse voltage withstand values which characterise the insulation of the circuit-breaker. (Ref. Table 12.1)

TABLE 3.1.
Rated Voltage of Circuit-Breaker

Nominal System Voltage $kV_{r.m.s.}$	*Rated Voltage of Circuit-breaker* $kV_{r.m.s.}$
0.240	0.264
0.415	0.440
3.3	3.6
6.6	7.2
11	12
22	24
33	36
66	72.5
132	145
220	245
400	420
500	525
750	765

The circuit-breakers connected in a power-system are subjected to power-frequency over voltages due to regulation, Ferranti effect, higher tap-setting, etc. The circuit breaker should be capable of withstanding the power frequency over-voltages which are likely to occur. These capabilities are varified by conducting power frequency voltage withstand tests and impulse-voltage withstand tests. The circuit-breaker is subjected to impulse over-voltage due to causes like lighting surge and switching surge.

During single-line to ground faults, the voltage of healthy lines to earth increases to $\sqrt{3}$ time to normal value in systems with insulated neutral. Hence higher values of insulation are recommended for circuit-breaker connected in non-effectively earthed systems. The following insulations are provided in the circuit-breaker:

— Insulation between live parts and earth for each pole external and internal.

— Insulation between poles.

— Insulation between terminals of the same pole-external and internal.

The design of these insulation depends upon the structural form of the circuit-breaker and the rated insulation level desired Ref. Ch. 12 for further details.

3.18.3. Rated frequency

The standard frequency for a three pole circuit-breaker is the frequency of the power system (50 Hz). The characteristics like normal current breaking capacity etc. are based on the rated frequency.

The frequency of the current influences the circuit-breaker behaviour as follows :

— The temperature rise of current-carrying parts and neighbouring metallic parts is influenced by eddy-current heating. The increase in frequency results in increased eddy currents. Hence, with specified limits of the temperature rise the rated current of a circuit-breaker needs de-rating for application on higher frequency.

— The frequency corresponds to the number of current-zeros per second. Since the breaking time of the circuit-breaker is associated with the time for half cycles during the arc extinguished process, the breaking time is influenced by the frequency of current. The breaking time increases with reduction in frequency.

— The increase in frequency influences the TRV and rate-of-rise TRV. Hence a circuit-breaker desinged and rated for a certain frequency cannot be recommended for other frequencies unless its capabilities are proved for those frequencies.

— The d.c. circuit-breakers generally adopt a different principle of arc-extinction and have different construction than a.c. circuit-breakers.

3.18.4. Rated Normal Current (Rated Current)

The rated normal current of a circuit-beaker is the r.m.s. value of the current which the circuit-breaker can carry continuously and with temperature rise of the various parts within specified limits.

Preferred Values of Rated Currents A rms

400, 630, 800, 1250, 1600, 2000, 2500, 3150, 4000, A rms

The design of contacts and other current carrying parts in the interrupter of the circuit breaker are generally based on the limits of temperature rise. For a given cross-section of the conductor and a certain value of current, the temperature rise depends upon the conductivity of the material. Hence, high conductivity material is preferred for current carrying parts. The cross-section of the conductors should be increased for materials with lower conductivity.

Table 3.2. Permissible Temperature Rise*

	Item	*Maximum value of temperature °C*	*Temperature rise at ambient temperature of 40°C*
1.	**Copper contacts**		
	(*a*) in air with silver plating	105	65
	(*b*) in air without silver plating	75	35
	(*c*) in oil with silver plating	90	50
	(*d*) without silver plating in oil	80	40
2.	**Oil**		
	in oil circuit-breakers	80	40
3.	Terminals or the Circuit-breakers (*a*) With Silver plating	105	65
	(*b*) Without silver plating	90	50
4.	**Metal part in contact**	100	60
	With class E insulation in oil.		

* Ref. Sec. 10.2.2 Temperature Tests.

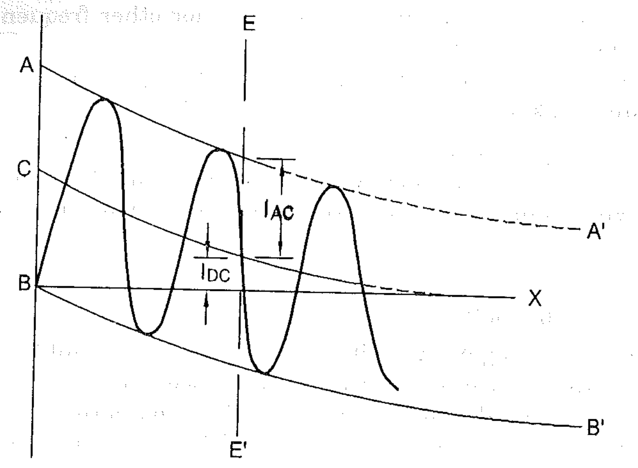
The use of magnetic materials in close circuits should be avoided to prevent heating due to hysteresis loss and eddy currents. The rated current of a circuit-breaker is verified by conducting temperature rise tests.

3.18.5. Rated Short Circuit-Breaking Current

The rated short-circuit breaking-current of a circuit-breaker is highest rms value of short-circuit current which the circuit-breaker is capable of breaking under specified conditions of transient recovery voltage and power frequency voltage. It is expressed in kA r.m.s. at contact separation.

Referring to Sec. 3.6, Fig. 3.6 the short-circuit current has a certain value at the instant of contact separation, ($t = T_1$). The breaking current refers to value current at the instant of the contact separation.

The transient recovery voltage refers to the transient voltage appearing across the circuit-breaker pole immediately after the arc interruption. The rated values of transient recovery voltage are specified for various rated voltages of circuit-brekers. For specified conditions of rated TRV and



$\left.\begin{array}{l} AA' \\ BB' \end{array}\right]$ Envelope of current wave

BX = Normal zero axis of wave

CX = Displaced zero axis of wave

EE = Instant of contact separation

I_{AC} = Peak value of A.C. component at EE

I_{DC} = D.C. component of current at EE

$\dfrac{I_{DC} \times 100}{I_{AC}}$ = Percentage of D.C. component at the instant EE

$\dfrac{I_{AC}}{\sqrt{2}}$ = r.m.s. value a.c. component.

Fig. 3.29. Determination of breaking current.

rated power frequency recovery voltage, a circuit-breaker has a certain limit of breaking current. This limit is determined by conducting short-circuit type tests on the circuit-breaker. The waveforms of short-circuit current are obtained during the breaking test. The evaluation of the breaking current is explained in Fig. 3.29.

The breaking current is expressed by two values :

(1) the r.m.s. value of a.c. component at the instant of contact separation EE, given by

$$\frac{I_{AC}}{\sqrt{2}}$$

(2) the percentage d.c. component at the instant of contact separation given by

$$\frac{I_{DC} \times 100}{I_{AC}}$$

The r.m.s. values of a.c. components are expressed in kA, the standard values being 8, 10, 12.5, 16, 20, 25, 31.5, 40, 45, 63, 80 and 100 kA.

The earlier practice was to express the rated breaking capacity of a circuit breaker in terms of *MVA* given as follows:

$$MVA = \sqrt{3}\ \text{kV} \times \text{kA} \qquad \text{...(3.31)}$$

where MVA = Breaking capacity of a circuit-breaker

kV = Rated voltage

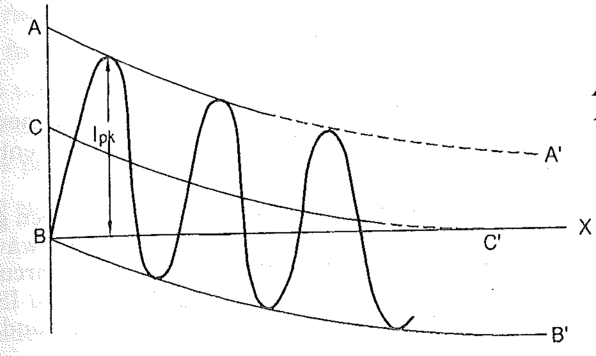
kA = Rated breaking current.

This practice of specifying the breaking capacity in terms of *MVA* is convenient while calculating the fault levels. However, as per the revised standards the breaking capacity is expressed in kA for specified conditions of TRV, and this method takes into account both breaking current and TRV.

While selecting the circuit-breaker for a particular location in the power system the fault level at that location is determined. (Section II of the book). The rated breaking current can then be selected from the standard range.

3.18.6. Rated Short-circuit Making Current

It may so happen that circuit-breaker may close on an existing fault. In such cases the current increase to the maximum value at the peak of first current loop. The circuit-breaker should be able to close without hesitation as contacts touch. The circuit-breaker should be able to withstand the high mechanical forces during such a closure. These capabilities are proved by carrying out making



$\left.\begin{array}{l} AA' \\ BB' \end{array}\right]$ = Envelope of current wave

BX = Normal zero axis

CC = Displaced zero axis

I_{pk} = Peak making current.

Fig. 3.30. Determination of peak making current.

current test. The rated short-circuit making current of a circuit-breaker in the peak value of first current loop of short-circuit current (I_{pk}) which the circuit-breaker is capable of making at its rated voltage (Ref. Fig. 3.7, Sec. 3.6).

The rated short-circuit making current should be least 2.5 times the r.m.s. value of a.c. component of rated breaking current.

$$\begin{aligned} \text{Rated making current} &= 1.8 \times \sqrt{2} \times \text{Rated short-circuit breaking} \qquad \text{...(3.32)} \\ &= 2.5 \times \text{Rated short-circuit breaking current.} \end{aligned}$$

In Eq. 3.32 the factor $\sqrt{2}$ converts the r.m.s. value to peak value. Factor 1.8 takes into account the doubling effect of short-circuit-current (Ref. Sec. 3.6) with consideration to slight drop in current during the first quarter cycle.

3.18.7. Rated duration of short-circuit (Rated short time current)

The short time current of a circuit-breaker is the r.m.s. value of current that the circuit-breaker can carry in a fully closed position during a specified time under prescribed conditions of use and behaviour. It is normally expressed in terms of kA for a period of one second. Adjacent poles experience mechanical force during this test.

The rated duration of short circuit is generally 1 second and the circuit breaker should be able to carry short-circuit current equal to its rated breaking-current for one second. During the short-time current test, the contacts should not get damaged or welded. The current carrying parts and insulation should not get deteriorated. Generally the cross-section of conductors based on normal current rating requirements is quite adequate for carrying the rated short-circuit current for the duration of 1 second.

3.18.8. Rated Operating Sequence (Duty Cycle)

The operating sequence denotes the sequence of opening and closing operations which the circuit-breaker can perform under specified conditions. The operating mechanism experiences severe mechanical stresses during the auto-reclosure duty. As per IEC, the circuit-breaker should be able to perform the operating sequence as per one of the following two alternatives:

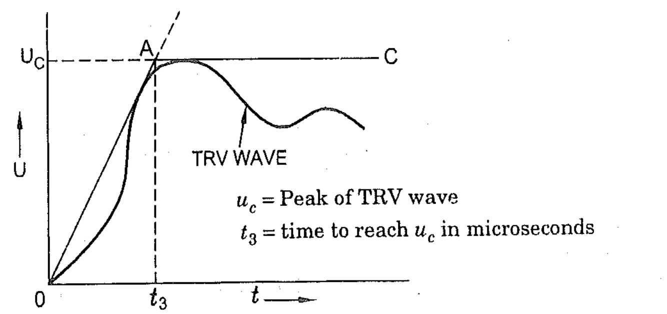


Fig. 3.31 (*a*) Representation of TRV wave by two parameter method.

(*i*) *O–t–CO–T–CO*

where, O = opening operation

C = closing operation

CO = closing followed by opening

t = 3 minutes for circuit-breaker not to be used for rapid auto-reclosure

t = 0.3 second for circuit-breaker to be used for rapid auto-reclosure

T = 3 minutes

(*ii*) *CO–t′–CO*

where t'–15 second for circuit-breaker not to be used for rapid auto-reclosure.

3.18.9. Rated Transient Recovery Voltage for Terminal Faults

The methods of specifying a TRV wave were briefly discussed in Sec. 3.18. As per new standards on circuit-breakers, the circuit-breakers should have rated TRV. The breaking current test is carried out on circuit-breaker with specified TRV.

The standard parameters such as voltage co-ordinate time coordinates have been given in the standards. Based on these parameters the line segments can be drawn. The TRV wave can then be drawn within the segments. Thus the circuit-breaker should be tested for short-circuit-breaking current test with TRV waveform above the standard waveform. IEC 56.2, 1971 and IS 2516 Part I/sec. 3, 1972 recommended the following two alternative methods for specifying standard TRV.

— Method of two parameters.

— Method of four parameters.

3.18.10. Representation of a TRV waveform by four parameter method [Ref. Fig. 3.31 (*b*)]

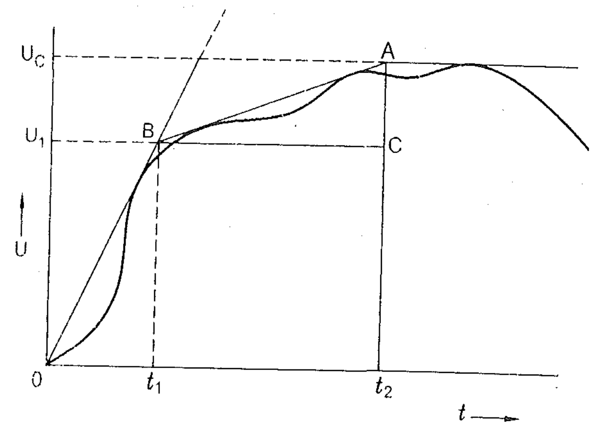
In the systems rated above 100 kV or locations where the short-circuit currents are relatively heavy compared to the maximum short circuit current in the system (Ref. Sec. 3.7.), the TRV wave has initial period of high rate of rise followed by later period of low rate of rise. Such waveforms can be represented by four parameter method. The four parameter are the following :

u_1 = first reference voltage kV.

t_1 = time to reach u_1 μ sec.

u_c = second reference voltage, Peak value of TRV. kV

t_2 = time to reach u_c, μ sec.



u_1 — first reference point of TRV wave

t_1 — time to reach u_1 in microseconds

u_c — peak of TRV

t_2 — time to reach u_c in microseconds

Fig. 3.31. (*b*) Representation of TRV wave by four parameter method.
(Ref. Fig. 3.8 (*b*) A portion of TRV shown therein is magnified here)

The values of four parameters μ_1, t_1, u_c, t_c have been specified in the standards for various values of rated voltages. Based on these values the segments can be plotted as shown in Fig. 3.31 (*b*) and the student TRV wave can be drawn such that it is contained in the three segments. The parameters u_c and u_1 can be calculated from rated phase to phase r.m.s. voltage u_1 as follows:

(*a*) For systems with non-effective earthing (Ref. Sec. 18.6)

$$u_1 = \frac{1.5 \times \sqrt{2} \times u_r}{\sqrt{3}}$$

(*b*) For systems with effective earthing (Ref. Sec. 18.6)

$$u_1 = \frac{1.3 \times \sqrt{2} \times u_r}{\sqrt{3}}$$

where u_r = rated voltage of circuit-breaker (highest system voltage), phase to phase r.m.s. kV

u_1 = first reference kV

t = time to reach u_1, μs

t_2 = time to reach u_c, μs

u_c = peak value of TRV wave

t_1 and t_2 are specified in standards for various rated voltages of circuit-breakers.

Factors 1.3 or 1.5 in equation given above is called *First pole to clear factor* (Ref. Sec. 3.10; Sec. 18.6)

$$\text{Amplitude factor} = \frac{u_c}{u_1} \text{ (Ref. Sec. 3.10)}$$

$$\text{Natural frequency} = \frac{10^3}{2t_2} \text{ kHz (Ref. Sec. 3.10)}$$

3.18.11. Representation of TRV waveform by two-parameter method

The wavaform of TRV in systems rated below 100 kV or locations where short-circuit current is low compared with the maximum short-circuit current in the system can be approximately represented by a single frequency transient. Such a waveform can be defined by method of two parameters as follows:

u_c = peak of TRV wave, kV

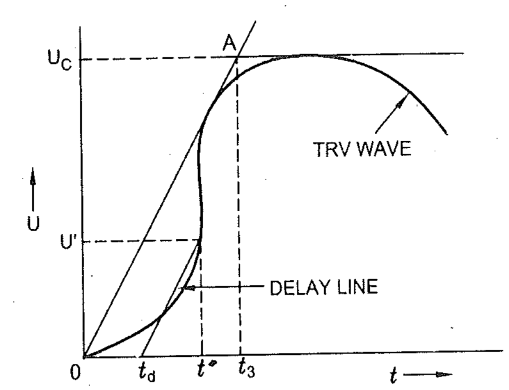
t_3 = time to reach peak, μs

The standard values of u_c and t_3 have been given in IEC-56-2 and IS2615-I/3 for various rated voltage of circuit-breaker. From these values the segments of line can be plotted and the TRV waveform contained in these segments can be defined [Ref. Fig. 3.31 (*a*)].

U_c can be calculated as described in the method of four parameters.

The delay line. The initial rate of rise of TRV wave contained within segments drawn according to the method of two parameters and four parameters is defined the delay line.

(Ref. Fig. 3.8. (*b*). The portion of TRV therein is magnified here).



The TRV wave should cross the delay line only once and should not recross it.
Fig. 3.32 The Delay Line.

The parameters u', t', and t_d are specified in the standards for various rated voltages. From these parameters, the delay line can be drawn. The TRV waveform should cross the delay line only once and should not recross it. By this method the initial rate of rise of TRV wave is defined.

Initial TRV. (ITRV) to TRV for one or two microseconds after current zero.

Example of Rating of a 145 kV Circuit Breaker

Rated Voltage..................145 kV rms

Rated Frequency.....................50 Hz

Rated Insulation Level

— 1 Min. Power Frequency Withstand...........275 kV rms

— Impulse Withstand...........650 kV_p

Rated Normal Current...............1600 A rms

Rated Short-Circuit Breaking Current........25 kV

Rated Operating Sequence.........O—0.3 sec—CO—3 min—CO

Rated Duration of Short Circuit........1 sec

Rated Short Circuit Making Current..........62.5 kA_p

Total Break Time (maximum)..........3 cycles.

3.18.12. Rated Peak Withstand Current

The rated peak withstand current is the instantaneous value (peak value) of short-circuit current which the circuit-breaker in closed position is capable of withstanding. The closed circuit-breaker may be subjected peak short-circuit current during every short-circuit beyond a circuit-breaker. (Fig. 3.30 Ipk). The adjacent phases are subjected to maximum mechanical force at the instant of adjacent phases are subjected to maximum mechanical force at the instant of this peak (Sec. 17.18). These forces are inversely proportional to the distance between adjacent poles. In LV and HV circuit-breakers upto rated voltage of 72.5 kV, the phase to phase clearances are relatively small and the forces during peak short-circuit current are high. The circuit-breaker should be capable of withstanding these stresses without damage.

As per IEC-56 the assigned value of rated peak withstand current is equal to the rated short-circuit making current. It is expressed in terms of kA, instantaneous.

For making current test the breaker is closed on existing short-circuit. For peak withstand current test the short-circuit with maximum asymmetry in one phase is applied to a closed breaker. Peak withstand current test is combined with the short-time current test (Sec. 11.6).

TABLE 3.3

Preferred Ratings of High Voltage circuit-breakers Selection Chart

Rated Voltage kV, rms	*(L.V.) 0.460*	*(H.V.) 3.6*	*7.2*	*12*	*36*	*72.5*	*145*	*245*	*420*
1 Minute p.f. withstand kV rms		21	27	32	75	140	230/275	395/460	680
Impulse withstand kV peak		45	60	75	170	325	550 650	900 1050	1425
Rated normal current A rms		400-40 0							
Rated S.C. breaking current kA rms	8-60	8-40	8-40	8-40	20-31.5	20-31.5	25-40	25-50	25-60
Rated S.C. making current kA, peak	*	*	*	*	*	*	*	*	*
Rated duration of S.C. sec	3 sec	1/3	1/3	1	1	1	1	1	1
Rated operating sequence	(O—3m—CO—3m—CO) (CO—15 Sec—CO)				(O—0.3 Sec—CO—3m—CO)				

Reference standards :

(1) IS 2516, IEC-56 for Ratings and Testing of High Voltage a.c. current breakers.

(2) IEC 60, IEC 71 for High Voltage Testing and Insulation Co-ordination.

(3) ICE 157 for Low Voltage Switchgear and Controlgear.

(4) Total breaking time varies between 80-120 ms for circuit breakers up to 12 kV and 40-80 ms for circuit breakers above 36 kV. It is less than 60 ms for 145 kV, less than 50 for 420 kV circuit breakers.

3.18.13. Rated Quantities for Auxiliary Circuits and Operating Mechanisms for opening and closing

In addition to the specified ratings for the main circuit and poles, the performance of auxiliary supply circuits and operating mechanisms is also important. The auxiliary circuits which supply voltage to the trip-coil and closing coil should have certain minimum voltage. Below this limit the tripping mechanism and closing mechanism may not operate even after getting a command. In case of AC auxiliary supply, the frequency should be between specified range to ensure correct operation of AC trip coils and AC electromagnetic operating mechanisms (if any).

The following ratings are mentioned in IEC 56 (1987).

— Rated supply voltage of closing and opening devices and auxiliary circuits.

— Rated supply frequency of closing and opening devices and auxiliary circuits.

No load operation tests are carried out on a circuit-breaker (s) before carrying out main short-circuit duty tests and main short circuit duty tests.

These comprise O, C, CO operations on no-load with

— Closing of auxiliary energized at 105%, 100%, 85% of rated supply voltage of auxiliary closing devices.

— Shunt opening release (trip coil) energized at 110%, 100%, 85%, rated auxiliary supply voltage in the case of AC and 110%, 100% and 70%, in the case of DC supply voltage.

3.18.14. Rated Pressure of supply for pneumatic and hydraulic operating devices

Air-blast circuit-breaker and some single pressure SF_6 circuit breakers use pneumatic operating mechanisms. Some SF_6 circuit-breakers use hydraulic operating mechanisms. The minimum rated maximum pressures of air pressure and hydraulic pressure are specified.

The no-load tests short circuit test duties with rated operating sequency (0-0.3S—CO-3m—CO) are performed with certain conditions of these pressures.

The pressure switches are fitted in the auxiliary-systems of the operating mechanism.

3.18.15. Rated Pressure of Interrupting Medium and Insulating medium (If applicable)

Fir Air-blast circuit-breakers and SF_6 circuit-breakers these quantities are specified along with lowest, normal and highest permissible value. The type tests are performed as per rules. The settings of limit switches are also decided accordingly.

Satisfactory performance of circuit-breakers during various type tests and during switching operation in service is with reference to minimum and maximum pressure of insulating medium in the breaker pole unit.

The dielectric type tests and short-circuit type tests are performed on new circuit-breaker filled with specified normal pressure of interrupting medium and insulating medium. Breaker should be leakage free.

During service, the pressure switches sound an alarm for lower pressure or upper pressure. In case pressure drops below safe limits, pressure which sends tripping command or locking command.

3.18.16. Summary of Rated Characteristics of HV (a.c.) Circuit-breakers

(A) Rated Characteristics to be specified for every circuit breaker.

Every high voltage a.c. circuit-breaker should have the following rated characteristics : (Ref. : Table 3.3). These are assigned for every circuit breaker supplied by manufacturer. The type test certificates are furnished for confirming these rated characteristics.

(1) Rated Voltage

(2) Rated Insulation Level

(3) Rated Normal Current

(4) Rated Frequency

(5) Rated duration of short-circuit or Rated short-time current

(6) Rated short-circuit breaking current

(7) Rated short-circuit making current

(8) Rated peak withstand current

(9) Rated TRV for terminal fault

(10) Rated Operating Sequence

(11) Rated supply voltage for closing and opening devices and auxiliary circuits.

(12) Rated pressure of compressed gas (Air or SF_6) for interruption (if applicable)

(13) Rated pressure of compressed gas or oil for pneumatic or hydraulic operating mechanism (if applicable)

(B) Additional Rated Characteristics to be specified in certain cases.

In addition to (A) above, following rated characteristics are assigned in following specific cases.

(14) Rated characteristic for short-line faults for CBs controlling overhead lines rated 52 kV and above.

(15) Rated line charging current for CBs controlling overhead lines rated 72.5 kV and above.

(C) Rated characterictics to be given on request by user or consultant

For special switching duties like capacitor switching, reactor switching, DC switches, inductive current switching etc. The circuit-breaker is subjected to unusual and severe stress. Each type of CB behaves differently *e.g.* MOCB is prone to restrict during capacitor switching. SF_6 is very good for interruption of low inductive currents. VCB is excellent for capacitor current switching etc. The severity of each special duty is different and each type of CB behaves differently. The suitability of circuit-breakers for following special duties should be varified by the user and the manufacturer before ordering.

The following rated characteristics are to be furnished on special request from user for particular intended application.

(16) Rated out-of-phase breaking current

(17) Rated cable-charging breaking current

(18) Rated single capacitor bank breaking current

(19) Permissible switching overvoltages

(20) Rated capacitor bank inrush overvoltages

(21) Rated small inductive breaking current

(22) Rated time quantities

(23) Repeated operating duty

The user requests the manufacturer for the specific assigned (16 to 23) and the ratings are mutually selected for particular application. Necessary circuit arrangements are made to limit the stresses in actual installation within assigned rating. This applies to the circuit-breaker in question and also all the associated CTs, VTs Surge Arresters, busbars etc. failure in an installation can occur in the weakest spot, internal or external. In case of special switching duties (16 to 23) particular investigations are essential for each installation before arriving a required rating of the circuit breakers and associated equipments in the installation.

3.18.17. Rated out-of-phase breaking current

Refer Sec. 3.17. Phase opposition switching the circuit breaker used for synchronising should be capable of opening under nonsynchronous condition. The recovery voltage across the circuit-breaker pole is higher than normal short circuit duties. The out-of-phase current is assigned to a circuit breaker to be used for synchronising. The rated out-of-phase current that the circuit-breaker shall be capable of breaking under the prescribed conditions of power frequency recovery voltage and transient recovery voltage.

The power frequency recovery voltage is 20 times rated voltage for earth neutral systems. The TRV is specified in the standards.The rated out-of breaking current is 0.25 times rated short-circuit breaking current. The circuit breaker should be capable of opening and closing. It is assumed that there is no fault on either sides of the breaker. Ref. Sec. 11.11 out-of-phase switching test.

3.18.18. Rated Cable-charging breaking current

Ref. Sec. 3.14.2 switching of unloaded cables. The circuit breakers to be used for high voltage cable switching should be capable of breaking cable charging current. Such circuit breakers are assigned the rated cable-charging breaking current. The rated cable-charging breaking current is the maximum cable-charging current that the circuit breaker shall be capable of breaking at its rated voltage. It is expressed in Amperes. Table 3.4 gives the standard values of rated cable-charging breaking current.

TABLE 3.4

Rated Voltage of CB (kV) r.m.s., ph. to ph.	3.6	7.2	12	36	72.5	145	245	420
Rated Cable Charging breaking current (A r.m.s.)	10	10	25	50	125	160	250	400

Ref. Sec. 11-13 cable-charging current test.

3.18.19. Rated Single Capacitor bank breaking current

Ref. Sec. 3.14.1. Switching of capacitor banks is a severe duty on circuit breaker. The circuit-breaker to be used for opening capacitor banks should have adequate rating for breaking capacitor current without giving restrikes. Single capacitor banks does not have a parallel capacitor bank. Hence there is no question of high frequency inrush current. The rated single capacitor bank breaking current is the maximum capacitor current that the circuit breaker is capable of breaking at its rated voltage.

This breaking current refer to the switching of a single shunt capacitor bank and with no other shunt capacitors, connected on source side of the circuit-breaker. Ref. Sec. 11.12 for single capacitor current breaking tests. The assigned current is given on the basis of type tests. Single capacitor bank tests may be made in the laboratory or on actual side. The breaker should be restrike-free.

3.18.20. Permissible Maximum Switching Over-Voltages When Interrupting Line-Charging, Cable-Charging and Single Capacitor bank Breaking Current.

As per IEC 56, the maximum switching over voltages occurring during interrupting capacitive currents have been specified as given in Table 3.5.

Switching overvoltage is defined in terms of instantaneous peak value of the transient recovery voltage. It is also defined in terms of power unit value with rated phase to ground voltage as the base.

3.18.21. Rated Capacitor Bank Inrush Making Current

When capacitor bank is to be connected in parallel with another capacitor bank, inrush high frequency inrush current flow through the breaker contact at the time of contact touch. These inrush currents produce severe stresses on circuit-breakers. Various breakers behave differently with such stresses. The breakers to be used for paralleling capacitor bank should have adequate rated capacitor bank inrush making current. The rated capacitor bank inrush making current is the peak value of the current that the circuit-breaker is capable of making at its rated voltage and with given frequency of inrush current.

— In service the frequency of the inrush current is normally in the range 2 to 5 kHz.

— The circuit-breaker is considered to be suitable for any frequency of the inrush current lower than that for which it has been tested.

3.18.22. Rated Small Inductive breaking current

Ref. Sec. 3.12. The requirements of switching low inductive currents. The testing requirements are covered in Sec. 11.13. The rated low inductive breaking current has not been covered in IEC and in under consideration. However for particular application such as motor switching no load transformer switching the manufacturer gives result of low inductive current tests. The switching over voltages due to current chopping if any should be lesser than the permissible values (Ref. Table 3.5)

A present permissible switching over voltage specified for switching capacitive currents. The same over voltages limits may be consider for switching low inductive currents. The standards give the specifications. Apart from the inductive load, the supply cable; surge capacitive, surge arresters, surge absorbers connected to breaker terminals limit the over voltages and the tests on particle installations are carried out with such devices, in the circuit,

Let U_n = Rated voltage of *CB*, phase-to-phase kV, r.m.s., r.m.s. value of phase to phase rated voltage of the *CB*

U' = r.m.s. value of phase to earth rated voltage $= \dfrac{U_m}{\sqrt{3}}$

U'_m = Peak value of rated phase to earth voltage $= \sqrt{2}\, U'$

Any voltage above U'_m is called switching over voltage U.

Switching overvoltage factor $K = U/U'_m$.

where U = Instantaneous value of overvoltage

U'_m = Peak value of rated phase to ground Voltage $= \sqrt{2}\, U'$

IEC 56-1987 gives the table which gives permissible values of switching overvoltage factor for capacitive current breaking. While testing the circuit-breaker for line charging, cable charging, single capacitor bank breaking current tests, the switching over voltage should be within specified limits.

3.19. REIGNITION AND RESTRIKE

Recall the definition described in the last part of Sec. 3.6; Reignition is the reappearing of arc after arc extinction within one-fourth of a cycle from final current zero. Reignition may occur by chance if the moving-contact travel was too small after arc extinction current zero. The contact gap breaks down and arc reignites without overvoltage. The arc gets quenched at the very next current zero by which time moving-contact should have moved sufficiently away from the fixed-contact to withstand the TRV. The reignition itself is not harmful as it does not give any overvoltage beyond permissible limit.

Restrike is defined as the reappearance of arc after one-fourth cycle from the arc extinction current zero. The phenomenon is explained in sec. 3.14.1. In Capacitor current Breaking, a single restrike gives an overvoltage of about 4 p.u. and a second restrike gives an overvoltage of about 6 p.u. resulting in internal and external flashovers, phase to phase as well as phase to ground. Restrikes were possible with MOCBs and OCBs used for Capacitor Switching. *For Capacitor switching, cable switching, switching of unloaded transmission lines, the restrike-free SF and Vacuum Circuit Breakers are not preferred.*

Summary

The sudden short-circuit in an a.c. system causes a rise in current in the short-circuited phases. The current increases to several times the normal current, during the first quarter cycle. Thereafter the amplitude of the waveform reduces successively, while passing through the sub-transient, trasient, and steady state. The waveform is asymmetrical about the normal zero axis. The value of current at the peak of the first major or current loop is called making current. The r.m.s. value at the intant of contact separation is called breaking current.

The voltage appearing across the circuit-breaker pole after final current zero is called recovery voltage. The recovery voltage containing the high frequency component is called Trasient Recovery Voltage (TRV). TRV tries to restrike the arc. The ability of the circuit-breaker to clear the short-circuit depends upon the rate of rise of dielectric strength of the gap, which should be more than the rate of rise of TRV.

Table 3.5

Recommended values of Maximum Permissible Swithching Overvoltage for Interruption of Capacitive Currents by CB

Rated Voltage of CB rms, ph to ph	*Rated Lightning Impulse withstand voltage*	*Maximum permissible switching overvoltage, phase to earth For line charging breaking current*		*For cable charging capacitor bank and back to back capacitor bank breaking current*	
		Peak value	*Switching overvoltage factor*	*Peak value*	*Switching overvoltage factor*
kV(rms)	*kV(peak)*	*kV(peak)*	*K*	*(p.u.)*	*(p.u.)*
3.6	20	8.8	3	7.3	2.5
3.6	40	13.2	4.5	7.3	2.5
7.2	40	17.6	3	14.7	2.5
7.2	60	26.4	4.5	14.7	2.5
12	60	29.5	3	24.5	2.5
12	75	39.5	4	24.5	2.5
36	145	88	3	73	2.5
36	170	112	3.8	73	2.5
72.5	325	207	3.5	148	2.5
145	550	356	3	297	2.5
145	650	415	3.5	297	2.5
245	850	540	2.7	400	2
245	950	600	3	400	2
245	1050	600	3	400	2
420	1300	790	2.3	688	2
420	1425	895	2.6	688	2
765	1800	1125	1.8	1125	1.8
765	2100	1250	2	1250	2

The rated characteristics of circuit-breaker include: the rated normal current, rated voltage, rated insulation level, rated transient recovery voltage, rated short-circuit breaking current, rated circuit making current, rated operating sequence etc. These ratings are assigned to a circuit-breaker after conducting the type tests. (Ref. Sec. 15.7 for low voltage circuit-breaker).

QUESTIONS

1. Define and discuss the following ratings of a.c. circuit-breakers : — rated short-circuit breaker current, rated short circuit making current.
2. Discuss the following : — two parameter method of defining TRV waveform
   — four parameter method of defining TRV waveform
3. Explain the fault clearing process by illustrating the oscillograph of short-circuit current and transient recovery voltage.
4. Explain the variation of short-circuit current through sub-transient, transient and steady state.
5. Explain the phenomena of transient recovery voltage and its influence on the behaviour of circuit-breaker performance.
6. A three phase alternator of rated line to line voltage of 13.5 kV is connected to a circuit-breaker. The inductive reactance up to the circuit-breaker is 4 ohms per phase. The distributed capacitance upto the circuit-breaker between phase to neutral is 0.2 μF. Determine the following neglecting First Pole to clear factor.

4

The Arc-Extinction

Introduction—Matter and Plasma—Ionization—Deionization—Electric Arc—Arc Formation in Circuit-Breaker—Modes of Arc Extinction—Zero Point Extinction—Electronegative Gases—Vacuum Arc—Arc Interruption Theories—Slepian's Theory—Cassie's Energy Balance Theory—Summary.

4.1. INTRODUCTION

The electric arc is a type of a electric discharge between electrodes. In circuit-breakers, the arc persists during the brief period after separation of current carrying contacts. The circuit-breaker should be capable of extinguishing the arc without getting damaged. The arc plays an important role in the behaviour of the circuit breaker. The interruption of d.c. arcs is relatively more difficult than a.c. arcs. In a.c. arcs, as the current becomes zero during the regular wave, the arc vanishes and it is prevented from restriking. In this chapter we shall study technical aspects regarding the arc and the techniques employed for arc extinction.

The arc extinction duty, though not frequent, produces highest stresses on the circuit-breaker. The techniques adopted for the arc extinction can be classified into the following three categories:

— **High resistance interruption.** The resistance of the current path is increased rapidly resulting in the increased voltage drop. The arc gets extinguished when the system voltage can no longer maintain the arc, due to high value of the voltage drop. This principle is used in d.c. circuit-breakers and air-break type a.c. circuit breakers of relatively low capacities of the order of a few hundred MVA. The energy stored is system inductance is gradually dissipated in the arc.

— **Current zero interruption.** The arc is interrupted at natural current zero of the alternating current wave and the dielectric strength of the contact-gap is increased to such an extent that it can withstand the voltage stress across it.

— **Artificial current zero interruption.** This is used for breaking DC currents in HVDC systems.

4.2. THE MATTER AND PLASMA

In the physical world, the matter manifests itself in various states known as solid, liquid and gaseous states. Each substance consists of molecules formed of atoms with their nucleus and orbiting electrons. Normally the molecules and atoms are electrically neutral, *i.e.*, the positive and negative charges are equal. However, the matter can be *ionized*. The ionized matter consists of charged particles such as ions and electrons. Consider the gas in a container, the temperature being gradually increased. Initially the molecules experience a motion in all sorts of directions. At higher temperatures the velocity of the particles increases and they collide against particles coming in their way. At temperatures of the order of 3000° K the molecules break up into simpler forms such as simpler molecules and atoms. This process is called dissociation. If the temperature is further increased (to about 6000° K) the internal forces which hold the electrons to the atoms are affected and the electrons manage to escape. The atom becomes truly charged and the electrons may attach a neutral atom or may remain free. The matter is thus ionized. Further increase in temperature enhances the process of ionization and *Plasma* state is reached. The plasma consists of charged

particles. The conductivity of plasma depends upon number of ions per unit volume. Plasma is conducting medium for electric current.

The non-ionized gas is generally a good dielectric medium. Even dissociated gas is a dielectric. However the ionized gas is a conducting medium. In circuit-breakers the contact space is ionized by the following causes:

(1) Thermal ionization of gas.

(2) Ionization by collision of particles.

(3) Thermal emission from surface of contacts.

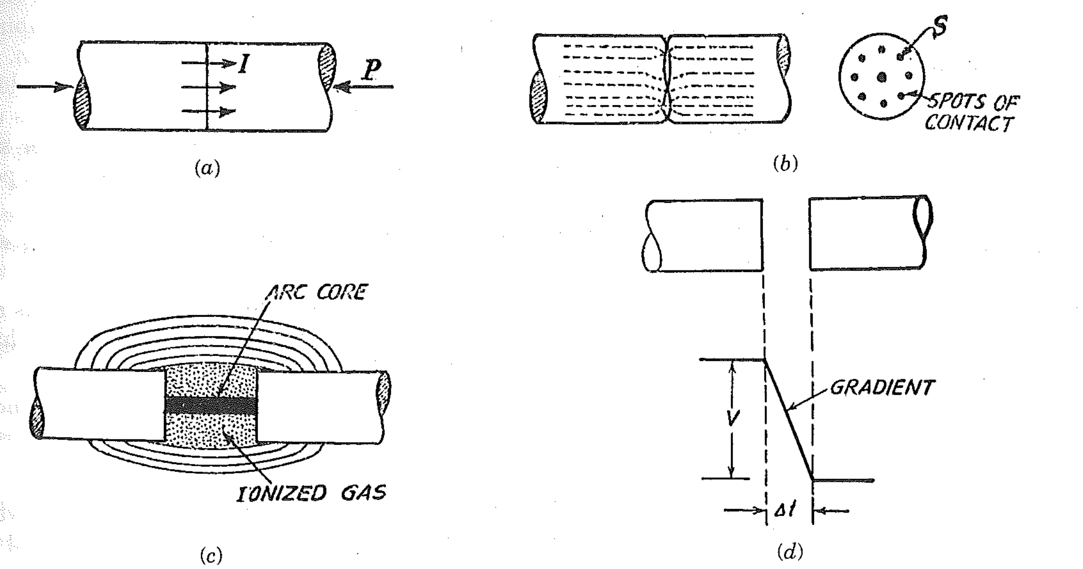
(4) Secondary emission from surface of contacts.

(5) Field emission from the surface of contacts.

4.3. IONIZATION OF GASES

(*a*) **Thermal Ionization.** At normal temperatures the molecules of gas are in a state of constant agitation and they move at various velocities in various directions. A molecule at velocity V and mass m possesses kinetic energy equal to $1/2\ mV^2$. At temperature about 3000°C the molecules break up in simpler forms and further to atoms. This process is known as dissociation. At higher temperatures (about 6000°C) the agitation of these atoms is vehement and their impact against each other can produce ionization by mutual collision. This type of ionization brought about by heat is called thermal ionization.

(*b*) **Ionization by Collision.** A particle (electron, ion or molecule) at a higher velocity (produced by electric field) may strike another particle. Thereby the energy of the moving particle is imparted to the other one. This energy may be enough to dislodge the electrons from atoms. Such ionization is called ionization by collision.



(*a*) Contacts pressed at high pressure in closed position

(*b*) Pressure reduced. Hence contact area reduced. Current concentrated on a few spots of high current density.

(*c*) Contacts separated, arc down, arc is surrounded by ionized gas and hot column of gas. (See Front Cover — The Arc).

(*d*) The voltage gradient = $V/\Delta l$

If $V = 1$ kV, $\Delta l = 1$ mm, Gradient = 1000 V/mm

Fig. 4.1 Electron emission.

(c) **Thermal Emission from Surface of Contacts.** In closed position, the contacts are pressed against each other at a high pressure causing plastic and elastic deformation. As the contacts start separating, the pressure between contacts reduces first. Thereby the true area of contact is reduced to area of a few spots on the surface. The current crosses the contact surface at the spots producing high current densities. Therefore, spots of high local temperature are produced on the surface of contacts. Next the arc has high temperature as the energy is dissipated in the form of heat. BY virtue of these causes thermal emission takes place at contact surface. (Fig 4.1)

(d) **Secondary Emission at Contact Surface.** The electrons move rapidly under the influence of strong electric field between the contacts and strike the surface of the other contact. Thereby they produce emission from contact surface by collision.

(e) **Field Emission at Contact Surface.** If the voltage gradient at the surface of the contact is high (even more than 1000 V/cm) the electrons can be dislodged from the surface of the electrode. As the contacts separate, the distance between them being too small, initially, high potential gradient (kV/cm) appears near the contact surfaces. The gradient can be more than 10^6 V/cm. and is enough to breakdown the gas. The ionization produced by electric field is called field emission [Fig. 4.1 (d)].

(f) **Photoemission.** The electron emission from contact surface caused by incidence of light energy is called photoemission.

4.4. DEIONIZATION

Deionization can take place by the processes of recombination or attachment as well as by process of diffusion and drift. These have been discussed here very briefly.

(a) **Recombination.** If a gas containing positive ions and electrons there is a tendency for these to come together and combine to form a neutral atom. This phenomenon is termed as recombination. Recombination takes place directly in gas, and is important in the process of arc extinction. As the ions penetrate from the heavily ionized space near the arc to the walls of the container, electrons reach the walls first as they are light. As the walls are of insulating materials electrons cannot escape and the inner side of container, is negatively charged. Thereafter the wall inner surface repels electrons and attracts positive ions. Thereby the combination takes place between positive ions and negative charges.

(b) **Diffusion.** The electrons from highly ionized space diffuse to the surrounding weakly ionized space. This is an important process in building up of dielectric strength.

(c) **Conduction of Heat.** Conduction of heat brings down the temperature and assists recombination. The particles of higher temperature travel to the space at lower temperature. In this way kinetic energy is removed from the ionized space between the contacts.

In circuit-breakers the deionization is an important process because it assists arc extinction.

4.5. ELECTRIC ARC

The electric arc is a self-sustained discharge of electricity between electrodes in gas or vapour, which has a voltage drop at cathode of the order of minimum or minimum exciting potential of gas or vapour.

When D.C. voltage applied to electrodes places at a small clearance, say a few centimeters, is gradually increased a flow of current takes place through gas. This phenomenon is called discharge in gas. The volt-ampere characteristic has several distinct zones classified as glow discharge, townsend discharge and arc discharge. During arc discharge the voltage across the electrode is low and current is high. The current is limited by external impedance. The voltage across arc decrease as the current increases. The arc is self-sustained discharge.

The arc has a brightly burning core of high temperature ranging from 6000° to 25,000°K. If the arc is cooled the temperature increases. This is rather perplexing. The cooling reduces its

diameter and thereby the current density increases resulting in higher temperature. The current density of arc core is several thousand amperes per cm^2. The central core is surrounded by a column of hot gases at a temperature of about 1000° K down to a low temperature.

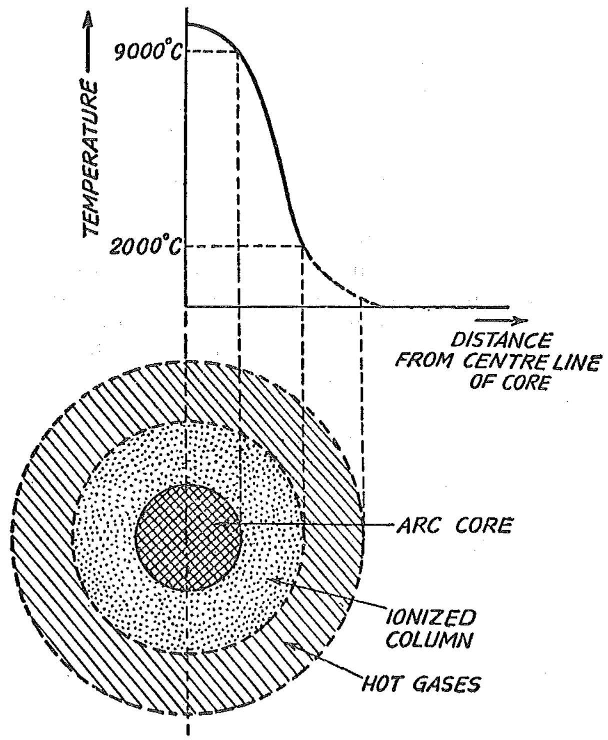


Fig. 4.2. Temperature zones in the arc.

The volt-ampere characteristics of a steady are is given by an equation,

$$V_{arc} = A + Bd + \frac{C + Dd}{i_{arc}} \quad ...(4.1)$$

where d = length of arc

V_{arc} = voltage across arc

i_{arc} = current in arc

A, B, C, B = constants.

$$A + \frac{C}{i_{arc}}$$

in arc cathode plus anode voltages

$$\left(B + \frac{D}{i_{arc}}\right)d$$

is the component of voltage across the length of the arc. For lengthy arcs this component should be considered and for small length arc this component should be neglected. Hence Eq. (4.1) reduces to

$$V_{arc} = A + \frac{C}{i_{arc}} \quad ...(4.2)$$

for small legnth arc.

The voltage across arc reduces as the current increases as shown in Fig. 4.3.

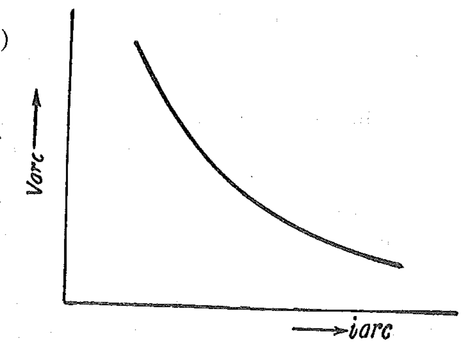


Fig. 4.3 Static characteristic of arc.

The energy dissipated in the steady arc is the form of heat is given by

$$E_{arc} = V_{arc} I_{arc} t \quad (4.3)$$

where E_{arc} = Energy in joules

V_{arc} = Voltages in volts

i_{arc} = arc current in Amps.

t = Duration of arc in sec.

The time t is of the order of 0.02 sec. in a.c. circuit-breakers.

The energy in the system is given by

$$E_s = 1/2 L_i^2 \text{.....joules} \quad ....(4.4)$$

In AC system instantaneous current i is zero during the end of every half cycle. At this instants the energy in the system is also zero. Arc can be interrupted at such natural current zeros. The arc quenching is related with system energ, arc energy.

4.6. ARC FORMATION IN A.C. CIRCUIT-BREAKERS

As discussed earlier, the separation of contacts leads to high local temperatures on the contact surface. The electrons are emitted from contact surface by thermal secondary field and photoemission. The gases between contact space are ionized by thermal ionization by collision. The space between the contact is in the state of plasma and therefore, is conducting. Thereby, arc discharge takes place between the contacts as the current carrying contacts separate.

Fig. 4.4 illustrates the characteristics of a.c. arc current and voltage with respect to time. The voltage across the arc is in phase with the arc current as arc current is predominantly resistive. The voltage across the arc reverse with the current. At current zero, the voltage across the contact reverses.

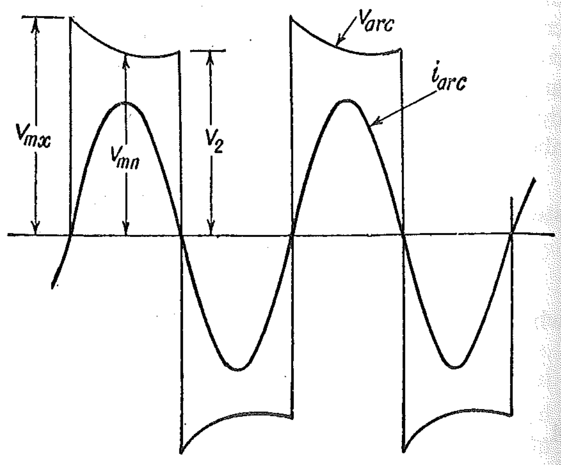


Fig. 4.4 Waveform of a.c. arc: Current and voltage V_s time.

4.7. MODES AT ARC EXTINCTION

Two mcdes of arc interruption can be identified :

(1) High resistance interruption.

(2) Low resistance or zero point-interruption.

(3) Artificial current zero principle (Ch. 16)

4.7.1. High Resistance Interruption, Blow-Out coils

The high resistance interruption is obtained by increasing the resistance of the arc.

$$r_{\text{arc}} = \frac{V_{\text{arc}}}{i_{\text{arc}}}$$

Assuming i_{arc} to be constant the resistance of the arc can be increased by increasing voltage of the V_{arc}. From Eq. (4.1), *i.e.*

$$V_{\text{arc}} = A + Bd + \frac{C + Dd}{i_{\text{arc}}}$$

where d is the length of the arc, we understand that the arc voltage hence the arc resistance can be increased by increasing length of the arc.

In high resistance interruption method the length of the arc is increased so as to increase the voltage across the arc.

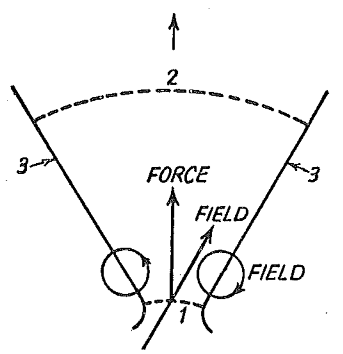
The voltage of the arc is increased till it more than the system voltage across the contacts. At this point the arc gets extinguished.

The method is used in low and medium voltage a.c. and d.c. circuit breakers (Refer Sec. 5.2).

The arc resistance is increased by the following methods :

(*a*) **Lengthening the arc by means of arc runners** (Refer Fig. 4.5 and also Ref. Sec. 5.2)

Arc runners are horn-like blades of conducting material, which are connected to arcing contacts with their tips radiating upwards in 'V' shape. The arc originates at the bottom and blows upwards by electromagnetic force. The tips of the arc more upwards along arc runners or arc horns rapidly. The length of the arc increases and the arc is extinguished.

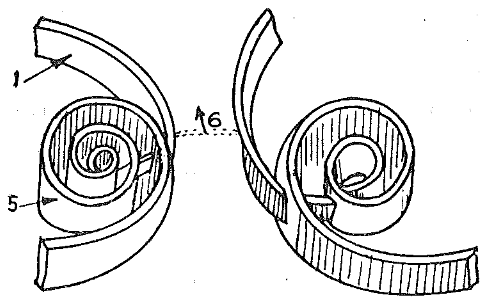


1. Initial position of arc
2. Final position of arc.
3. Arc runners (in vertical plane)
4. Field (in horizontal plane)
5. Force due to electrodynamic forces (in vertical plane)

Fig. 4.5 Function of the arc runners.

(*b*) **Splitting of Arc** (Refer Fig. 4.7)

The arc is elongated and split by arc splitters. These are specially made plates of resin bonded fibre glass. These are placed in the path perpendicular to the arc and the arc in pulled into them by electromagnetic force experienced by the arc by means of magnetic field applied in proper direction so as to pull the arc upwards. When the arc is pulled in space between the plates, it gets elongated constrained split and cooled. By virtue of these effects the arc gets extinguished. Fig. 4.7 illustrates the arrangement of magnetic blow out coils extinguished Fig. 4.7 illustrates the arrangement of magnetic-blow out coils employed in air magnetic circuit-breakers.



1. Arc runners (metallic)
2. Arc splitters
3. Elongated arc
4. Arc in process of travelling
5. Blow-out coils (metallic)
6. Origin of Arc

Fig. 4.6. Details of blow-out coil (See Fig. 4.7)

(*c*) **Cooling of Arc.** Cooling of the arc brings about recombination of ionized particles. Cooling removes the head from the arc. Cooling is brought by bringing the arc is contact with cooler air.

4.7.2. Low Resistance of Zero Point Extinction

This method is employed in a.c. arc interruption. Actually the alternating current passes through zero 100 times per seconds in 50 cycles current wave. At every current zero the arc vanishes for a brief moment. However, the arc appears again with the rising current wave. In a.c. circuit-breakers the arc is interrupted at a current zero. At current zero, the space between contacts is deionized quickly by introducing fresh unionized medium such as oil or fresh air, or SF_6 gas, between the contacts. The dielectric strength of the contact space increases to such an extent that the arc does not continue after current zero. A high voltage may appear across the contacts. The voltage may re-established the arc if the dielectric strength of gap is less than the restriking voltage. In that case the arc continues for another half cycle and may get extinguished at next current zero.

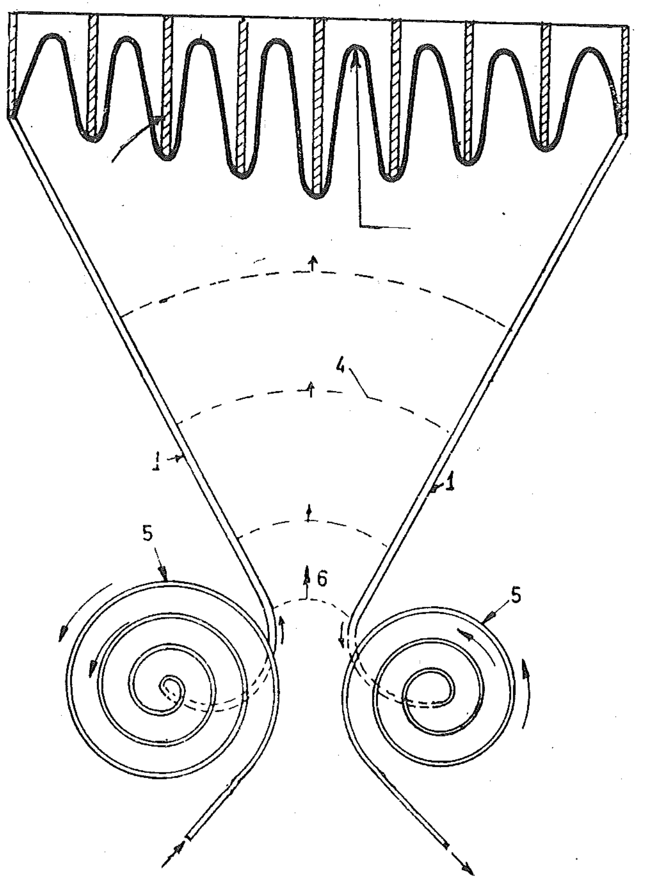


Fig. 4.7 The configuration of magnetic blow-out coils.

In various types of circuit-breaker designs, the provision is made to remove the hot gases from the contact space immediately after the arc so as to fill the contact space by fresh dielectric medium of high dielectric strength.

The arc extinction process can, therefore be considered to have three phases

— Arcing phase, — current zero, — post arc phase.

The arcing phase is governed by temperature stresses due to the arc. Every attempt is made in the interrupter design to remove the heat of arc quickly by radial and axial flow of gases. The experimentation has shown that the power arc cannot be broken abruptly. However, the arc diameter can be reduced to a low value by the flow of a gases over the arc. The arc diameter reduces during a portion of the a.c. wave approaching current zero. At current zero, the arc diameter reduces to a very low value and arc gets extinguished. But the contact space contains hot gases. These are removed by fresh dielectric medium having high dielectric strength. Hence the interrupter design attempts a removing the heat from the arc during the arcing period and flushing the contact space with fresh dielectric medium during the post-arc period.

The abilities of various media used for arc-interruption are generally different. As the various media used for arc extinction have different densities, thermal conductivities, dielectric strengths, arc-time constants, etc. the designs of interrupters using different media have distinct differences.

4.8. ARC INTERRUPTION THEORIES

Several theories have been postulated to explain the arc interruption but they are not perfect. However some theories have helped in the development of circuit-breaker. The first theory was that of Slepian of U.S.A., postulated in 1928-30. Later in 1931, Prince (also from U.S.A.) postulated displacement theory. Cassies of U.K. put forward another theory in 1938. Mayer of Germany put forward another theory similar to Classie's theory. Some of these theories have been briefly reviewed.

(*a*) Slepian's Theory. Splepian described the arc extinction process as the race between dielectric strength and restriking voltage. After current zero, there exists a residual column of ionized gas. If the dielectric strength builds up rapidly so that it is always greater than the restriking voltage, the arc does not restrike. If dielectric strength is less, the arc restrikes. Referring to Fig. 4.8 the three curves are the following:

— dielectric strength against time curves (*a*) and (*c*)

— restriking voltage against time, curve (*b*) (TRV)

According to the theory, if the dielectric strength of contact gap is more than the restriking voltage as shown by curve (*a*) above (*b*) the arc gets extinguished. But if the dielectric strength builds as in curve c, the arc restrikes.

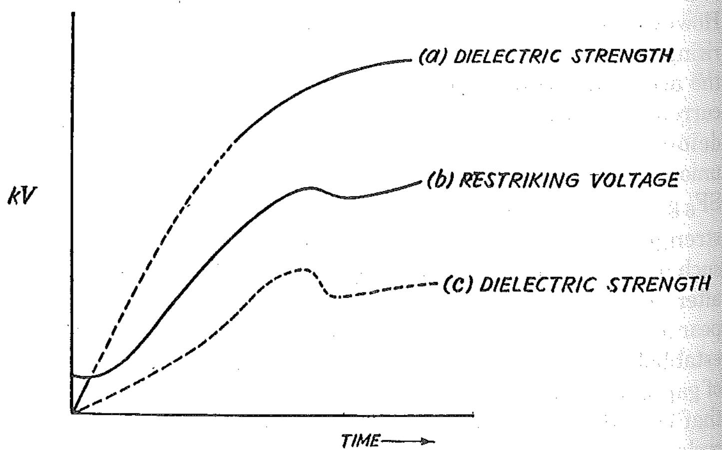


Fig. 4.8 Growth of dielectric strength and transient recovery voltage.

The theory assumes that the restriking voltage and build up of dielectric strength are comparable quantities. The assumption is not quite correct. These two entities are not identical. Secondly this theory does not consider the energy relations in the arc extinction. This theory does not cover the arcing phase, hence it is incomplete. Slepian was the first to point out that the restriking voltage plays an important role in arc extinction.

(*b*) Energy Balance Theory. Cassie made the following assumptions in his Energy Balance Theory :

(1) Arc consists of a cylindrical column at a substantially uniform temperature over its cross-section with well defined boundary. There is a uniform distribution of energy in this column *i.e.*, volume energy density is constant for the complete column of the arc.

(2) The temperature remains constant.

(3) The cross-section of arc adjusts itself to accommodate the arc current.

(4) Power dissipation is proportional to arc cross-sectional area of arc column. Cassie expressed the energy equation as

$$\frac{dQ}{dt} = EI - N \qquad ...(4.3)$$

where Q = energy content/cm of arc length

E = volts/cm

I = total current

N = total power loss/cm.

Breakdown occurs if power feed in the arc is more than power loss. The theory is approximately true for high currents. Mayer's theory is similar to Classie's theory but with different assumptions. This theory does not cover post-arc phase, hence it is incomplete.

Summarising the arc extinction can be obtained at current zero by building up dielectric strength of arc rapidly and by dissipating the energy fed into the arc.

Both the theories mentioned above give certain understanding of the arc extinction phenomenon. **The arc extinction process in circuit-breaker is influenced by several aspects such as**

— Speed of contact.

— Material of contact

— The pattern of flow of quenching medium.

— Magnitude of arc current and variation of arc diameter.

— Energy liberated during arcing, energy in system inductance.

— Rate of rise of transient recovery voltage.

— Rate of gain of dielectric strength.

— Instant of contact separation with respect to voltage, current.

As the governing parameters arc very much diverse in character, the arc extinction process becomes too complex for analysis. The arc-extinction process can be considered in three different zones:

— arcing zone. — current zero zone. — post arc zone.

During the arcing zone, the thermal stresses produced by the arc are predominant. In every circuit-breaker, an attempt is made to reduce the arc diameter by using various techniques.

The current zero zone provides transition.

During post arc zone, the voltage stresses become predominant. In every circuit-breaker, and attempt is made to introduce fresh dielectric medium between contact space after final current zero, is that the dielectric strength is rapidly regained.

4.9. ARC EXTINCTION IN OIL

The arc decomposes the dielectric oil. The gases formed due to the decomposition of the oil cause increase in pressure within the chamber fitted in the interrupter. The flow of gases is channelised through the vents in the chamber. The arc gets extended into the vents and is cooled by the flowing gases. The gases contain about 70% of hydrogen which has good dielectric strength. After the arc extinction the contact space is filled with fresh dielectric oil. In some circuit-breakers a piston attached to the moving contact causes the oil flow in the contact space assuring a rapid gain of dielectric strength. In some other designs, the interrupter is pressurised by nitrogen gas. The pressure on the oil ensures the flushing of contact space with fresh dielectric oil after final arc interruption. The amount of gas formed during the arcing is proportional to the arc current. Such circuit-breakers are called 'Internal energy type circuit-breakers' (Refer Ch. 8 for detail analysis).

4.10. ARC EXTINCTION IN VACUUM

When the contact of vacuum interrupter are separated the arc is drawn between them. The current leaves the electrodes from small, intensely hot spot (or spots). The metal vaporizes from the spots. The vapour stream constitutes the plasma in vacuum arc. The vapour formed is proportional to rate of vapour emission, which is proportional to the current in arc. Therefore, at current zero the plasma may vanish. Therefore the arc is interrupted at current zero. The vacuum has high dielectric strength, hence the arc may not restrike. The contact material shape are very important. Arc time constant of vacuum is lowest.

4.11. ARC EXTINCTION IN AIR-BLAST

In air-blast circuit, breakers the air flows from high pressure reservoir to the low atmospheric pressure during the arc extinction process. The flow rate is governed by the throat diameter of the nozzle, the pressure difference and the nozzle profile. The design is such that almost supersonic speeds of flows are achieved. The axial flow of air at high velocity causes rapid reduction in the diameter of the arc and the arc does not reappear after the final current zero.

4.12. ARC EXTINCTION IN SF_6 GAS*

In plasma, most of the current is carried by electrons. In certain gases like SF_6 the atoms and molecules have the property of attracting electrons to form negative ions. Negative ions are heavier than electrons and move slowly, thereby the resistance of plasma increases rapidly. Therefore electronegative gas like SF_6 is excellent arc extinction medium.

The arc extinction process in SF_6 gas is based on axial heat dissipation. The gas flows from high pressure to the low pressure through a well designed nozzle over the arc. The flowing gases take away the heat of the arc causing reduction in the diameter of arc. After current zero, the medium regains its dielectric strength very rapidly. This property of rapid recovery of the dielectric strength is due to the electronegativity of the gas.

4.13. ARC TIME CONSTANT

The time required by the quenching medium to gain original dielectric strength after final current zero. It is expressed in microseconds.

QUESTIONS

1. Explain the arc extinction process is alternating current circuit breaker.
2. State the theories postulated to explain the arc extinctions phenonmenon. What is the significance of restriking voltage in the arc extinction process?
3. An electric arc of 5 cm has a current of 1000 amperes and voltage across the arc is 25 volts. Calculate the energy consumed by the arc in one second.

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* *Puffer type SF_6 circuit-breakers are becoming popular for HV & EHV systems Whole Breaker is filled with gas at 5 kgf/cm^2.*

Puffer type single pressure SF_6 circuit-breaker uses Puffer principle for arc exinction. A cylinder called Puffer cylinder is attached to the moving contact. Puffer cylinder moves against fixed piston during opening stroke. The SF_6 gas trapped in the Puffer cylinder is compressed due to relative movement between the puffer cylinder and the piston. The gas pressure in puffer cylinder depends upon the speed of Puffer cylinder. Higher opening speeds (6 to 7 metres/sec) are used. The compressed gas in Puffer cylinder is released through convergent-divergent nozzles. The gas flows with almost supersonic velocity over the arc. Arc diameter is reduced to zero. Arc is quenched at first or second current zero. Dielectric strength is regained due to electronegativity of SF_6 gas.

Self-Extinguishing Principle : The heat of arc generates pressure which forces the arc in hollow moving contact. The arc gets lengthened and cooled. The arc is exinguished at current zero. For smaller current the puffer principle is used.

5

Air-Break Circuit-Breaker

Introduction—Design features—Heavy duty air-break circuit-breaker—Low voltage air breaker circuit-breaker—Arc extinction by means of magnetic field—D.C. air breaker circuit-breaker—Summary

5.1. INTRODUCTION

The air at atmosphere pressure is used as an arc extinguishing medium in Air-Break Circuit-Breakers. These circuit-breakers employ the high resistance interruption principle. The arc is rapidly lengthened by means of the arc runners and arc chutes and the resistance of the arc is increased by cooling lengthening and spliting the arc. The arc resistance increases to such an extent that the voltage drop across the arc becomes more than the supply voltage and the arc extinguished.

Air-breaker circuit-breakers are used in d.c. circuits and a.c. circuits upto 12 kV.

The air-break circuit-breakers are generally indoor type and installed on vertical panels or indoor draw-out type switchgear.

A.C. air-break circuit-breakers are widely used in indoor medium voltage and low voltage switchgear. Typical reference values of ratings of air-break circuit-breakers are:

460 V, 400—3500 A,	40—75 kA.
3.3 kV, 400—3500A,	13.1—31.5 kA.
6.6 kV, 400—2400 A,	13.1—20 kA.

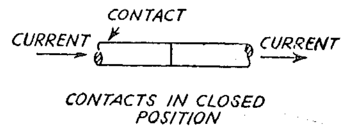
Magnetic field is utilised for lengthening the arc in high voltage air-break circuit-breakers.

5.2. CONSTRUCTION OF AIR-BREAK CIRCUIT-BREAKER

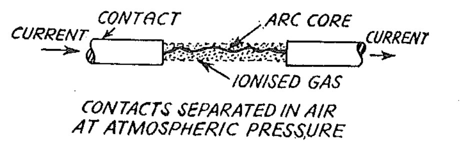
In the air-break circuit-breaker the contact separation and arc extinction takes place in air at atmospheric pressure. Fig. 5.1 (a) shows the closed current carrying contacts. As the contacts are opened arc is drawn between them. The arc core is a conducting path of plasma. The surrounding medium contains ionized air. By cooling the arc, the diameter of arc core is reduced. The arc is extinguished by lengthening the arc, cooling the arc and splitting the arc. The arc resistance is increased to such an extent that the system voltage cannot maintain the arc and the arc gets extinguished at current zero of AC wave.

Fig. 5.1 (*c*) illustrates the normal arrangement of an air-break circuit-breaker. This type of breaker is used for medium and low voltages.

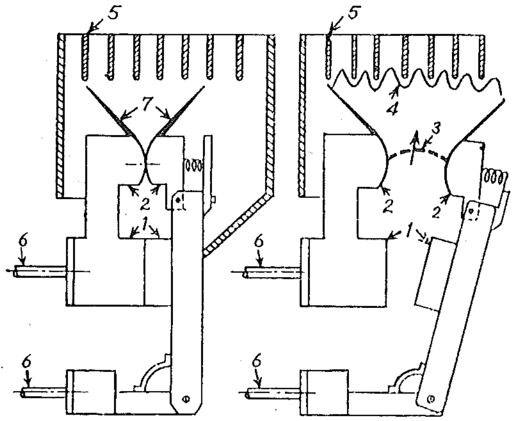
There are two sets of contacts: Main contacts and Arcing contacts. Main contacts conduct the current in closed position of the breaker. They have low contact resistance and are silver plated. The arcing contacts (2) are hard, heat resistant and are usually of copper alloy. While opening the contact, the main contacts dislodge first. The current is shifted to the arcing contacts. The arcing contacts dislodge later and arc is drawn between them (3). This arc is forced upwards by the electromagnetic forces and thermal action. The arc ends travel along the Arc Runner (Arcing horns.) The arc moves upwards and is split by arc splitter plates (5) as shown by the arrow (4). The arc is extinguished by lengthening, cooling splitting etc. In some breakers the arc is drawn in the direction of the splitter by magnetic field.



(a) Contacts in closed position



(b) Contacts Separated in air at atmospheric pressure



1. Main contacts
2. Arcing contacts
3. Arc rising in the direction of the arrow
4. Arc getting split
5. Arc splitter plates
6. Current carrying terminals
7. Arc runners

(I) Contacts Closed (II) Contacts Open
Principle of air-break circuit-breaker

Fig. 5.1. Arc extinction is air-break circuit-breaker.

Furthermore, air-break circuit-breakers have been developed with current limiting feature, magneting blow-up of arc, etc. Air break a.c. circuit breakers are widely used for industrial switchgear auxiliary switchgear in generating stations.

Air-break principle of lengthening of arc, arc runners, magnetic blow-up is used for d.c. circuit-breakers upto 15 kV.

5.3. ARC EXTINCTION IN A.C. AIR-BREAK C.B. (Ref. Sec. 4.7.1)

In a.c. air-break circuit-breakers the arc is lengthened cooled and splitted so as to increase the resistance of the arc. The rapid increase in the arc-resistance causes the reduction in the fault current and the fault current does not reach the prospective high value. The arc extinction process is assisted by the current zeros in the a.c. wave. The voltage drop across the arc goes on increasing with the increase in the arc resistance and at a current zero, when the recovery voltage across the contacts is less than the arc-voltage, the arc gets extinguished. The energy in the system inductance at current zero is zero. Hence the arc interruption is easier (Refer. Sec 4.7).

Arc Runners (Arcing Horns). As soon as the arc leaves the vicinity to the contacts it commutes to a pair of run out horns. In doing so the outer blow out system is switched on. These blow out coils provide a magnetic field such that the arc footing is subjected to a strong magnetic field. We know from the electromagnetic theory that force is experienced by current carrying element of length $\overline{dl}$ metres, carrying current I amperes and placed in magnetic field B webers/m^2 is given by the cross product:

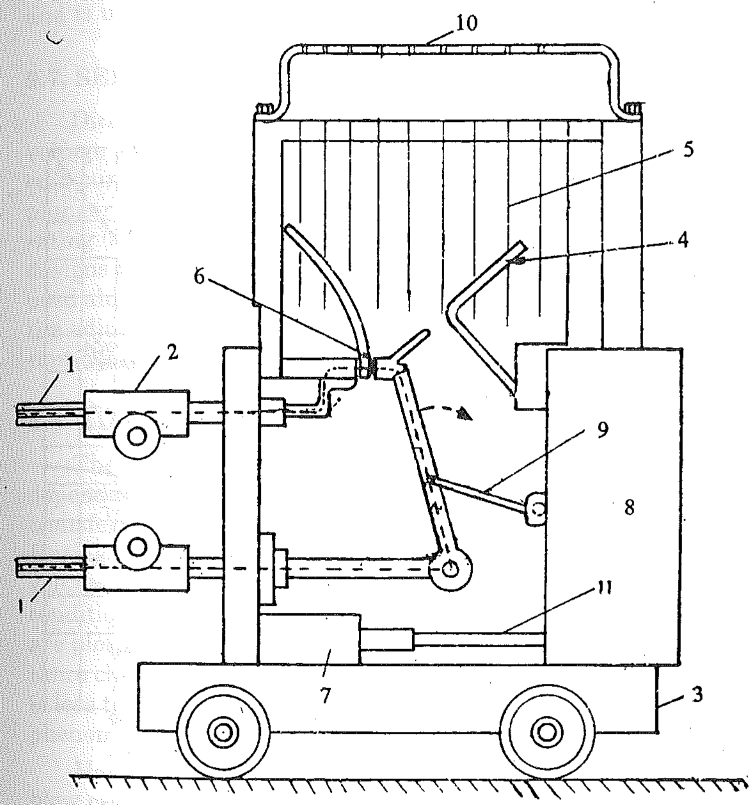
$$dF = I\,(\overline{dl} \times \overline{B}) \text{ Newtons}$$

By the virtue of this force the arc travels upward and its length increases. The tips of the arc run along the arc runners and come to extremity. As the length of arc increases. At a particular length the system voltage is unable to maintain the arc and the arc is extinguished. For systems having low inductance the energy $\frac{1}{2}LI^2$ joules is small and arc gets extinguished before reaching the extremity of runners. For high inductance circuits special techniques such as magnetic blow-out, additional larger arcing horns etc. are used.

5.4. LENGTHENING OF ARC BY MEANS OF MAGNETIC FIELDS

The arc is directed into arc splitters by application of magnetic field provided by current in blow out coils. These blow out coils are usually not connected permanently but come in the circuit completed by the arc. The blow out coil is energized during the breaking process automatically as the roots of the arc move over to the arc runners. It is important to connect the coils at correct polarity so that the arc is directed upwards.

The magnetic field itself does not extinguish the arc. It moves the arc rapidly into the arc splitters. As the arc moves in the cooler still air, it deionizes partly. It is brought in contact with cool arc splitters, the partitions remove heat from the arc and affect deionization. The plates are of a material which can with stand high temperatures.



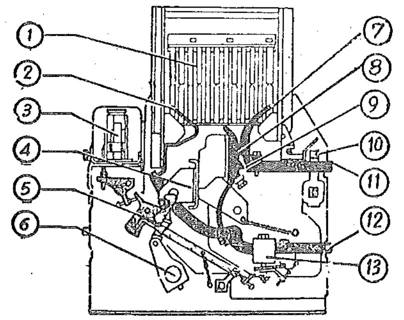
1. Isolating contacts
2. Insulating bushing
3. Carriage
4. Arc runner
5. Arc splitters
6. Contacts
7. Operating solenoid
8. Operating mechanism
9. Operating Lever
10. Cover with vents .... current path.
11. Link

Fig. 5.2 Truck-mounted air-break circuit-breaker shown in closed position.

5.5. DESCRIPTION OF A LOW VOLTAGE AIR-BREAKER CIRCUIT-BREAKER

The air-break circuit-breakers have current limiting feature. Because of current limiting property, there is considerable saving in other equipment such as bus bars, cables, insulating supports, etc. by reducing the heating effect as well as the electrodynamic forces. This novel property is illustrated in Figs. 5.4 and 5.5. In Fig. 5.4 we observe that the prospective short circuit current, (*i.e.* the current that would flow in the circuit if the circuit-breaker is replaced by conductor), would be as indicated by thin line. But the circuit-breaker modifies the current waveform and has a limiting effect so as to obtain the waveform shown by thick line of let through current. The contacts open rapidly and the increased arc length gives the current limiting property.

The peak values of current attained corresponding to prospective value of current are given in Fig. 5.5.



1. Arc chutes having deionization plates coated with plastic paint on the top half.
2. Arc runner for extending the arc for effective and quick extinction.
3. Magneto thermal release with inverse time current characteristic on overload and instantaneous tripping on heavy fault currents.
4. Moving contact carrier.
5. Main trip rocker arm on which the super rapid tripping device acts.
6. Main operating shaft.
7. Arcing horn.
8. Arcing contacts.
9. Main contacts.
10. Current transformer for feeding releases.
11. Line terminal.
12. Load terminal.
13. Super rapid tripping device a built-in protection device which trips the breaker from the function point.

[*Courtesy* : Larsen and Toubro Ltd. India]

Fig. 5.3 Sectional view of a low voltage circuit-breaker.

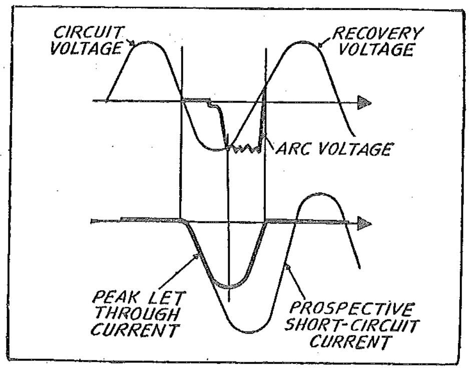


Fig. 5.4. Characteristic of voltage and current.

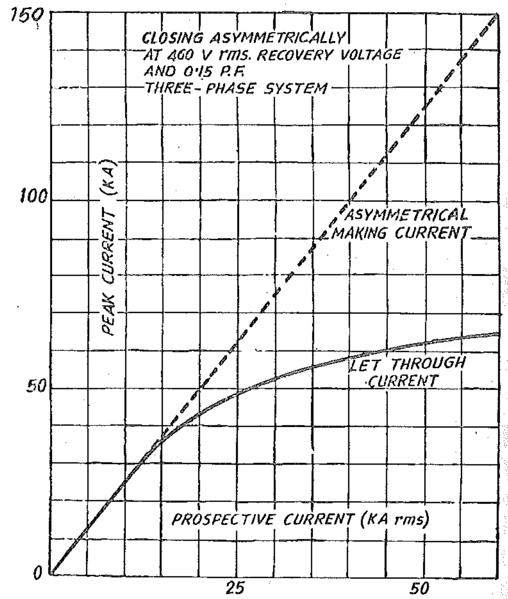


Fig. 5.5. Current limiting feature.

These circuit-breakers can be supplied with the following type of protective releases.

(1) **Thermal Tripping Releases.** It consists of an adjustable bimetallic thermal release having inverse time current characteristic for protection against overloads.

(2) **Super Rapid Trip.** A non-adjustable super rapid magnetic release is provided in each phase. The tripping time is of the order of 13-15 milliseconds. This has been achieved by collapsing from the fulcrum point instead of actuating the trip bar.

(3) Under voltage release suitable for d.c. or a.c. supply.

(4) **Shunt Trip.** Suitable for a.c. or d.c. supply with remote control.

Typical Ratings of low voltage air-break a.c. circuit-breakers

Nominal current rating	640 A r.m.s.
Rated voltage	460V r.m.s.
Breaking current at 50 Hz, p.f. = 0.15	75 k.A r.m.s. (Refer Sec. 15.9)

5.6. OPERATING MECHANISMS FOR AIR-BREAK CIRCUIT-BREAKERS

The operating mechanisms of Air-Break Circuit-Breakers are generally with operating spring. The closing force is obtained from one of the following means:

— solenoid
— spring charged manually or by motor
— pneumatic

The solenoid mechanisms drive power from battery supply or rectifiers. The solenoid energised by the direct current gives the necessary force for closing the circuit-breaker.

The springs used for closing operation can be charged manually or by motor driven gears. At the time of closing operation the energy stored in the spring is released by unlatching of the spring and is utilised in closing of the circuit-breaker.

5.7. SERIES CONNECTED OVER LOAD TRIP COIL ARRANGEMENT

Direct acting overload trip coils can be incorporated with the circuit-breaker. In some medium voltage and low voltage circuit-breakers, the coils are connected in series and are rated for the circuit current. The tripping is based on electromagnetic attraction by the field of solenoid. The plunger, when lifted, initiates the trip-mechanism of the switching device. Upto a certain current rating (*e.g.* 800 amperes in one design), such coils have been developed. However the direct acting designs for 5 amps. or 1 amp. are developed to be used in conjunction with CTs. Oil dashpots, are used along with the plunger which facilitates time-lag. Certain time lag adjustment is possible with the adjustment of the initial position of the plunger. Design is developed to give accurate time current characteristic for wide range of ambient temperature.

5.8. AIR-BREAK D.C. CIRCUIT-BREAKERS FOR MEDIUM VOLTAGES

The d.c. circuit-breakers should limit and interrupt any short circuit currents in the circuit dependably and rapidly. Accordingly, as soon as the fault occurs, the contacts separate, the arc is transferred from contacts to the arc runners where it rises upwards and extinguishes of its own. During this process the arc resistance is increased and the voltage across the arc exceeds the supply voltage. Every length of the free arc corresponds to a definite arc characteristic. Assuming that the conditions of the free burning arc can be applied to the arc under consideration, the characteristics are plotted for three different lengths of the arc as in Fig. 5.6. In the region of length , the resistance characteristics shown by straight line intersects arc characteristic at point A. The arc voltage is less than supply voltage and therefore, arc continues to burn till the contacts are destroyed. The phenomenon is known as *Standing Arc*.

However, the arc is extended by means of magnetic blow out system thereby increasing the arc voltage above the supply voltage, to cause arc extinction. There is no intersection with the characteristic of supply system. The energy stores in the system inductance is dissipated and the arc is extinguished. During the time of burning of the arc the supply source continues to give up the energy, the longer the arc burns, the greater the energy, in other words larger the system of inductance and lower arc voltages. Hence the entire interrupting operation is a question of energy. The arc moves from the contact zone at a speed of sound. Its uniform extension poses special problems influenced by thermal electro-dynamic stress.

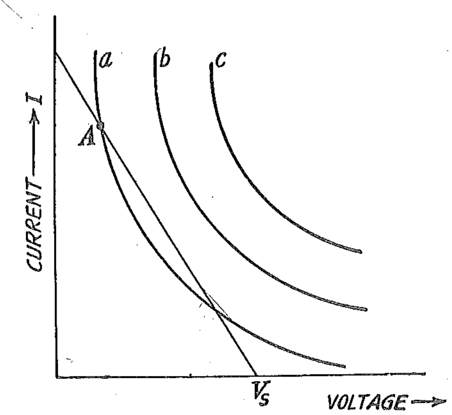


Fig. 5.6. D.C. arc characteristics for different arc lengths.

Typical rating of d.c. circuit breaker

1500 V., 10 kA continuous, 80 kA breaking

5.9. MINIATURE CIRCUIT-BREAKER, MOULDED CASE CIRCUIT-BREAKERS

These are used extensively in low voltage domestic, commercial and industrial applications. They replace conventional fuses and combine the features of a good HRC fuse and a good switch. For normal operation it is used as switch. During overloads or faults, it automatically trips off. The tripping mechanism is actuated by magnetic and thermal sensing devices provided within the MCB.

Tripping mechanism and the terminal contacts are assembled in a moulded case, moulded out of thermosetting powders. They ensures high mechanical strength, high dielectric strength and virtually no ageing. The current carrying parts are made out of electrolytic copper or silver alloy depending upon the rating of the breaker. All other metal parts are of non-ferrous non-rusting type. Sufficient cross-section for the current carrying parts is provided to ensure low temperature rise even under high ambient temperature environment. The arc chute has a special construction which increases the length of the arc by the magnetic field created by the arc itself and the arc chute is so placed in the breaker that the hot gases may not come in contact with any of the important parts of the breaker.

The breaker has unit construction whereby multiple pole breakers can be made by assembly of single pole breakers.

Typical Ratings of MCB

Current Rating : 5, 10, 15, 20, 30, 40, 50, 60, Amp. also 0.5, 1, 2, 2.5, 3, 3.5, 6, 7.5, 8, 10, 12, 35, 45, 55 Amp.

Voltage Rating : 240 V/415 V AC; 50 V/110 VDC

Rupting Capacity: AC : 3 kA at 50 V (non-inductive)

1 kA at 110 V (non-inductive).

QUESTIONS

1. Describe with neat sketches the principle of medium voltage-air-break circuit-breakers.
2. Explain the arc interruption process in air-break circuit-breakers incorporating arcing horns, arc splitters, magnetic blow-out coils.
3. Describe current limiting feature of Air-break circuit-breakers.

6

Air Blast Circuit-Breaker

Introduction—Principle of ABCB—Circuit-Breaker with External Extinguishing Energy—Design Features—Multi-Unit Design—Resistance Switching—Voltage Distribution—Cross-jet Design—Technical Data—Merits—Maintenance—Compressed Air System—Generator C.B.—Summary.

6.1. INTRODUCTION

Air blast circuit-breakers were used before 1980s for 11 to 1100 kV. A compressor plant is necessary to maintain high air pressure in the air receiver.

During the period 1950-1970, Air-blast circuit-breakers were preferred for 220 kV and above. However today, SF_6 circuit-breakers are preferred for this range. For 11 kV and 33 kV applications. VCBs are preferred Air-blast Circuit Breakers have become obsolete. (1995)

6.2. CONSTRUCTION OF AN AIR BLAST CIRCUIT-BREAKER

In air blast circuit-breaker (also called compressed air circuit-breaker) high pressure air is forced on the arc through a nozzle at the instant of contact separation. The ionized medium between the contacts is blown away by the blast of the air. After the arc extinction the chamber is filled with high pressure air, which prevents restrike. In some low capacity circuit-breakers the isolator is an integral part of the circuit-breaker. The circuit-breaker opens and immediately after that the isolator opens, to provide additional gap.

In EHV switch-yards of today, isolators are generally independently mounted.

Fig. 6.1 shows one pole of the EHV air blast circuit-breaker. In the complete assembly there are three identical poles.

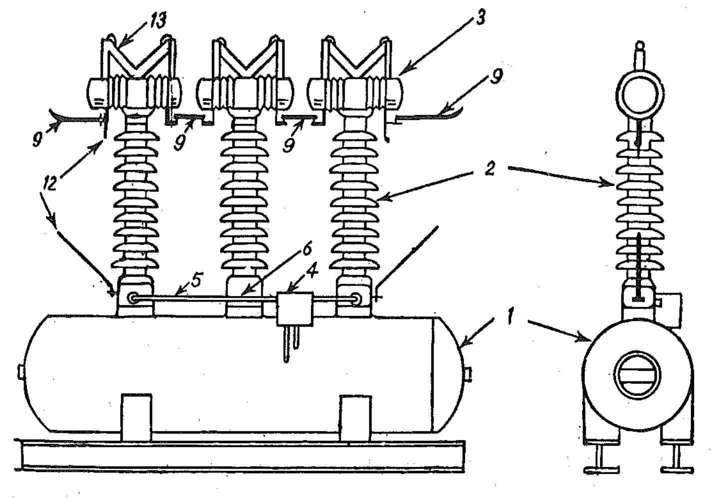


Fig. 6.1. (*a*) One pole of an extra-high voltage air blast circuit-breaker.

Description. High pressure air, at a pressure between 20 to 30 atm is stored in the Air reservoir (Item 1 in Fig. 6.1). Air is taken from compressed air system.

Three hollow insulator columns (Item 2) are mounted on the reservoir with valves (6) at their base. The double arc extinguishing chambers (3) are mounted on the top of the hollow insulator chambers. The current carrying parts (9) connect the three arc extinction chambers to each in series and the pole to the neighbouring equipment. Since three exists a very high voltage between the conductors and the air reservoir, the entire arc extinction chamber assembly is mounted on insulators.

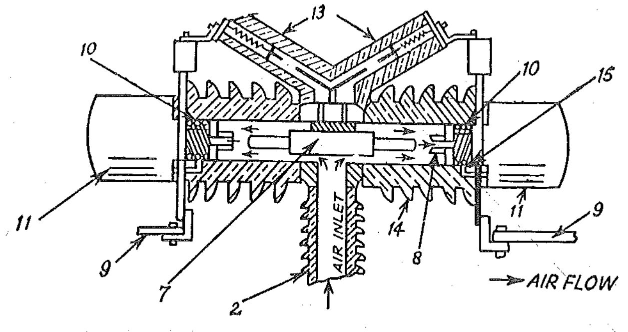


Fig. 6.1. (*b*) Details of (3) Double arc extinction chamber.

S.No. Item	Nos.	Material
15. Port		
14. Enclosure	6	Porcelain
13. Resistance switching unit	3	Assembly
12. Arcing horns Optional	4	Steel
11. Openings for air outlet	6	—
10. Compression springs	6	Alloy steel
9. Connection for current	—	Copper or its alloy
8. Moving contact (in 3)	2	Copper, silver or its alloy
7. Fixed contact (in 3)	3	Copper, or its alloy
6. Pneumatic valve		
5. Operating rod	1	Steel
4. Pneumatic operating mechanism	1	
3. Double arc extinction chamber	3	(Assembly)
2. Hollow insulator assembly	3	Steatite
1. Tank air reservoir (receiver)	1	Boiler plate steel

The details of the double arc extiction chambers (3) arc shown in Fig. 6.1 (*b*). Since there are three double arc extinction poles in series, there are six breaks per pole. Each arc extinction chamber [Fig. 6.1. (*b*)] consists of one twin fixed contact (7). There are two moving contacts (8) which are shown in the opening process. The moving contacts can move axially so as to open or close. Its position open or close depends on air pressure and spring (10) pressure.

The operating mechanism (3) operates the rod (5) when it gets a pneumatic or electrical signal. The valves (6) open so as to send the high pressure air in the hollow of the insulator. The high pressure air rapidly enters the double arc extinction chamber [*Air inlet* in Fig. 6.1(*b*)]. As the air enters into the arc extinction chamber the pressure on the moving contacts (8) becomes more than spring pressure and contacts open.

The contacts travel through a short distance against the spring pressure. At the end of contact travel the port for outgoing air (15) is closed by the moving contact and the entire arc extinction chamber is filled with high pressure air, as the air is not allowed to go out. However, during the arcing period the air goes out through the openings (11) and take away the ionized air of arc.

While closing the valve (6) is turned so as to close connection between the hollow of the insulator and the reservoir. The valve lets the air from the hollow insulator to the atmosphere. As a result the pressure of air in the arc extinction chamber (3) is dropped down to the atmospheric pressure and the moving contacts (8) close over the fixed contacts (7) by virtue of the spring pressure.

Air blast circuit-breakers were preferred for Arc Furnace Duty and traction system, because they were suitable for repeated duty. Now vacuum circuit-breakers are preferred for these duties upto rated voltage of 33 kV.

In multi-unit breaker grading capacitors are connected across the interrupter unit for the equal distribution of voltage between the units. Closing resistors are connected across the interrupter units for limiting the over voltages during closing operation. Opening resistors are connected across the interrupter units to make the circuit-breakers restrike free. Now, single pressure puffer type SF_6 CB is preferred for 132 kV, 220 kV, 400 kV, 765 kV applications.

6.3. PRINCIPLE OF ARC QUENCHING IN ABCBs

The air blast circuit-breaker needs an auxiliary compressed air system which supplies air to the air receiver of the breaker. For opening operation, the air is admitted in the arc extinction chamber. It pushes away the moving contacts. In doing so the contacts are separated and the air blast takes away the ionized gases along with it and assists arc extinction. Within one or two cycles the arc is extinguished by the air blast and the arc extinction chamber is filled with high pressure air has higher dielectric strength than that of atmospheric pressure. Hence a small contact gap of few centimeters is enough.

The flow of air around contacts is guided by the nozzle shaped contacts. It may be axial cross or a suitable combination [Fig. 6.2. (*a*), (*b*), Sec.7.5)]

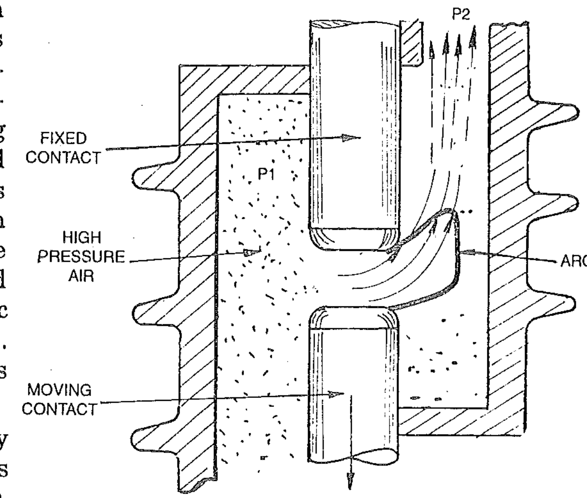


Fig. 6.2 Flow of air in Air-blast C.B.

In the axial blast type air flow Fig. 6.2 (*a*) the flow air is longitudinal along the arc. (Refer Sec. 4.11 and 7.5).

In axial blast type air flow, the air flows from high pressure reservoir to the atmosphere through a convergent divergent nozzle. The difference in pressure and the design of nozzle is such that as the air expands into the low-pressure zone, it attains almost supersonic velocity. The mass flow of air through the nozzle is governed by the parameters like pressure ratio, area of throat, exit area of nozzle, and is influenced by the diameter of the arc itself.

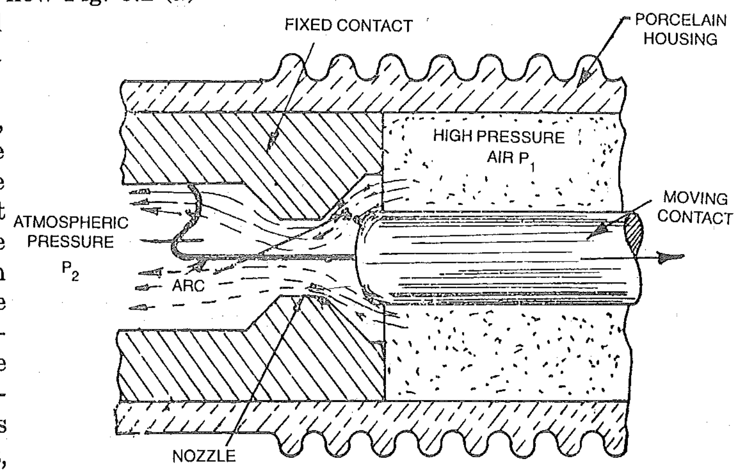


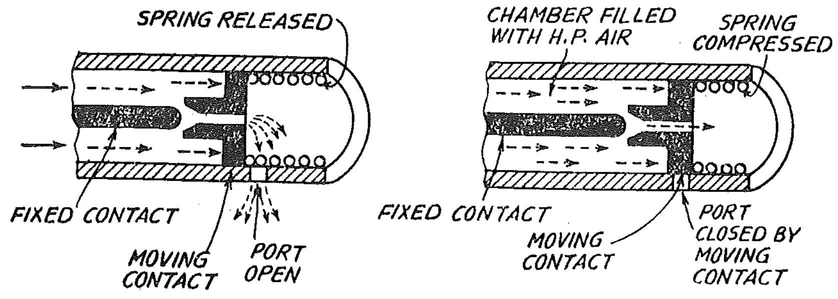
Fig. 6.2 (*a*) Axial Flow.

The air flowing at a high speed axially along the arc causes removal of heat from the periphery of the arc and the diameter of the arc reduces to a low value at current zero. At this instant the arc is interrupted and the contact-space is flushed with fresh air flowing through the nozzle.

The flow of fresh air through the contact space ensures removal of hot gases and rapid building up of the dielectric strength.

After the brief duration of air flow, the interrupter is filled with high pressure air. The dielectric strength of air increases with pressure. Hence the fresh high pressure air in the contact space is capable of with standing the transient recovery voltage.

For closing operation, the air from this chamber is let out to the atmosphere. Thereby the pressure on the moving contacts from one side is reduced and the moving contacts close rapidly by the spring pressure (Fig. 6.3).



Opening by air pressure against spring pressure. Air is going out from the port.

Contacts open, port closed, the Chamber filled with high pressure air.

Fig. 6.3. (*a*) Sequence of operation in ABCB.

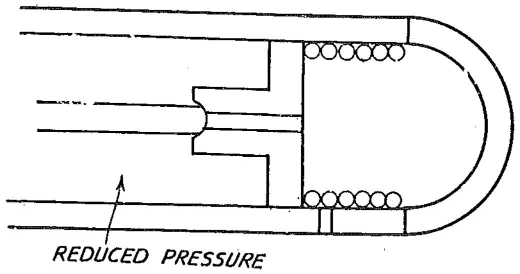


Fig. 6.3. (*b*) Contact close by spring pressure against reduced air pressure.

The air blast circuit-breakers come under the class external extinguishing energy type. The energy supplied for arc extinction is obtained from high pressure air and is independent of current to be interrupted.

6.4. CIRCUIT-BREAKERS WITH EXTERNAL EXTINGUISHING ENERGY

If the pressure generated in the arc extinction chamber is derived from arc current *e.g.*, by decomposition of oil in oil circuit breaker, the circuit-breaker is said to be of internal energy source. If the pressure is independent of arc current the circuit-breaker is said to be of external energy source. The behaviour of these two types are inherently different.

In the air blast circuit-breakers that air pressure used for the arc interruption is constant and does not depend on the arc current. The air pressure is of such magnitude that it can break rated breaking current (say 40 kA) satisfactory at natural zero. High pressure (60kg/cm^2) are used for breakers above 400 kV.

The arcing time does not change appreciably for lower magnitudes of currents as the air pressure is independent of arc current. Now consider that the breaker has to interrupted small currents

(say 10 A). For the current the air pressure used for the arc interruption is too high, the current gets chopped out before reaching natural zero. This current chopping gives rise to high restriking voltage. The resistance of contact space being high, the contact space being high the contact space is not likely to break down. However resistance switching should be employed.

The arcing time of ABCB is almost independent of arc-current [Fig. 6.4]. Whereas in oil current breakers the arcing time is more for lower currents [Fig. 6.3 (*a*)] and the restriking voltages are damped out by contact space of law dielectric strength.

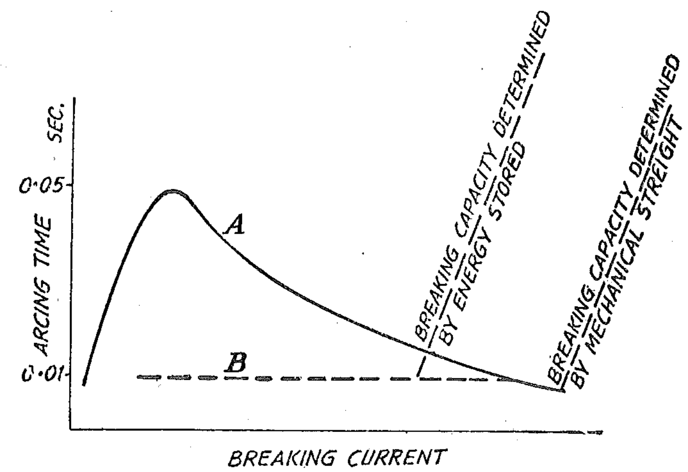


Fig. 6.4. Comparison between circuit-breakers with *A* internal source of extinguishing energy and *B* external source of extinguishing energy.

In the circuit-breakers with external energy source the breaking capacity of the unit is determined by the pressure of extinguishing medium. In circuit-breakers with internal energy source the capacity limit is determined by the design features.

6.5. RESISTANCE SWITCHING IN ABCB

We have noted earlier that the post zero resistance of contact space is high in air blast circuit-breakers. This is because the contact clearance space is filled with high pressure air after final current zero and high pressure air has high dielectric strength. The high restriking voltage appearing across the contacts does not damp out through the contact gap because of the high post zero resistance.

Further, voltages of the order of several times the normal voltage appear across the contacts because of current chopping. If these voltages are not allowed to discharge, they may cause break down of insulation of the circuit-breaker or the neighbouring equipment. To overcome this difficulty. Resistance Switching is adopted. The usual procedure is to connect a resistance is shunt with the arc.

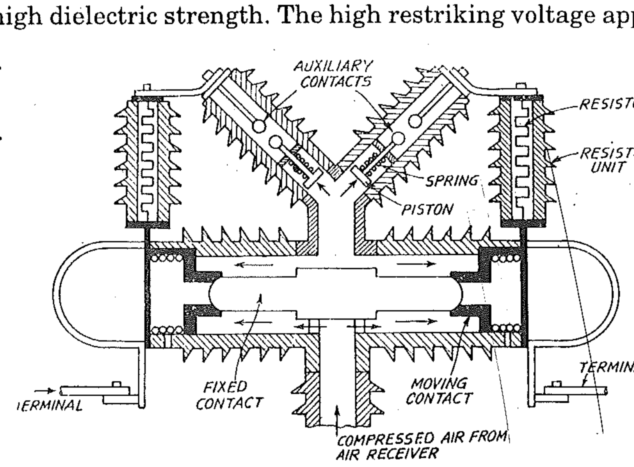


Fig. 6.5. Configuration of switching resistors.

Fig. 6.5 shows another popular arrangement used for a double arc extinguishing chamber explained in section 2.6. During the opening operation, air is admitted in the arc extinguishing chamber. It separates main contacts and pushes the auxiliary contacts. The auxiliary contacts close, thereby the resistors are connected across the arc for a short time of arcing. The auxiliary contacts are located in the inclined V-shaped insulators while the resistors are located in the vertical insulators. Immediately after arc extinction, the pressure on either side of the piston of auxiliary contacts gets so adjusted that the auxiliary contacts open and resistor circuit is interrupted. Ceramic resistances of non-linear characteristics, similar to those used in the lightning arresters were used for resistance switching.

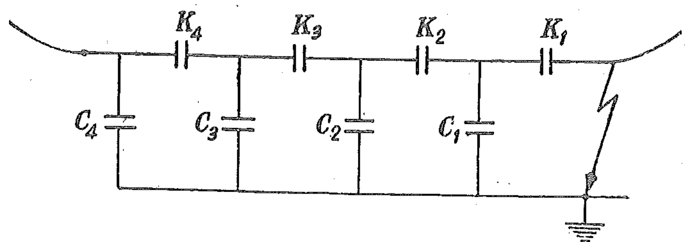
These consist of 'Silicone-carbide, bound by inorganic binders subjected to head treatment. During high current, non-linear resistor offers low resistance. Thus the main arc currents is partly diverted through resistor unit. As current reduces the resistance offered by non-linear resistors increases causing a greater drop across the resistor units. Thereby the voltage available for arc between auxiliary contacts is no more sufficient and arc between auxiliary contacts is automatically extinguished.

6.6. VOLTAGE DISTRIBUTION IN MULTI-BREAK CIRCUIT-BREAKERS (ABCB-MOCB, SF_6)

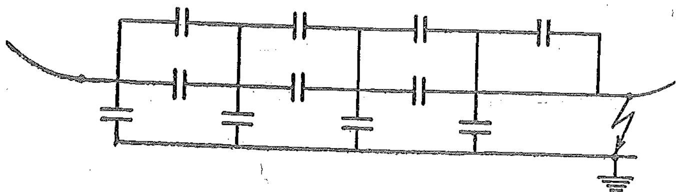
The voltage distribution should be even, between the gaps in series. If not, the breaking capacity shared by the different gaps will be unequal. The unequality of voltages and breaking capacity occurs mainly at the instant of recovery voltage, when the potential across the contact spaces is determined by capacitance between contact members and between contact and earth.

These potentials may vary according to the kind of short-circuit but will be least even when the fault involves earth (*e.g.,* L-G fault). In Fig 6.6 (*a*), 4 contact pairs 1 to 4 have been shown. Fault occurs near to the contact 1. The capacitances between the contacts are K_1, K_2, K_3, K_4 respectively and capacitances between contacts and earth are C_1, C_2, C_3, C_4 respectively. Because of the unsymmetry, the capacitances do not get equally charged and the recovery voltage is least over C_1 and

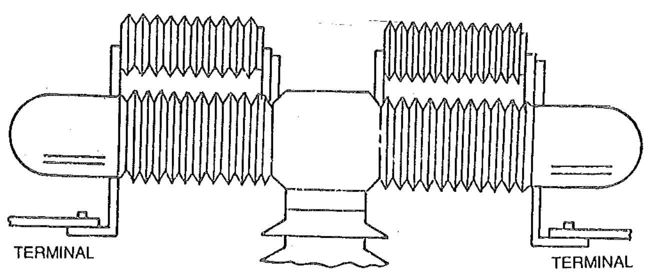
(*a*) Four contact pairs of c.b. pole.



(*b*) Distribution of capacitance.



(*c*) Equalization by means of parallel capacitance.



(*d*) External appearance

Fig. 6.6 Capacitors for voltage grading in multi-break breaker.

To equalize these voltages capacitances are connected across contact space as shown in Fig. 6.6 (*a*) by *C, C, C, C*. The shunt capacitor *C* is much larger than the natural capacitance in order to nullify the effect of the unequal capacitance of contact spaces. These capacitors are rigidly connected across the breaker arc extinction chamber as shown in Fig. 6.6 (*d*). The value of grading capacitors varies between 1200 pico-farads and 1650 pf depending upon number of breaks per pole and capacitance per break.

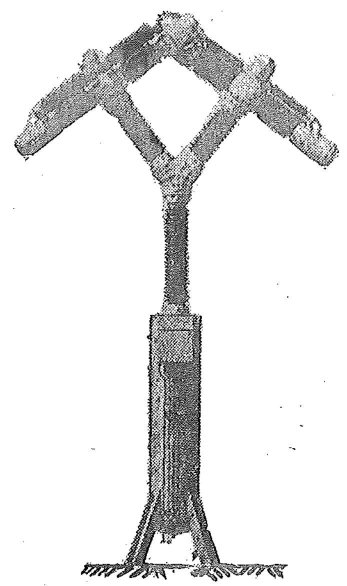


Fig. 6.7. One pole of an EHV Air Blast Circuit Breaker with four interrupters per pole. *Courtesy :* Brown Boveri.

6.7. REDUCING SWITCHING OVER-VOLTAGES BY PRE-CLOSING RESISTOR (Ref. Sec. 18.8)

The design of lines rated 420 kV and above is influenced by switching overvoltages. The switching overvoltages can be minimised by improving the design of circuit breakers. The features desirable for EHV and UHV circuit breakers are the following:

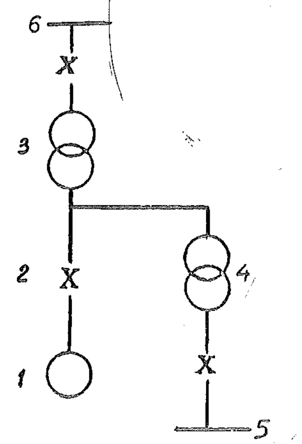
1. Pre-insertion of closing resistors in parallel with main contacts. This is either single stage or multi-stage.

2. Simultaneous closing three poles.

3. Simultaneous closing lines at both ends. The closing of line is first initiated through pre-closing resistors. Shortly after this, the pre-closing resistors are shunted out. The optimum value of pre-closing resistors for airblast circuit breakers is about 0.5 to 2 times the voltage of surge impedance of the line. Better damping effect is achieved by multi-stage pre-closing. As per recent ICC specifications, overvoltage factors less than 1.7 have been recommended for system above 550 kV. Such condition can be achieved by employing two-stage closing. In first stage a high resistance comes into circuit, in the second stage low resistance comes into circuit.

6.8. GENERATOR CIRCUIT BREAKERS

Development of Generator Breakers has brought about a significant change in the layout of generator connections. Generator circuit breakers are indoor, metal-enclosed air-blast circuit breakers suitable for connection between generator and its main transformer. (The typical 22 kV, 3500 MVA). Ref. Sec. 17.61. After 1985, SF_6 C.B.s have been developed and used for Generator Circuit-breakers.



1. High capacity generator
2. Generator circuit breaker
3. Main Transformer
4. Unit-Auxiliary Transformer
5. Auxiliary-bus
6. EHV bus

Fig. 6.8 Use of Generator Circuit Breaker.

6.9. COMPRESSED AIR SYSTEM FOR ABCB

The EHV-ABCB's are outdoor equipment. The air pressure in the receivers of the circuit breaker is of the order of 20–30 kgf/cm^2. The local receivers are of such a size that the air pressure is maintained for some 4 to 12 repeated operations. When the pressure in the receiver of the breaker reduces below a certain value [say 20 kg/cm^2] the pneumatic valves automatically open and air is let into the receivers from compressed air system of a higher pressure [30 kgf/cm^2 to 40 kgf/cm^2], and the pressure in the air receiver is maintained a desired value.

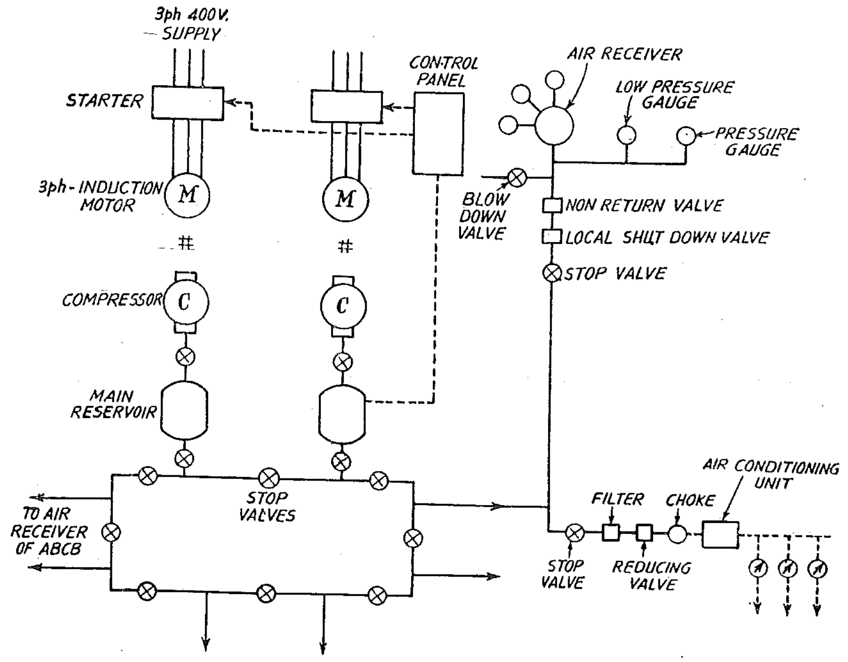


Fig. 6.9 Schematic diagram of compressed air system.

7

Sulphur Hexafluoride (SF6) Circuit-Breaker and SF6 Insulated Metalclad Switchgear (GIS)

Part I—Properties of SF_6 Gas—Physical properties—Chemical properties—Dielectric properties—Arc extinguishing properties of SF_6 gas.
Part II—Outdoor High Voltage SF_6 Circuit-Breakers—Type of designs—Single pressure puffer type SF_6 Circuit-breakers—Double pressure dead tank type SF_6 Circuit-breaker—Merits of SF_6 Circuit-breakers—Some demerits—SF_6 filled load-break switches—Auxiliaries and accessories.
Part III—SF_6 Insulated Metalclad Switchgear—Introduction—Advantage—Demerits—design aspects—Busbars—Isolators—Earthing switch—Circuit-breakers Components—Gas systems—Typical Ratings—Summary.

7.1. INTRODUCTION

Sulphur hexafluoride (SF_6) is an inert, heavy gas having good dielectric and arc extinguishing properties. The dielectric strength of the gas increases with pressure and is more than that of dielectric of oil a pressure of 3 kgf/cm^2. SF_6 is now being very widely used in electrical equipment like high voltage metal enclosed cables; high voltage metalclad switchgear, bushings, circuit-breakers, current transformers, etc. This gas liquefies at certain low temperatures, the liquefaction temperature increases with pressure. This gas is commercially manufactured in many countries and is now being extensively used by electrical industry in Europe, U.S.A. and Japan.

Several types of SF_6 circuit-breakers have been developed by various manufactures in the world during last fifteen years, for rated voltages from 3.6 to 760 kV.

SF_6 gas insulated-metalclad switchgear comprises factory assembled metal clad, sub-station equipment like circuit-breaker, isolators earthing switches bus-bars etc. These are filled with SF_6 gas. Such sub-stations are compact and are being favoured in densely populated urban areas.

Sulphur hexafluoride gas is prepared by burning coarsely crushed roll sulphur in fluorine gas, in a steel box, provided with staggered horizontal shelves, each bearing about 4 kg of sulphur. The steel box is made gas-tight. The gas thus obtained contains other fluorides such as S_2F_{10}, SF_4 and must be purified further SF_6 gas is generally supplied by chemical firms. The cost of gas is low if manufactured on a large scale.

The gas is transported in liquid form in cylinders. Before filling the gas, the circuit-breaker is evacuated to the pressure of about 4 mm of mercury so as to remove the moisture and air. The gas is then filled in the circuit-breaker. The gas can be reclaimed by the gas-handling unit.

Part I—Properties of SF_6 gas

7.2. PHYSICAL PROPERTIES OF SF_6 GAS

— Colourless.
— Odourless.
— Nontoxic, Pure SF_6 gas is not harmful to health.

— Non-inflammable. However impure SF_6 gas contains toxic impurities.

— State-Gas at normal temperature Pressure.

— Density-Heavy gas density 5 time that of air at 20°C and Atmospheric pressure.

Liquefaction of SF_6 Gas

The gas starts liquefying at certain low temperatures. The temperature of liquefaction depends on pressure. At 15 kg/c m² the gas starts liquefying at 10°C Hence this gas is not suitable for pressures above 15 kgf/c m². Ref. the notes at end of ch. 7 for units of pressure.

The temperature at which the SF_6 gas changes to liquid state depends on pressure. With higher pressure, this temperature increases. To avoid the liquefaction of SF_6 gas the temperature of SF_6 should be maintained above certain value. For 15 atm. pressure, SF_6 gas starts liquefying at a temperature of about 10°C. Hence thermostatically controlled heaters are provided, which maintain the gas temperature above about 16°C in case of high pressure system. Fig. 7.1 illustrates the characteristics of SF_6 medium. The curve shows transition condition, the left side represents liquid state and right side represents gaseous state. The inclined lines (L/kg) represent constant specific volume. (litres per kg).

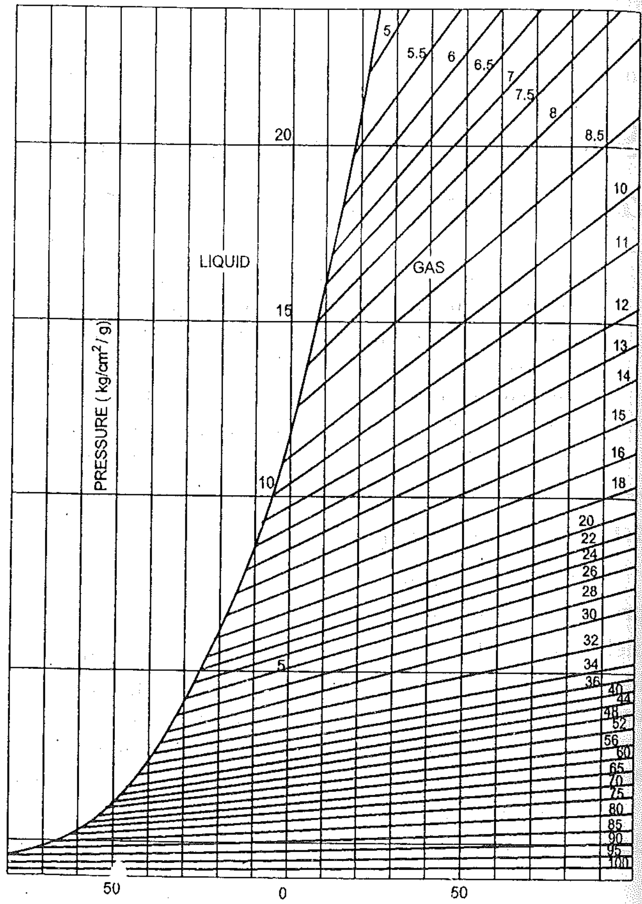


Fig. 7.1. Temperature-Pressure variation characteristics of SF_6 gas at constant specific volumes (litre/kg).

Heat transferability. The heat transferability of SF_6 gas is 2 to 2.5 times that of air at same pressure. Hence for the equal conductor size, the current carrying capacity is relatively more.

Enthalpy. Heat content property at temperatures below 6000°K is much higher than nitrogen. This assists cooling of arc space after current zero, due to continuous removal of heat from the contact space by the surrounding gas.

Low arc-time constant. The time constant of the medium is defined as "the time between current zero and the instant the conductance of contact space reaches zero value."

Due to the electronegativity of SF_6 gas the arc time constant of SF_6 gas is very low and the rate of rise of dielectric strength is high. Hence SF_6 circuit-breakers are suitable for switching condition involving high rate of rise of TRV.

7.3. CHEMICAL PROPERTIES OF SF_6 GAS

(*i*) Stable upto 500°C.

(*ii*) *Inert.* The chemical inertness of this gas is advantageous in switchgear. The life of metallic part, contacts is longer in SF_6 gas. The components do not get oxidised or deteriorated. Hence the maintenance requirements are reduced. Moisture is very harmful to the properties of the gas. In the presence of moisture, hydrogen fluoride is formed during arcing which can attack the metallic and insulating parts in the circuit-breaker.

(*iii*) Electronegative-gas.

(*iv*) Does not react with structural material—upto 500°C.

(*v*) *Products of Decomposition.* During arc extinction process SF_6 is broken down to some extent into SF_4, SF_2. The products of decomposition recombine upon cooling to form the original gas. The remainder is removed by filters containing activated alumina (Al_2OI_3). Loss factor is small. The products of decomposition arc toxic attack certain structural materials.

(*iv*) The metallic fluorides are good dielectric materials hence are safe for electrical equipment. However, they must be removed during periodic maintenance, as they absorb moisture and loose their dielectric property. This happens if the breaker is dismantled during rainy-season.

7.4. DIELECTRIC PROPERTIES OF SF_6 GAS

(*I*) *Dielectric Properties.* Dielectric strength of SF_6 at atmospheric pressure is 2.35 times that of air, it is 30% less than that of dielectric oil used in oil circuit breakers.

(*ii*) At higher pressure the dielectric strength of the gas increases. At pressure about 3 kgf/cm² the dielectric strength of SF_6 gas is more than that of dielectric oil. This property permits smaller clearances and small size of equipments for the same kV.

(*iii*) *Effect of Pressure on Breakdown Voltage.* The breakdown voltage in SF_6 gas depends on several aspects such as electrode configuration, roughness of electrodes distribution of electric field, vicinity of insulating supports, moisture, waveshapes etc. other parameters remaining constant the breakdown voltage in SF_6 gas increases with pressure. The gas follows Paschen's law which states that "In uniformly distributed electric field. The breakdown voltage (V_b) in a gas is directly proportional to the product of gas pressure (p) and electrode-gap (d)"—$V_b \alpha pd$.

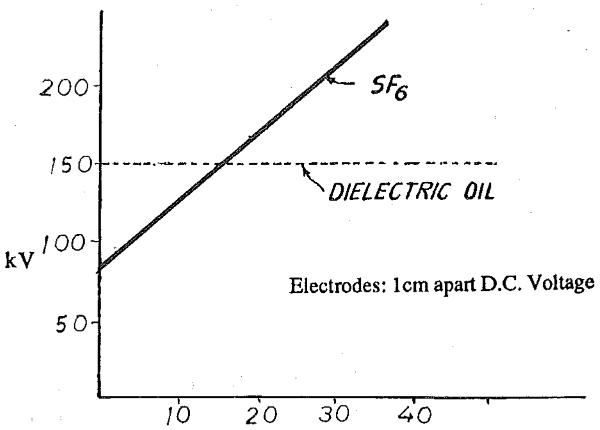


Fig. 7.2. D.C. break-down voltage of 1 cm gap in SF_6 gas.

(*ii*) *Critical Pressure Zone.* With the non-uniform field, the breakdown voltage versus pressure, curve does not follow the Paschen's law strictly. The probable curve is indicated in Fig. 7.3. The breakdown voltages increases with pressure. However after about 2.5 kgf/cm² it starts reducing and then rises again. The pressure at which the breakdown voltage starts reducing is called 'critical Pressure'. The dielectric strength at pressure between 2-3 kgf/c m² is high. Hence this pressure range is preferred in SF_6 insulated metal enclosed switchgear. However in circuit-breaker compartment, the pressure of the order of 5 kgf/cm² is preferred for arc quenching purposes.

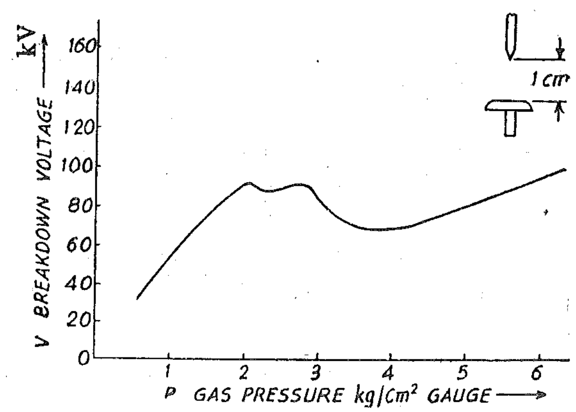


Fig. 7.3. Variation in Breakdown voltage in SF_6 gas with non-uniform fields.

(*v*) *Effect of Electrode Surface.* Rough electrode surface reduces the breakdown voltage with rough surface the ionisation starts earlier near the sharp points on conductors. Hence, conductor surfaces should be smooth.

(vi) Effect of Insulating Support on Breakdown Voltage. The conductors in SF_6 insulating equipment are supported on epoxy or porcelain insulators. The flashover invariably takes place along the surface of the support insulators.

The breakdown can occur at extremely low values if the insulator supports are covered by moisture and conducting dust. Hence the insulators should be extremely clean and should have anti-tracking properties.

(vii) Sharp Contours. The breakdown is initiated at sharp edges of conducting parts and parts having maximum stress concentration. The limiting value of breakdown stress is of the order of $24 \times P$ kV/cm for pure SF_6 gas, P is pressure of gas in kgf/cm^2. Good dielectric stress distribution is very important is SF_6 insulated equipment.

(viii) Effect of Wave-shape and Polarity. The breakdown value depends on the wave-shape characterised by peak value, wave front, wave-tail, polarity in case of impulse wave. Voltage withstand value reduces with increase in steepness and increase in duration of the wave. Negative polarity is generally more severe than positive.

Effect of Dilution of SF_6 Gas by Air on Dielectric Strength

SF_6 gas maintains high dielectric strength even when diluted by air (Nitrogen). 30% SF_6 + 70% Air by volume has a dielectric strength twice that of air at same pressure). Below. 30% by volume, the dielectric strength reduces quickly.

(ix) The gas is Electronegative. The ability of an atom to attract and hold electrons has been designed as its 'Electronegativity'. Such gases have high dielectric strengths.

The molecules of electronegative gases have an ability to attract, hold free electrons and form negative ions. The negative ions being heavy and practically immobile they do not flow easily. Hence the dielectric strength of electronegative gases is more than that of air.

Electronegativity of the gas gives lower arc-time constant. The time required for the medium to regain its dielectric strength after final current zero is called arc-time constant. The arc-time constant of SF_6 gas is of the order of a few Microseconds.

7.5. ARC EXTINCTION IN SF_6 CIRCUIT-BREAKERS (Ref. Sec. 11.20)

The arc extinction process in SF_6 circuit breakers is different from that in Air Blast Circuit Breakers.

During the arcing period, SF_6 gas is blown axially along the arc. The gas removes the heat from the arc by axial convection and radial dissipation. As a result, the arc diameter reduces during the decreasing node of the current wave. The diameter becomes small during current zero. Turbulent flow is introduced around current zero to extinguish the arc.

Due to its electronegativity and low arc-time constant, the SF_6 gas regains its dielectric strength rapidly after the final current zero, the rate of rise of dielectric strength is very high and the time constant is very small.

The arc extinguishing properties of SF_6 gas was pointed out in 1953*.

The paper points out that SF_6 is a remarkable medium for arc extinction. The arc extinguishing properties are improved by moderate rates of forced gas flow through the arc space.

Plain break contacts drawn apart, (AC Arcs), in SF_6 can interrupt about 100 times more current than in air at given voltage.

* An Investigation of the Arc Quenching Behaviour of SF_6 by H.J. Lingal, A.R. Strom T.E. Browne, Westinghouse Electric Corpn.—AIEE PAS April 1953, p. 242.

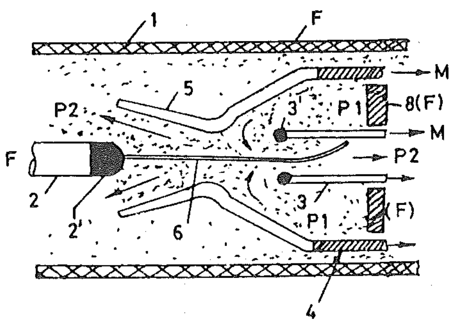
The basic requirements in arc extinction is not primarily the dielectric strength, but high rate of recovery of dielectric strength. In SF_6 gas, the electrons get attached with molecules to become ions. Thereby the dielectric strength is quickly regained. Problems connected with current chopping are, therefore minimum.

In SF_6 circuit-breakers, the gas is made to flow from a high pressure zone to a low pressure zone through a convergent-divergent nozzle. The mass flow is a function of nozzle-throat diameter the pressure ratio and the time of blow. The nozzle is located such that the gas flows axially over the arc-length. The gas flow attains almost supersonic speed in the divergent portion of the nozzle, thereby the gas takes away the heat from the periphery of the arc, causing reduction in the diameter of the arc. Finally the arc diameter becomes almost zero at current zero and the arc is extinguished. The arc space is filled with fresh SF_6 gas and the dielectric strengths of the contact space is rapidly recovered due to the electronegativity of the gas and turbulent flow of fresh gas in the contact space.

(SF_6 gas flows from P_1 to P_2 through the Convergent Divergent Insulating Nozzle over the arc lengthened during opening stroke.) P_1/P_2 is achieved by relative movement of Puffer Cylinder 4 against Fixed Piston.

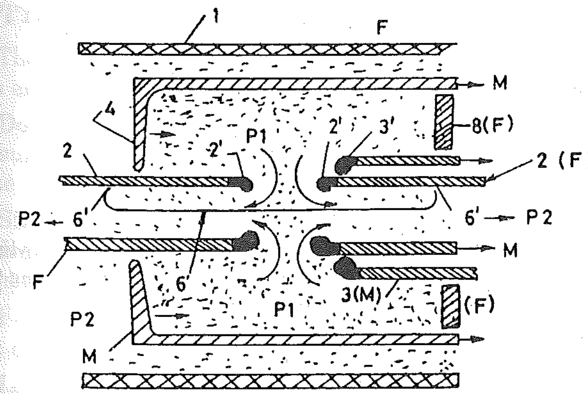
7.5.1. Single Pressure Puffer Type Circuit-breaker with Single flow of Quenching Medium

This flow pattern illustrated in Fig. 7.4 was first conceived during 1950s. Earlier puffer type circuit breakers were with single flow pattern.



1. Enclosure
2. Fixed contact stem
2'. Arcing contact tip
3. Hollow contact tube (M)
3'. Arcing contact tip
4. Puffer cylinder
5. Insulating Nozzle (PTFE) convergent divergent
6. The Arc
6'. SF_6 Gas
7. Fixed Piston
8. Fixed Piston
M = MOVING, F = FIXED

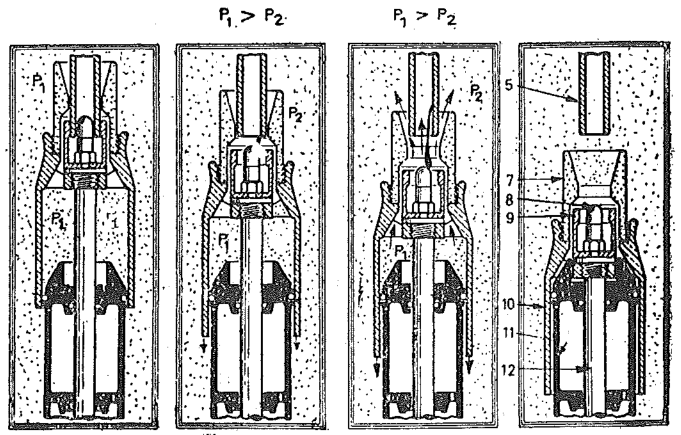
Fig. 7.4. (*a*) Arc Extinction in Single Pressure type puffer C.B. with insulating Nozzle. (Further details in Fig. 7.5 a-d)



1. Enclosure (F)
2. Fixed contact tubes (F)
2'. Graphic Nozzles (F)
3. Hollow conductor tube (M)
4. Puffer Cylinder (M)
5. SF_6 Gas
6. The Arc
6'. Arc-Roots (M)
7. Fixed Piston
8. Fixed Piston
H = MOVING, F = FIXED

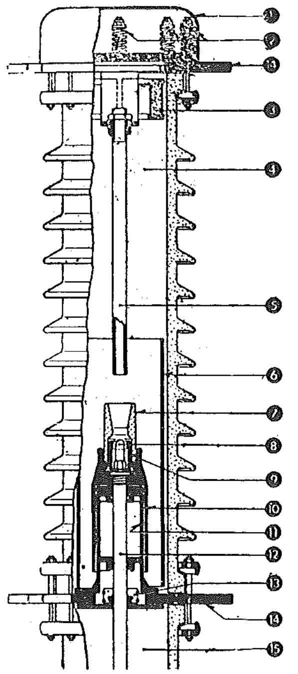
Fig. 7.4. (*b*) Arc Extinction in Single Pressure Puffer type SF_6 C.B. with Conducting Nozzles. (Further details in Fig. 7.12)

Fig. 7.5 (*a*) "Four stages of Puffer Action—Single Flow" explains the arc quenching process. When breaker is fully closed, the pressure in the puffer cylinder P_1 is equal to that outside the cylinder.



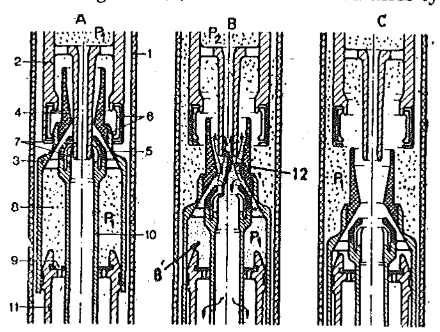
Contact closed $P_1 = P_1$ | Contacts separate nozzle about to open | Nozzel open flow starts | Arc quenches breaker fully open

Fig. 7.5. (*a*) Four stages of Puffer Action-Single flow.



1 Top cap
2 Springs
3 Activated Alumina
4 SF_6 Gas
6 Fixed contact
6 Protective tube
7 PTEE nozzle
8 Arcing contact tip
9 Finger contacts
10 Puffer cylinder
11 Fixed piston
12 Pull conductor
13 Sliding contacts
14 Lower support chamber.

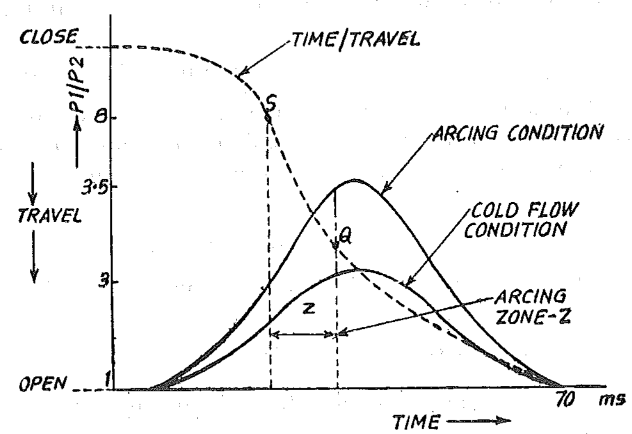
Fig. 7.5. (*b*) Cross-section of Puffer type SF_6 Interrupter. (Courtesy : Magrini)



1. Enclosure (Insulating tube)
2. Fixed contact holder
3. Puffer Cylinder
4. Insulating Nozzle (PTFE)
5. Insulating Cap
6. Parallel path for normal current flow
7. Normal path for current flow
8. Gas trapped between 3 and 11
8′. Compressed Gas
9. Valve for gas inlet during closing
10. Moving contact tube
11. Fixed Piston
12. Arc

Fig. 7.5. (*c*) Three stages of puffer action-Double Flow
A Breaker fully close B Contact Separate, Arcing present C Arc Quenched

During opening stroke puffer-cylinder and moving contact tube start moving. Gas gets compressed within puffer cylinder ($P_1 > P_2$). After a certain travel, contact separates arc is drawn. However compressed gas flows from higher pressure P_1 to lower pressure P_2 through the nozzle. Fig. 7.5 (*d*) gives pressure characteristics.



S = Arcing starts
O = Open
Q = Arc Quenched
C = Closed
Z = Arcing zone.

Fig. 7.5. (*d*) Explaining Puffer Principle.

Single flow pattern has limited quenching ability and is used for lower breaking currents. Fig. 7.5 (*b*) gives a cross-sectional view of an interrupter developed during early sixties.

7.5.2. Double Flow of Quenching Medium

In the second generation of puffer type circuit-breakers, the flow pattern was improved. The flow of quenching gas from puffer cylinder was made to flow in forward direction (like in single flow) through nozzle and also through hollow contact tube in inverse direction. Double flow gives lengthening of arc through hollow contact tubes and removes heat of arc more efficiently. Double flow pattern gives almost one-and-half times the breaking capacity compared with the single flow. Fig 7.5 (*c*) explains the flow pattern in double flow technique. All puffer type circuit-breakers of today employ double flow pattern.

Part—II Outdoor SF_6 Circuit-Breakers

7.6. TYPES DESIGN

The SF_6 circuit-breaker have been developed by several manufacturers and several designs have emerged. The types of circuit-breakers can be broadly identified as:

Double Pressure type. In which, the gas from high pressure system is released into the low pressure system through a nozzle, during the arc extinction processes. This design has become obsolete.

Single Pressure Puffer type. In which the gas is compressed by the moving cylinder system and is released through a nozzle while extinguishing the arc. This design is most popular over wide range of voltages from 3.6 kV to 760 kV. [Sec. 7.51].

Furthermore, in both the double pressure and single pressure designs the circuit-breakers have been developed in following two types of indoor and outdoor designs.

Live Tank design. In which the interrupters are supported on porcelain insulators (Fig. 7.7).

Dead Tank design. In which the interrupters installed within SF_6 gas-filled tank at earth potential (Fig. 7.8). This configuration is used in GIS, (Sec. T.13)

Single pressure puffer type live tank breakers are being preferred for conventional outdoor switchyards.

Puffer Principle. Refer Fig. 7.5 *a* to *d*. As the puffer cylinder moves downrwards for the opening stroke, the pressure ratio P_1/P_2 rises as shown in Fig. 7.5 (*d*). The pressure rise depends upon the throat-diameter of nozzle and speed of puffer cylinder. The pressure ratio P_1/P_2 increases to about five during opening condition. The compressed gas is released through the convergent-divergent nozzle (7). The arc is quenched at a current zero. For higher interrupting ability, the flow pattern is optimised.

Single pressure puffer type SF_6 circuit-breakers are sealed units filled with SF_6 gas at a pressure 5 kgf/cm^2. Both dead-tank and live tank designs have been developed for voltages from 3.3 to 760 kV and breaking currents from 20 to 80 kA. The designs are being continuously optimized for higher capacity per interrupter. There are two types of designs in single pressure puffer type SF_6 circuit-breakers.

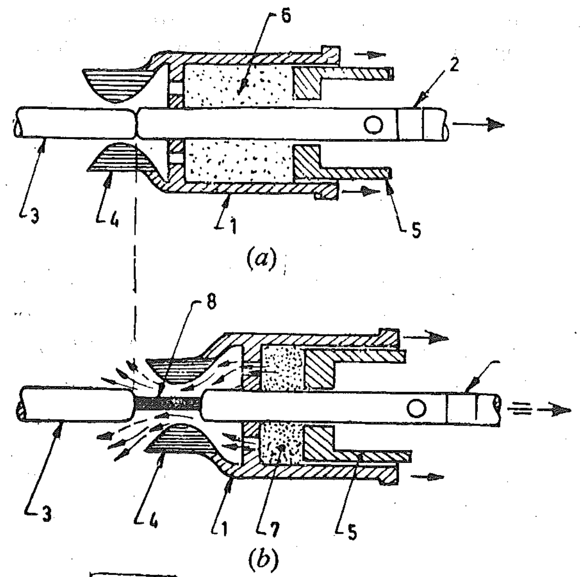
— Puffer type SF_6 breaker with insulating nozzle (Figs. 7.5-7.6).

— Puffer type SF_6 circuit breaker with conducting nozzle (Ref. Fig. 7.12)

7.7. SINGLE PRESSURE PUFFER TYPE SF_6 CIRCUIT-BREAKER

These circuit-breaker employ a novel principle of puffer action illustrated in Fig. (7.5 *b*, *c*, *d*).

Fig 7.6 (*a*) illustrates the fully closed position of the interrupter. The moving cylinder (1) is coupled with the movable conductor (2) against the fixed piston (5) and there is a relative movement between (1) and (5) and the gas is compressed in the cavity (6). This trapped gas is released through the nozzle (4), during arc extinction process. During the travel of the moving contact (2) and movable cylinder (1) the gas puffs over the arc and reduces the arc diameter by axial convection and radial dissipation. At current zero, the arc diameter becomes too small and the arc gets extinguished. The puffing action continues for some time even after the arc extinction and the contact space is filled with cool, fresh gas.



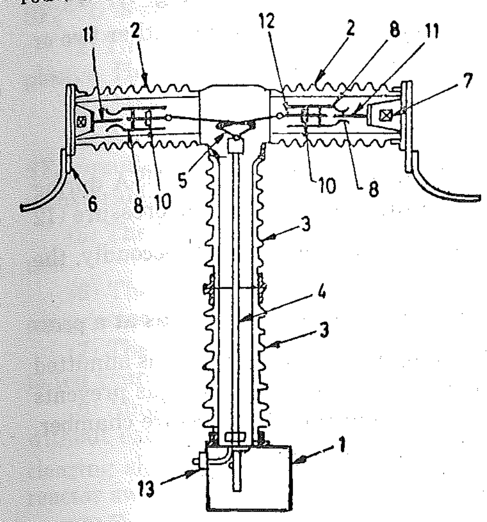
(1) Movable cylinder (puffer cylinder)
(2) Moving contact
(3) Fixed contact
(4) Insulating nozzle
(5) Fixed piston
(6) Gas trapped in before compression
(7) Compressed gas between 1 and 5
(8) The arc-being extinguished by puffer action.

SF_6 gas   Compressed gas SF_6

(*a*) Breaker fully closed (*b*) Contacts separated, puffing action in progress.
Fig. 7.6. Puffer action principle.

Fig 7.7 (*a*) illustrates the configuration of a 245 kV/420 kV single pressure puffer SF_6 circuit-breaker. The two interrupters (2) are mounted on the hollow support insulators (3). The principle

of arc interruption is illustrated in Fig 7.6. The operating mechanism (1) installed at the base of the insulator is linked with the movable contact in the interrupter by means of insulating operating rod (4) and a link-mechanism (5).



Item No.
1. Operating mechanism (pneumatic or hydraulic)
2. Interrupter.
3. Hollow support insulators (porcelain)
4. Insulating operating rod (glass fibre).
5. Linkage between (4) and (12).
6. Terminals.
7. Filters. (Activated alumina)
8. Movable (puffer) cylinder.
9. Nozzle (insulating material).
10. Fixed piston.
11. Fixed contact.
12. Moving contact (move with 8)
13. Gas inlet and monitoring system.

] Filled with SF_6 gas at 5 kgf/cm^2

Fig. 7.7. (*a*) One pole of a 245 kV puffer type SF_6 C.B.

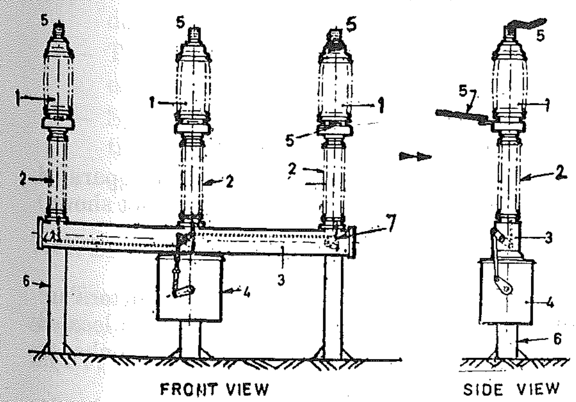
The circuit-breaker is filled with SF_6 gas at a pressure of about 5 kgf/cm^2. During the opening operation, the operating rod (4) is pulled down-wards by the operating mechanism. The link-mechanism (5) converts the vertical motion into horizontal motion. The contact and the movable cylinder in interrupter are moved against the fixed piston (10).

Break-time upto 3 cycles can be achieved by puffer principle described above. For achieving 2 cycle break time, differential piston is used in which the puffer-cylinder and piston move in opposite direction thus reducing total stroke and time of travel.

7.7.1. Configuration of a single Pressure Puffer Type EHV Circuit-Breaker

Fig 7.7 (*b*) illustrates the typical configuration of 145 SF_6 circuit-breaker having one interruption per pole Fig 7.7 (*a*) illustrates configuration of one pole of a 245 kV SF_6 circuit-breaker.

Referring to Fig. 7.7 (*b*), there are three identical poles mounted on a common base tube (3). Gas is filled permanently in all the three poles and the base tube. The sealing is provided by O-rings squeezed between porcelain and flanges.



1. Interrupter
2. Support Hollow Porcelain
3. Base Tube
4. Mechanism Housing and Control Cabinet, Gas Inlet System :
5. Terminals
6. Support Structure
7. Linkages

] Filled with SF_6 gas 5 kgf/cm^2

] Hydraulic/Spring/Pneumatic Mechanism

Fig. 7.7. (*b*) Configuration of an outdoor Puffer Type 145 kV SF_6 Circuit-Breaker.

The operating mechanism (4) is linked with moving contacts in the interrupters *via* insulating glass fibre rods. In this configuration, during closing operation it is pushed upwards.

A 245 kV circuit-breaker has generally one or two interrupters per pole [Refer Fig. 7.7 (*a*)].

Configuration of 420 kV SF_6 circuit-breakers follows same philosophy but it has either two or four interrupter per pole depending upon the design, rated breaking current.

7.8. DOUBLE PRESSURE DEAD TANK SF_6 C.B. (NOW OBSOLETE)

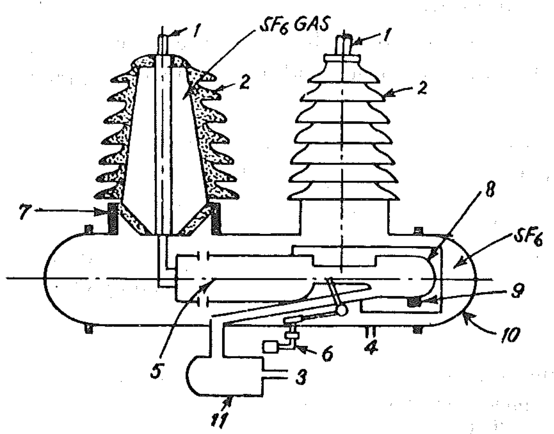
Double-pressure type of SF_6 circuit-breakers were developed by Westing-house USA during 1950's. The double pressure SF_6 circuit-breakers had a disadvantages that at higher pressure (12 kg/cm^2; heaters were necessary during lower ambient temperatures (below 15°C). Secondly, the design was complicated and costly.

The gas follows a closed circuit. An auxiliary tank or gas reservoir contains SF_6 gas at a pressure of about 14 kg/cm^2. During the arc extinction the gas from high pressure chamber is admitted to the low pressure chamber by opening of a valve. The arc is extinguished and the gas prevents restriking of arc. The compressor pumps back the excess SF_6 gas from the low pressure chamber, back to the high pressure chamber.

The operating mechanisms are pneumatic or electro-hydraulic.

The breaker has three identical poles.

Referring to Fig. 7.8 the SF_6 gas system is as follows. The gas from compressor (not shown in the figure) is let into the auxiliary high pressure reservoir 11 through inlet 3. From this reservoir, it is admitted in main SF_6 reservoir 8 at pressure of about 14 kg/cm^2. The gas is admitted in the arc extinction chamber 5, just before contact separation. The gas comes in the L.P. cylinder 10.



1. Connection terminals.
2. Bushing
3. SF_6 inlet 14 kgf/cm^2
4. SF_6 outlet 2 kgf/cm^2.
5. Arc extinction chamber.
6. Operating links.
7. Lower insulator
8. Main SF_6 reservoirs 14 kgf/cm^2.
9. Activated alumina
10. Low pressure chamber 2 kgf/cm^2, at earth potential.
11. Auxiliary H.P. reservoir

Fig. 7.8. One pole of a double pressure, dead tank type SF_6 C.B.

The current enters from 1, and leaves from terminal. The contacts (not shown) are separated in chamber 5. SF_6 gas from the low pressure chamber is pumped back by compressor (not shown) to auxiliary chamber.

The current carrying parts are the following :

The terminals 1, 1 are connected to the neighbouring equipment. From 1, the conductors are taken through bushings 2, 2. The arc extinction chamber (5) is multi break type and is located centrally in the tank. The chamber housing is made of dielectric material and the chamber is mounted on insulator supports.

The moving contacts are pulled apart from the fixed contacts by means of insulating links. At the same time valves on the high pressure cylinders are opened and the gas from high pressure tank flows towards the low pressure reservoir through nozzles. The arc is extinguished by has flow.

7.9. MERITS OF SF_6 CIRCUIT-BREAKERS

(1) Outdoor EHV SF_6 has less number of interrupters per pole than ABCB and MOCB. Outdoor SF_6 CB is simple less costly, maintenance free and compact.

(2) The gas is non-inflammable and chemically stable. The decomposition products are not explosive. Hence there is no danger of fire or explosion.

(3) Same gas is recirculated in the circuit. Hence requirement of SF_6 gas is small.*

(4) Ample overload margin. For the same size of conductors, the current carrying ability of SF_6 circuit-breakers is about 1.5 times that of air blast circuit-breakers because of superior heat transferability of SF_6 gas.

(5) The breaker is silent and does not make sound like air-blast-circuit breaker during operation.

(6) The sealed construction avoids the contamination by moisture, dust, sand etc. No costly compressed air system like ABCB.

(7) The maintenance required is minimum. The breaker may need maintenance once in four to ten years.

(8) Ability to interrupt low and high fault currents, magnetising currents, capacitive current, without excessive over-voltages. The SF_6 gas circuit-breaker can perform the various duties like clearing short-line faults, opening unloaded transmission lines capacitor switching transformer, reactor switching etc. much smoothly.

(9) Excellent insulating arc extinguishing physical and chemical properties of SF_6 gas is the greater advantage of SF_6 breakers.

(10) No frequent contact replacement.

Contact corrosion is very small due to inertness of SF_6 gas. Hence contacts do not suffer oxidation.

(11) No over-voltage problems.

Due to particular properties of SF_6 gas the arc is extinguished at natural current zero without current chopping and associated over-voltage originating in circuit-breakers.

7.10. SOME DEMERITS OF SF_6 CIRCUIT-BREAKER

— Sealing problems arise. Imperfect joints lead to leakage of gas.

— Arced SF_6 gas is poisonous and should not be in inhaled or let-out.

— Influx of moisture in the breaker is very harmful to SF_6 gas circuit-breakers. Several failures are reported due to this cause.

— Mechanism of higher energy level is necessary for puffer type SF_6 breakers. Lower speeds due to friction, misalignment can cause failure of breaker.

— The internal parts should be cleaned thoroughly during periodic maintenance under clean, dry environment. Dust of Teflon and sulfides should be removed.

— Special facilities are needed for transporting the gas, transferring the gas and maintaining the quality of gas. The deterioration of quality of the gas affects the reliability of the SF_6 circuit breaker.

7.11. SF_6 FILLED LOAD BREAK SWITCHES

The remarkable arc extinguishing properties of SF_6 can be exploited for various switching equipments such as load break switches, starters, controllers etc. The first SF_6 interrupter containing SF_6 gas at 3 atm. was built in 1953 which had a sealed chamber. The arc was drawn by moving

* One triple, pole 145 kV SF_6 C.B. requires only about 30 kg of SF_6 gas for first filling. No replacement is required for five years.

the contact and at the same time SF_6 gas flowed closed to the arc by virtue of a piston and cylinder arrangement. These load break switches rated from 15 to 161 kV and the break current of 600 A at 0.5 to 1 power factors. Transformer magnetising current can be easily interrupted by SF_6 switches. The capacitor banks can be switched off easily with SF_6 switches.

7.12. GAS MONITORING AND GAS HANDLING SYSTEMS

SF_6 circuit breakers are provided with gas monitoring system. The gas monitoring system comprises temperature compensated pressure switches. Provision for filling and removing gas, provision for heating the gas etc. The pressure switches are arranged such that for a certain reduction in pressure an alarm is sounded and for further reduction in pressure the circuit-breaker gets locked.

The gas handling unit is used for filling the SF_6 gas in the breaker and for reclaiming the SF_6 gas from the breaker. The gas handling unit comprises a vacuum pump, a compressor, an auxiliary receiver, gas-filtering units, valves and piping. Before filling the gas the circuit breaker is evacuated by means of the vacuum pump. After achieving a certain degree of evacuation, the gas from gas cylinders is filled into the circuit breaker.

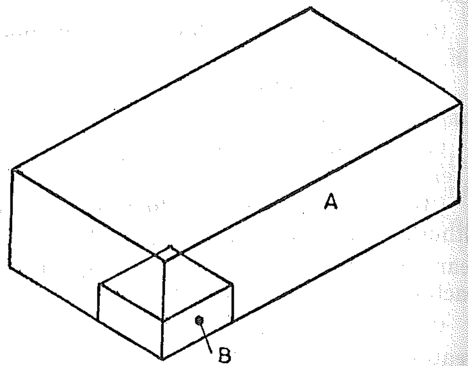


Fig. 7.9. Comparison of space requirement of 245 kV substation.
(A) Conventional (B) SF_6 Metalclad.

While reclaiming the gas from the circuit breaker, the compressor is used for transferring the gas from the circuit-breaker to the auxiliary receiver.

Part III—SF_6 GIS

7.13. INTRODUCTION TO SF_6 SWITCHGEAR (GIS)

SF_6 gas insulated metalclad switchgear is also called Gas Insulated Substation (GIS) and is preferred for 12kV, 36kV, 72.5kV, 145 kV, 245 kV, 420 kV and above. In such a substation, the various equipment like circuit-breakers. Bus bars, Isolators, Load break switches. Current-transformers, Voltage transformers, Earthing switches etc. are housed in separate metal enclosed modules filled with SF_6 gas. The SF_6 gas provides the phase to ground insulation. As the dielectric strength of SF_6 gas is higher than air, the clearances required are smaller. Hence the overall size of each equipment and the complete sub-station is reduced.

The various modules are factory assembled and are filled with SF_6 gas. Thereafter, they are taken to site for final assembly. Such sub-stations are compact and can be installed conveniently on any floor of a multi-streyed building or in an underground sub-station.

As the units are factory assembled, the installation time is substantially reduced. Such installations are preferred in composition cities, industrial townships, hydro-stations—where land is very costly and higher cost of SF_6 insulated switchgear is justified by saving to reduction in floor-area requirement.

SF_6 insulated switchgear is also preferred in heavily polluted areas where dust, chemical fumes and salt layers can cause frequent flashovers in conventional outdoor sub-stations.

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* Normal Pressure: 5 to 6 kgf/cm^2 gauge
Alarm at : 4.5 kg/cm^2
Automatic Trip of Lockout : 4 kgf/cm^2

7.14. ADVANTAGES

(*a*) *Compactness.* The space occupied by SF_6 installation is only about 10% of that of a conventional outdoor sub-station (Refer Fig. 7.6). High cost is partly compensated by saving in cost of space.

(*b*) *Protection from pollution.* The moisture, pollution, dust etc., have little influence on SF_6 insulated sub-stations. However, to facilitate installation and maintenance, such substations are generally housed inside a small building. The construction of the building need not be very strong like conventional power houses.

(*c*) *Reduced Switching overvoltages.* The overvoltages while closing and opening line, cables motors capacitors etc. are low.

(*d*) *Reduced Installation Time.* The principle of building-block construction (modular construction) reduces the installation time to a few weeks. Conventional sub-stations require a few months for installation.

(*e*) *Superior Arc Interruption.* SF_6 gas is used in the circuit-breaker unit for arc quenching. This type of breaker can interrupt current without overvoltages and with minimum acing time. Contacts have long life and the breaker is maintenance free.

(*f*) The gas pressure (4 kgf/cm^2) is relatively low and does not pose serious leakage problems.

(*g*) *Increased Safety.* As the enclosures are at earth potential, there is no possibility of accidental contact by service personnel to live parts.

7.15. DEMERITS OF SF_6 INSULATED SWITCHGEAR

(*a*) High cost compared to conventional outdoor sub-station.

(*b*) Excessive damage in case of internal fault. Long outage periods as repair of damaged part at site may be difficult.

(*c*) Requirements of cleanliness are very stringent. Dust or moisture can cause internal flashovers.

(*d*) Such sub-stations generally indoor. They need a separate building. This is generally not required for conventional outdoor sub-stations.

(*e*) Procurement of gas and supply of gas to site is problematic. Adequate stock of gas must be maintained.

7.16. GENERAL CONSTRUCTIONAL FEATURES OF SF_6-GAS INSULATED SWITCHGEAR (GIS) (Fig 7.10)

In this type of switchgear, SF_6 gas at a pressure above atmospheric pressure (5 or 6 kg/cm^2) is used as a dielectric insulating medium as well as for arc quenching in the circuit breaker chamber. The pressure in the C.B. chamber is generally higher. Its range of application extends from voltage ratings of 7.2 kV upto 800 kV.

The main components of GIS (Fig 7.10 a-e) are bus-bars, circuit breakers, disconnectors (Isolators), earthing switch, instrument transformers (Current Transformers, Electro-magnetic Voltage Transformer), surge arrestors, Insulators, Interfaces & other monitoring devices contained in an enclosure filled with SF_6 gas. GIS is generally subdivided into separately monitored zones/modules like circuit breaker, main bus, termination, voltage transformers, etc.

The conductors of busbars are fabricated from aluminium tubular sections which are joined between different sections by using plug-in-tulip contacts which fit automatically during field connections. Enclosures are made of non-magnetic material, commonly used material is Aluminium, stainless steel enclosures are also being manufactured. As the resistance of stainless steel is higher that of aluminium the losses in stainless enclosures in therefore higher.

The Circuit Breakers have Pneumatic of Hydraulic operating mechanism with one to four breakers per pole depending on the voltage & current rating or rupturing capacity. The operating mechanism of the circuit breaker is designed for adequate capacity which should be enough for two close/open operations.

Disconnector-switches/Isolators, as in the case of conventional Air Insulated Switchgear, are provided for Isolating the system/section for Inspection/maintenance of the equipment. These are either pneumatically or D.C. motor operated suitable for three-phase gang operation. They are designed to meet the requirement of breaking capacitive charging, Transformer & Reactor (wherever provided) magnetization current and the loop current.

Earthing or grounding switches are provided for grounding of the switchgear to ensure that the accumulated static charges are discharged to earth before start of any inspection or maintenance work. Two types of earthing switches are commonly provided ; (*i*) Slow moving & (*ii*) High speed ; slow moving switches are used where the operator can visually verify that the section of the switchgear or bus to be grounded has been isolated by opening the above mentioned disconnectors. At such locations such as at bus connections, transformer bushing connections where it is not usually possible to usually verify that the section has been isolated or can not be isolated, high speed earthing switches are used. Provision for automatic opening of these High speed Earthing Switches exists after complete discharge (1 second to 10 seconds). For locations where ground switches of either type can not be installed like at the entrance of bushing terminal, the grounding can be accomplished by using a hot stick.

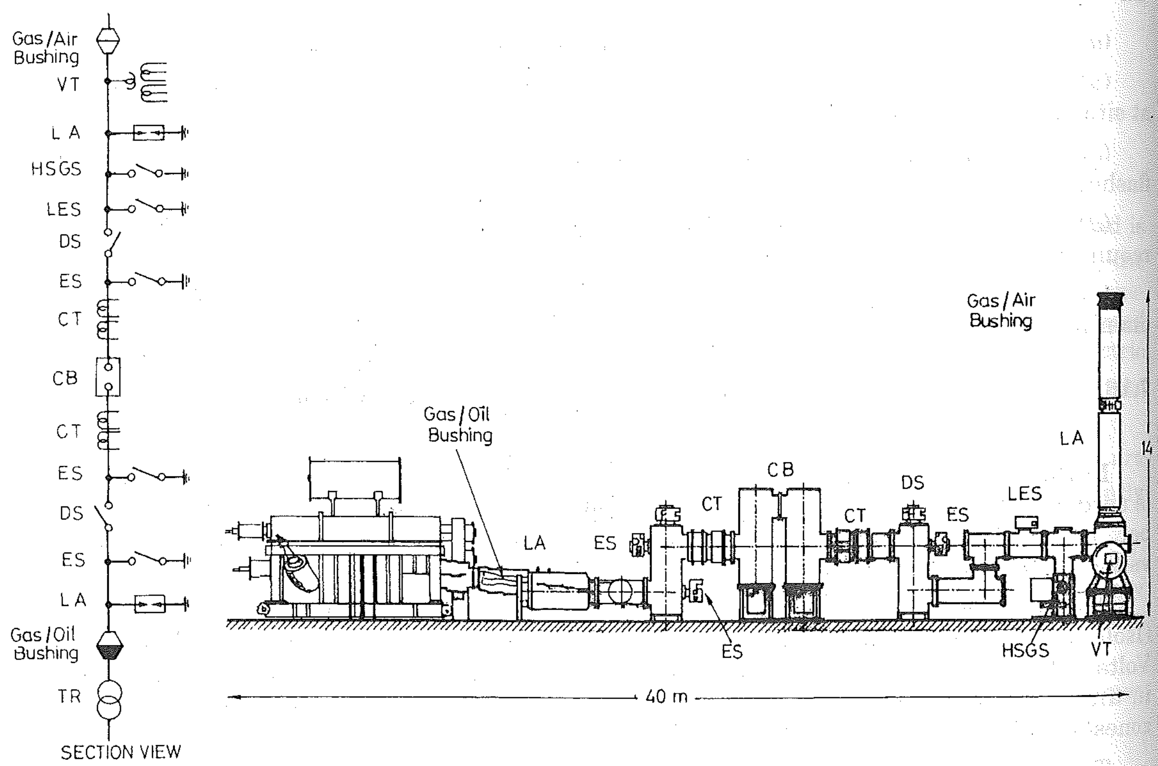


Fig. 7.10. (Main Components of GIS)

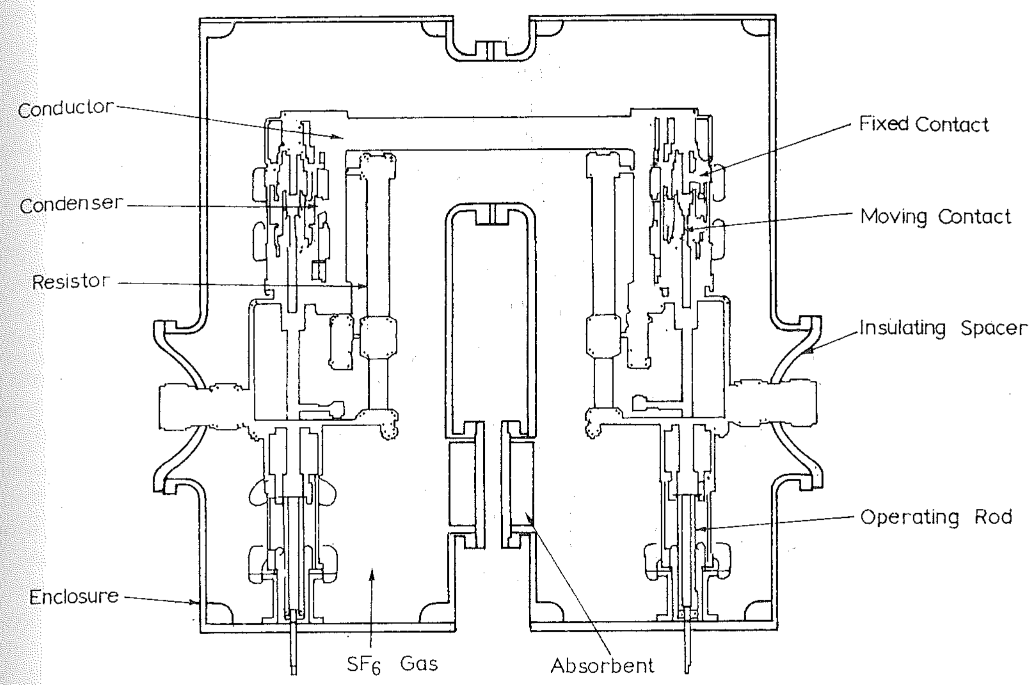


Fig. 7.10 (*a*) Circuit Breaker

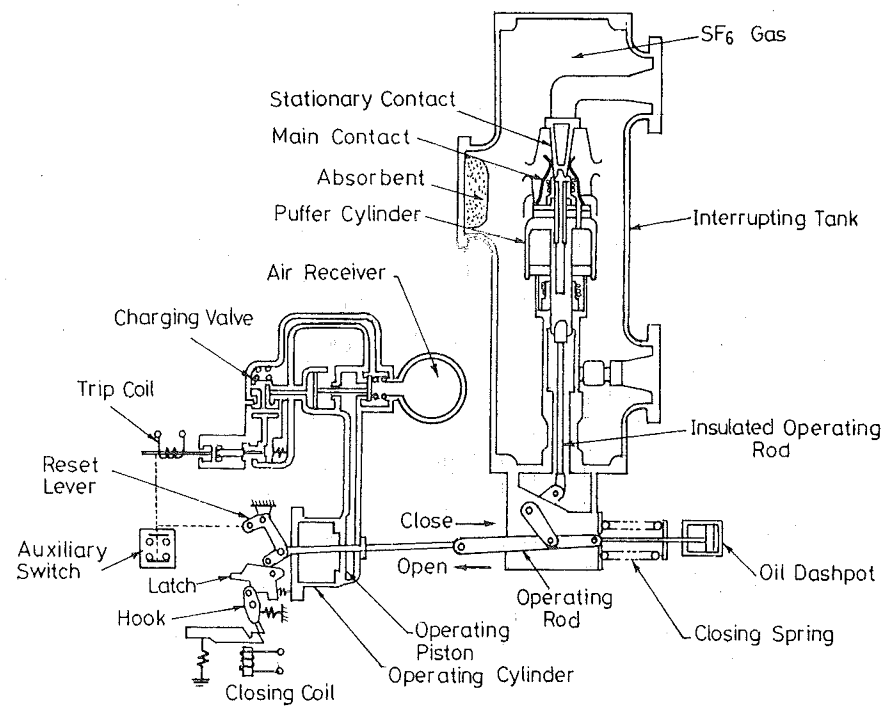


Fig. 7.10 (*b*)

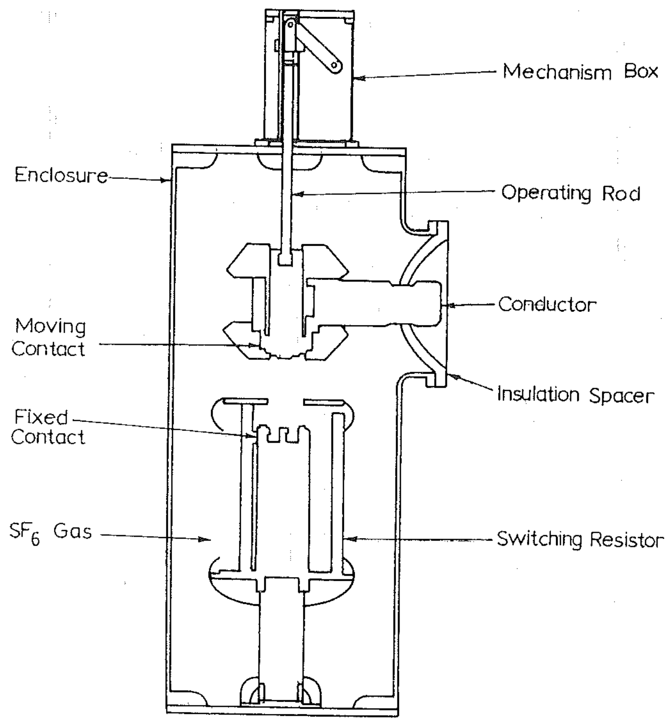


Fig. 7.10 (*c*) Disconnecting switch

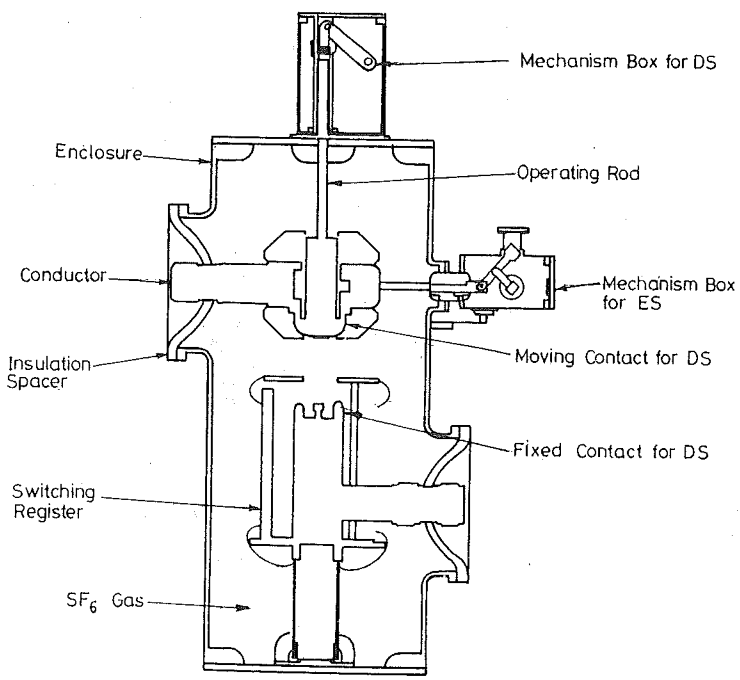


Fig. 7.10 (*d*) Disconnecting and Earthing switch

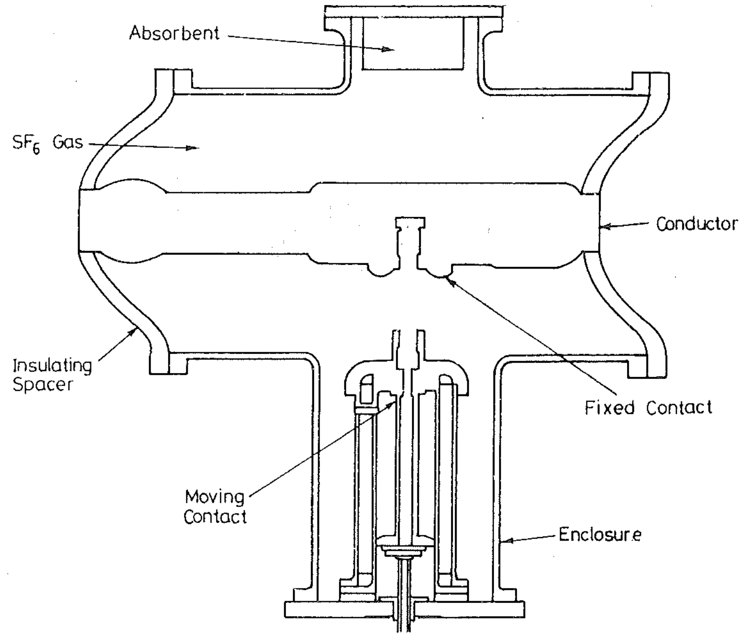


Fig. 7.10 (*e*) High speed ground switch

A mechanical indicator fixed to the operating shaft inside the operating mechanism provides a visual means of checking isolator position.

Instrument Transformers are metal enclosed cast resin type. They are used to meet the requirement of metering. Protection, synchronization etc. These are usually mounted externally to minimize the effect of electro-magnetic transient or enclosure current. Externally mounted construction also offers ease of installation or dismantling and maintenance.

Digital instrument transformers have now been developed in which electrically measured value (voltage or current) is converted to digital or optical signal while still at high voltage.

Insulators are the key components of the type of switchgear. It is said that the health of the GIS depends on its insulators and purity of SF6 gas. These insulators are made of epoxy resin. Normally, two types of insulators are used, Tripost or Conical. Tripost or conical insulators are used to support the conductor to the enclosure. In addition, one or more movable tripost insulators are rigidly attached to the conductor for thermal expansion. Conical Insulators are used as gas barriers to divide the system into separate gas zones / modules.

Surge arrestors are provided to protect the switchgear from high transient voltage and also to regulate the duration and amplitude of follow current. The location and number of Surge Arrestors is based on Insulation Co-ordination studies / surge analysis. Generally, station type, heavy duty, SF6 gas insulated, gapless, metal oxide (Zno) surge arresters are used.

Interfaces (Fig. 7.11, *a, b, c*).

GIS has to be connected to Transformer (oil filled bushing), XLPE cable or outdoor transmission lines. GIS connected directly to a transformer requires oil-SF6 transformer bushing to keep the SF6 gas separate from the transformer insulating oil.

Bellows are provide near the transformer bushing to compensate for alignment errors and to absorb vibration. For connecting to over-head transmission lines, porcelain gas-to-air bushings are used. The cable sealing end is provided to connect the cable, wherever provided. The cabling sealing end can accommodate any kind of cable with conductor X-section upto 2000 mm^2. Isolating contacts and connection facilities are provided for testing the cables.

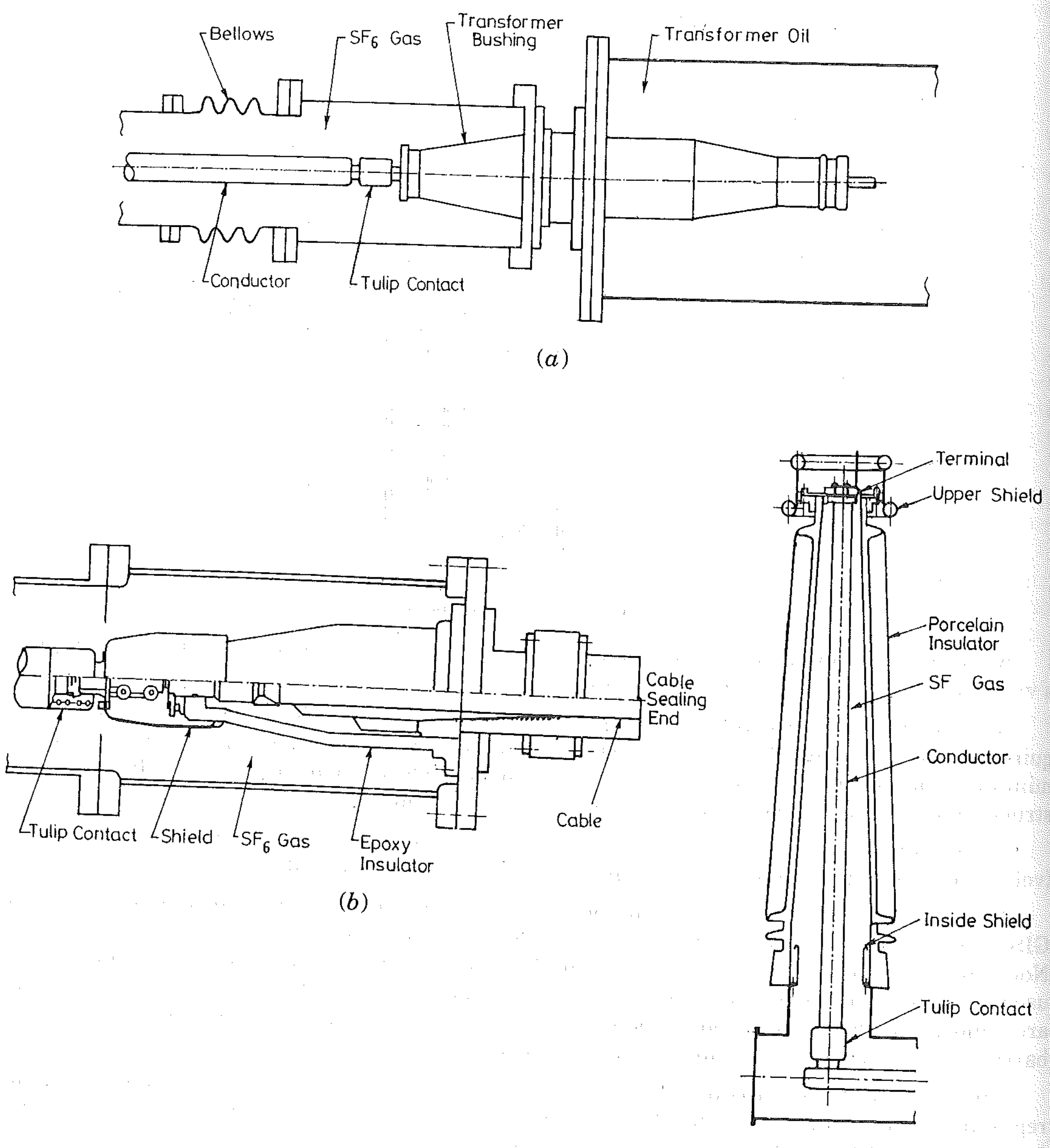


Fig. 7.11.

7.17. GAS MONITORING

The operation of GIS depends upon the pressure and the purity of the gas. Each GIS section is, therefore, provided with a gas density monitoring system. Since the relative dielectric strength of the gas depends on its density rather than pressure, and, density depends on temperature, factory set temperature compensated gas density switches are provided with contacts for alarm and trip. Leakage of gas does take place, 1% per-annum leakage is generally guaranteed. For leakage of very low rate, the gas is automatically admitted through solenoid valves.

Arcing causes the decomposition of the small amounts of the SF6 gas which recombines almost completely into SF6. The decomposition products react with water; So, the moisture content of the gas, particularly in the circuit breaker chamber has to be controlled. This is done by using drying

(molecular) filters. Moisture content, upto 300 ppm can be allowed under exceptional conditions, beyond the value, the gas needs to be subjected to drying process.

Each bay/module is provided with a Local or Bay Control Cubicle containing all the equipment needed for control, interlocking, signaling, supervision and auxiliary power supply. The Local Control Cubicles (LCC) can be connected to Control Room for remote control and signaling.

Grounding : IEE - 80 -"Guide for safety in Alternating Current Sub-station Grounding" is generally followed for grounding of the GIS.

The grounding system to be provided has to limit the potential gradient to acceptable values of assure safe voltage for step & touch, under both normal and abnormal operating conditions external to the GIS assembly. The design of the grounding shall be such as to secure the requirements of protective relaying and also satisfy the provisions necessary for telephone and communication facilities. Particular attention is to be given to the bonding and the grounding of metallic high magnitude enclosures as these enclosures carry high magnitude Induced Currents and these currents have to be confined to specific paths so as to avoid circulating currents. Precautions have to be taken to prevent excessive currents being induced into adjacent frames, structures or reinforcing steel and to avoid current loops via other station equipment, such as transformers etc.

Partial Discharge Monitoring

Partial Discharge (P.D.) monitoring system is provided for high sensitivity monitoring of Partial Discharge Phenomenon in GIS to assure high reliability and efficient preventive maintenance activities.

There are two types of Partial Discharge Monitoring System - On-line and stand alone; Stand alone system is preferred. The P.D. monitoring system initiates alarm when the partial discharge level exceeds the pre-set level which varies from 2.0 pc to 5.0 pc. However, this is subject to expenuine regarding interpretation of the measured values.

The system as shown in Fig. 7.12 consists of external sensors, Measuring unit and Man-Machine Interface; Connection between the external sensor and the PDM is by screened co-axial cable. The PDM kit kept as close as possible to the GIS (within 20 m length) and on the mobile trolley to move easily. The sensor unit is UHF type antenna with a frequency range of 9 KHz to 1.5 GHz. Measurement unit consists of spectrum analyzer, amplifier unit & switching module. Man-machine interface consists of a computer and other normal accessories / devices for data monitoring, recording and print outs. Other types of mobile partial discharge monitoring systems are also being manufactured.

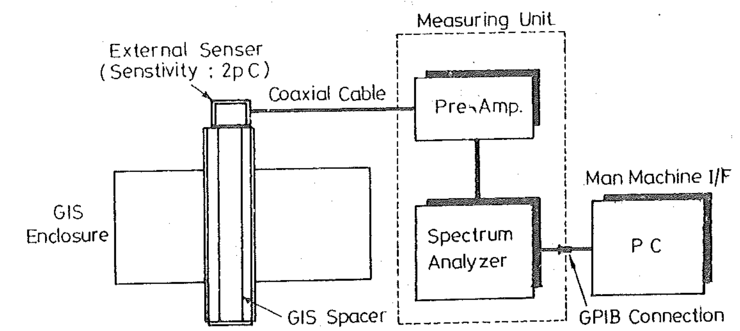


Fig. 7.12. Overall System Configuration of Stand alone Partial Discharge Monitoring System of GIS

Factory Acceptance Testing

GIS equipment should be tested in accordance with ANSI C37.122 and ANSI C37.09 or IEC 517. The various tests include :

- Rated continuous current thermal test
- Dielectric withstand tests
- Lightning impulse tests
- Mechanical life tests
- Mechanical bushing test including cantilever loading capability
- Pressure tests
- Circuit breaker sound level limits
- Short circuit current interrupting test
- Switching impulse tests
- Insulator tests
- Partial discharge tests

— Current and voltage transformer ratio, phase angle and polarity tests
— Nameplate checks
— Gas leakage tests
— Resistors, heaters and coil check test of control mechanisms
— Control and secondary wiring check and continuity tests
— Clearance and mechanical adjustment test
— Mechanical tests on operational assemblies
— Timing tests on operational assemblies
— Timing tests on operational assemblies
— Rated low-frequency withstand voltage tests on control and secondary wiring
— Gas monitoring system alarm contact test
— Finish requirements
— Stored energy system tests
— Interlocking operation tests

Field Acceptance Testing

Field acceptance testing is performed in accordance with ANSI C37.122 or IEC 517 as applicable on the completely assembled GIS assembly. The following tests are included :

— Gas leak or tightness check
— Gas moisture tests
— Continuity tests
— Current transformer ratio and polarity tests
— Voltage transformer ratio and polarity tests
— Voltage tests on control and auxiliary circuits
— Operational tests
— Grounding tests

LOSS MEASUREMENT & TEMPERATURE RISE TESTS OF CONDUCTOR AND ENCLOSURE

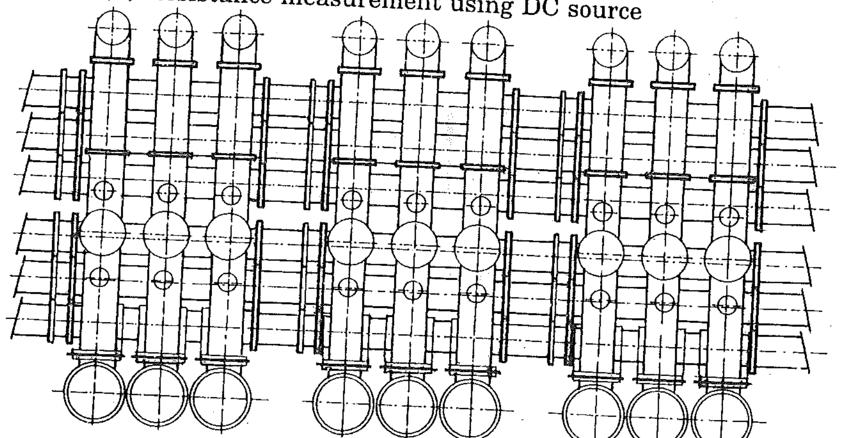
Loss Measurement Test

When current flows through the conductors, it induces emf in the enclosure resulting in the circulation of current in the enclosure. This loss in the energy is converted into heat. The magnitude of this heat loss depends on current flowing through the conductor, the clearance between conductor and enclosure, the material & thickness (Resistance) of the enclosure. The loss, both in conductor & enclosure, have to be kept within such limits so as not to cause temperature rise more than allowed by the relevant applicable standards. The value of losses and temperature rise are generally to be guaranteed by the manufacturer and hence are verified by the Purchaser.

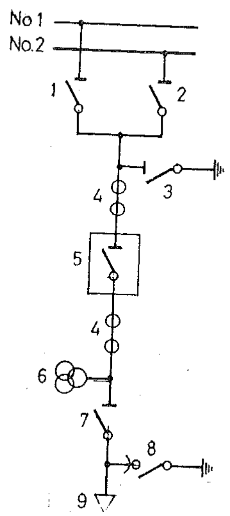
The following two methods are employed for measurement of conductor and enclosure losses.

(*i*) Watt-meter method

(*ii*) Resistance measurement using DC source



Double-bus type 420 kV GIS (Layout-Plan)
1. Busbar disconnector, 2. Busbar disconnector, 3. Maintenance earthing device 4. Current transformer, 5. Circuit breaker, 6. Voltage transformer, 7. Line disconnector, 8. Line earthing switch, 9. Cable sealing end.



Single line diagram

Fig. 7.13.

Temperature rise of conductor and enclosure is measured at rated current, rated SF6 gas pressure and at ambient temperature by using thermo couples.

The details of routine and field tests generally followed in Gas Insulated Switchgear are given in Section A & section B respectively.

Ratings of GIS Switchgear

Rated Voltage	*Rated BII, KV*	*Rated INT, KA*	*Rated Normal Current A*					
123	550	12.5	800	1250				
		20		1250	1600	2000		
		25		1250	1600	2000		
		40			1600	2000		
145	650	12.5	800	1250				
		20		1250	1600	2000		
		25		1250	1600	2000		
		31.5		1250	1600	2000	3150	
		40			1600	2000	3150	
		50				2000	3150	
170	750	12.5	800	1250				
		20		1250	1600	2000		
		31.5		1250	1600	2000	3150	
		40			1600	2000	3150	
		50			1600	2000	3150	
245	1050	20		1250	1600	2000		
		31.5		1250	1600	2000		
		40			1600	2000	3150	
		50				2000	3150	
300	1050	16		1250	1600			
		20		1250	1600	2000		
		31.5			1600	2000	3150	
		50			1600	2000	3150	
362	1175	20				2000		
		31.5				2000		
		40			1600	2000	3150	
420	1425	20			1600	2000		
		31.5			1600	2000		
		40			1600	2000	3150	
		50				2000	3150	4000
525	1550	40				2000	3150	
765	2100	40				2000	3150	

7.18. GAS FILLING AND MONITORING SYSTEM FOR SF_6 SWITCHGEAR

Gas tightness is basic requirement of SF_6 insulated sub-stations. The entire sub-station is divided into separate compartments. The gas pressure in each compartment is monitored separately. The gas monitoring system comprises temperature compensated pressure switches. The setting in such that when density of gas (related with temperature and pressure) reduces below safe level, an alarm is sounded. Further reduction in pressure gives a tripping command. Normally the leakage rate should be less than 1% per year. For leakage of very low rate, the setting of density monitors is such that the gas from SF_6 gas cylinders is automatically admitted in the modules to make-up the loss. The gas filling system consists of high pressure tank (6 to 10 kgf/cm^2 for circuit-breaker modules and low pressure tank for other modules. When gas pressure in the modules drops down the gas from tank is automatically admitted by solenoid valves. The SF_6 gas from cylinders can automatically go to tanks on opening the valves and regulators.

Typical Ratings of SF_6 Insulated Switchgear (GIS)

Rated Voltage kV	36	72	145	245	400	500
Rated currents Amp.	1200 to 2000	1200 to 2000	2000 to 3000	2000 to 4000	2000 to 4000	2000 to 4000
Rated Breaking current kA	32	32	32	50	50	50
Breaking capacity MVA	1800	3500	7500	10,000	35,000	50,000
Operating Time Cycles	3	3	3	2.3	2	2
Power frequency Voltage withstand kV_{rms}	75	160	275	460	680	840
Impulse Voltage withstand kV_p, peak	170	400	550	1050	1425	1800

7.19. TRANSPORTATION AND HANDLING OF SF_6 GAS

The SF_6 gas is transported liquid form in cylinders of various sizes (15 kg, 40 kg and 100 kg).

The gas cylinder has a valve on the top. When this valve is manually opened, the SF_6 is released through the valve in gaseous form. The necessary heat for conversion from liquid to gas is taken from atmosphere. In cold countries it becomes necessary to keep the gas cylinder in hot water to convert liquid into gas. But such heating is not necessary in India during summer.

The circuit-breaker is provided with a gas valve and gas monitoring system. A braided teflon hose is connected between the gas cylinder, gas handling unit and the circuit breaker valve. Before filling the gas, the circuit-breaker is evacuated and the air and moisture must be removed from inside the breaker. After evacuated to about 2 mm of mercury, the gas from the cylinder is admitted into the breaker. The pressure of gas in the breaker is indicated on the pressure gauge. When the desired pressure is reached, the gas valve on the breaker is closed.

During periodic maintenance, the gas sample from SF_6 circuit breaker is collected and tested for moisture and other impurities (IEC 376). The gas is circulated through filters containing activated alumina. The activated alumina absorbs the impurities like S_2 F_2, SF_4, moisture etc. The gas can be used again after regeneration.

7.20. GAS TRANSFER UNITS

These are employed primarily to erection and maintenance large SF_6 equipment such as circuit-breakers and GIS. During the maintenance it is necessary in most instances, to remove the SF_6 gas from the equipment. Because SF_6 is a relatively expensive gas, it is desirable to collect the gas during periods of maintenances and to recharge the equipment after the maintenance.

Functions of SF_6 Handling Unit

1. On initial start up, the unit evacuates itself.
2. The unit is connected, by means of a flexible hose, to the equipment to be serviced. After equalisation of pressure between the transfer unit and equipment, the SF_6 is pumped to the storage tank of transfer unit. The refrigeration system is energized to obtain liquefaction of the SF_6 gas.
3. The vacuum pump is energized ensuring complete transfer of SF_6 gas to storage tanks.
4. After maintenance the transfer-unit evacuated the service equipment prior to charging with SF_6 gas.
5. The tank heater is energized to boil off the SF_6 gas and recharge the equipment. This is for low ambient temperature.
6. If the transfer unit is equipped with an SF_6 purifier and gas dryer the gas is processed prior to recharging the serviced equipment by internal circulation through filters.

Features

— Transfer, stores, reclaims, and purifies 99.5% of the SF_6 gas.

— No lubricating oil contamination. All transfer units contain exclusive 4-step oil separation process.

— Automatically controlled refrigeration system.

— Convenient central control panel. All switches, gauges and instruments located for case of operation.

— Hand valves conveniently grouped on either side of control panel.

— Trailer mounted for portability. Can be towed.

The gas handling unit is used for filling the SF_6 gas in the breaker and for reclaiming the SF_6 gas from the breaker. The gas handling unit comprises a vacuum pump., compressor, an auxiliary receiver, gas-filtering units, valves and piping. Before filling the gas, the circuit-breaker is evacuated by means of the vacuum pump. After achieving a certain degree of evacuation, the gas from cylinders is filled into the circuit-breaker.

Gas transfer units for SF_6 gas are available is various forms for various applications.

1. Simple gas transfer unit comprises only a vacuum pump with valves. It is useful in evacuating the circuit-breaker to remove moisture and air. Such a unit is sufficient in most of the cases where only a few circuit-breakers are installed.

2. **Medium gas transfer unit.** This comprises a vacuum pump compressor and valves with piping. It can perform the following functions:

(a) Evacuating the breaker.
(b) Transferring the gas from the cylinder to the breaker.
(c) Reclaiming the gas from the breaker into another tank.

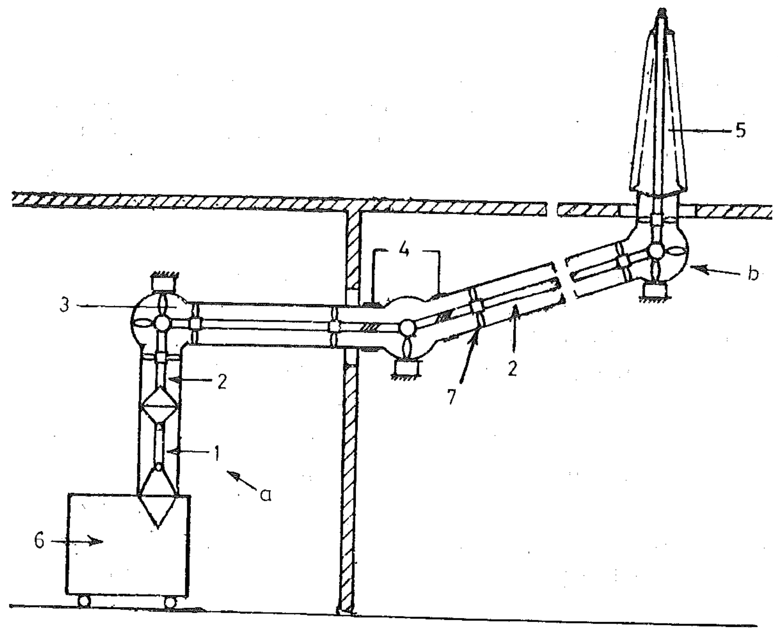
3. **Large Gas Transfer Unit.** It has the following components :

(a) SF_6 gas compressor
(b) Vacuum pump
(c) Gas storage tank
(d) Filter units containing activated alumina.

7.21. SF_6 INSULATED EHV TRANSMISSION CABLES (GIC)

The conventional transmission lines from generating station to receiving-station are outdoor overhead lines. The connection between the underground power-station and remote outdoor switchyard is generally made by high voltage oil filed cable usually 145 kV or above.

In recent years such connections are made by means of SF_6 gas Insulated metal enclosed cables (GIC). GIC is preferred for connection between step-up transformer and the outdoor switchgear. The three phases are enclosed in separate enclosures filled with SF_6 at 4.5 kg/cm^2. Conductors are supported on epoxy insulators, Fxpansion joints are provided by plug-in contacts. [Fig. 7.14].



1. Oil/SF_6 Bushing
2. GIC
3. 90° bend, ball joint
4. Expansion joint
5. SF_6/Air Bushing
6. Transformer
7. Support insulators

Fig. 7.14. A 420 kV, SF_6 Gas Insulated Cable (GIC) SF_6 Gas pressure; kg/cm^2 Absolute [*Courtesy* Brown Boveri.]

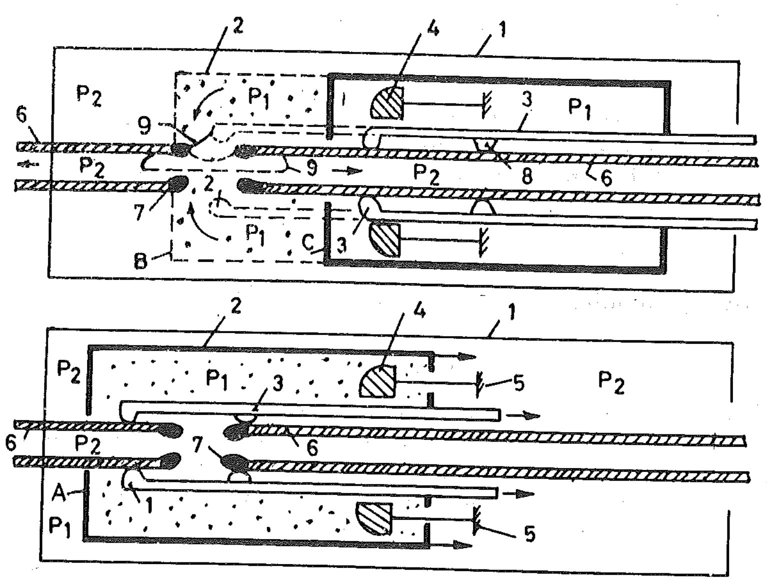
Summary

SF_6 circuit-breakers are preferred for rated voltages of 3.3 kV, to 760 kV, SF_6 filled switchgear (GIS) and cables (GIC) are preferred for sub-stations. Puffer type single pressure SF_6 circuit-breakers employing puffer principle have higher interrupting capacity per interrupter (60 kA at 245 kV).

Note : 1. SF_6 circuit-breakers are now preferred for indoor metalclad switchgear rated 3.3 kV to 36 kV. (Refer Ch. 15).

2. SF_6 outdoor circuit-breakers are now preferred for rated voltages from 36 kV to 760 kV.

3. SF_6 GIS has been developed for wide range from 3.3 kV to 760 kV.



1. A. Fully closed
   B. Contact separated
   C. Full open
2. Puffer cylinder
3. Moving contact tube
4. Fixed piston
5. Support for 4
6. Fixed Nozzle
7. Conducing nozzles
8. Finger contacts on 3
9. Arc drawn into 6
10. Gas flow

Fig. 7.15. Three stages of Puffer Action in Interrupter with fixed conducting nozzles. (Courtesy: Siemens, West Germany.)

4. In outdoor EHV range SF_6 CB is the most popular, cheaper and satisfactory type of breaker. It has made MOCBs and ABCBs obsolete.

The puffer cylinder (2) moves towards right (A → B → C →) along with the moving contact tube (3). The gas compressed in (2) is released through conducting tubes (6 – 6) as the art (9) is drawn. The arc (9) is driven in two directions axially in the tubes (6 – 6). The conducting nozzles at the tips of conducting tubes (7) made of graphite accelerate the arc roots into the tubes. The arc is quenched by cooling and lengthening in the tubes. Fresh SF gas between the two fixed nozzles gives the dielectric recovery, the hot gas is driven away.

QUESTIONS

1. Explain briefly the arc extinction process in SF_6 circuit-breakers.
2. Explain the following terms regarding SF_6 gas
   — Electronegativity
   — Arc time constant.
   Discuss the merits and limitation of SF_6 gas as insulating and arc quenching medium.
3. Explain the principle of puffer type SF_6 circuit-breaker.
   With the help of sketches explain the configuration of a puffer type SF_6 circuit-breaker.
4. Explain the procedure to filling SF_6 gas in a circuit-breaker.
5. What are the applications of SF_6 gas ?
6. Describe arc quenching process in puffer type SF_6 circuit-breaker.
7. Explain precautions to be taken to avoid dust, moisture, leakage in case of SF_6 circuit-breakers.
8. Explain the difference between a conventional outdoor substation and an GIS.

Units of Gas Pressure :

SI Unit of pressure : 1 Newton per meter-squared

$1\ Nm^{-2}$

Conversion factors :

1 atmosphere = 1 atm = 101325 Nm^{-2}

1 bar = $10^5\ Nm^{-2}$

1 kilogram force = 1 kgf = 9.806 N

1 atm = 101.325 kNm^{-2} = 1.01325 bar

1 atm at standard temp and pressure = 760 mm of mercury.

1 torr = 1/760 mm of mercury = 133.32 Nm^{-2}.

7-A

Routine, Site/Field Testing of GIS

7.22. ROUTINE TESTING OF GIS

Purpose : The routine tests serve the purpose of knowing any defects and deviations in material, during assembly of component/device or manufacturing faults. These tests ensure that the product is in accordance with the equipment specifications/relevant standards and shall meet the specific environmental & operating conditions. The routine tests are made on each apparatus or device or on each transport unit or on a complete bay at the manufacturers works.

These Routine Tests are performed in accordance with the provision of various standards and guidelines. Wherever deviations exist between such standards, the method and input values and the results are then mutually agreed between the purchaser and the supplier.

The various applicable standards generally followed for main components of GIS is given below:

Item/Equipment	Applicable Standards
Gas Insulated Switchgear assembly	IEC 60517
	IEC 60694
	IEEE C:37.122
Circuit Breaker	IEC 60056
Disconnecting Switch and Earthing Switch	IEC 60129
Current Transformer	IEC 60044-1
	IEC 60185
Voltage Transformer	IEC 60044-2
	IEC 60186
Lightning Arrestor	IEC 60099-4 & IEC 60517
SF_6-Air Bushing	IEC 60137

The main tests generally specified for various components are as follows:

(*a*) **Routine Tests on Surge Arrester (Metal Oxide Type)**

— Residual Voltage Test
— Visual & Dimensional Check
— Gas leakage test on housing
— Insulation Resistance Test
— Measurement of the operating current at max. Continuous Operating Voltage
— Leakage Current Test
— Measurement of Reference Voltage
— Partial discharge measurement test at 1.05 × max. continuous operating voltage

Partial discharge levels are measured at phase voltage × 1.05 after prestressing at 390 kV (for 420 kV) for 10 seconds.

— SF_6 gas leakage tests.

(By accumulation method, using gas leak detector)

Surge Arrestor Component testing during their manufacture comprise:

— Pressure test and gas tightness test on enclosures. Each enclosure is subjected to two times design pressure for 1 minute.
— Dielectric test on barrier insulators *e.g.* for 420 kV switchgear, ac voltage of 680 kV, 50 Hz is applied for 60 seconds.
— Dielectric test on foil insulated grading tubes where ever applicable.
— Each individual Metal oxide disc is subjected to the following routine tests:
— Loading with high energy (3 × 3 rectangular waves)
— Measurement of residual voltage and rated discharge current
— Measurement of Watt-loss at 50 Hz Service voltage
— Current sharing check on Metal oxide columns in case of multi-column arresters

(*b*) **Routine Tests on Voltage Transformer**

— Induced over-voltage withstand test
— Lightning Impulse Voltage Test
— Switching Impulse Voltage Test
— Power frequency test on secondary windings
— Partial discharge measurement test
— Voltage error and phase displacement tests, verification of terminal markings
— Pressure test and gas lightness (leakage) test on enclosure

(*c*) **Routine Tests on each Disconnecting Switch & Earthing Switch**

— Visual inspection, Wiring check
— Mechanical operation tests.
— Measurement of insulation resistance of auxiliary and control circuit
— Power frequency voltage withstand test on auxiliary, control circuit and main circuit
— Measurement of the resistance of the main circuit
— Measurement of motor current
— Interlock Test
— Gas leakage test

(*d*) **Routine Test on Current Transformer**

— Visual, Dimensional check including verification of terminal markings
— Polarity check
— Power frequency withstand test on secondary windings
— Inter-turn over-voltage test
— Determination of errors
— Measurement of excitation characteristics
— Secondary winding resistance test
— Turns Ratio Test
— Composite Error Test

High voltage dielectric tests are performed subsequently on these current transformers on their mounting / integration with GIS module / Transport Unit.

(*e*) **Tests on SF_6-air bushings**

The following tests in accordance to IEC 137 are performed by the manufacturer.

— Measurement of the dielectric dissipation factor and the capacitance at ambient temperature.
— Power frequency voltage withstand test (dry) for one minute at rated SF_6 gas pressure (at 20°C).

— Measurement of the partial discharge quantity at $1.5 \times U_m/\sqrt{3}$ and at minimum rated gas pressure (at 20°C) (value to be less than 5 pc).
— Gas lightness of cast enclosure by filling it with Helium gas and detect any leakage followed by vacuum/pressure rise test and sniffing tests on welds & joints.
— Pressure test on enclosure; each enclosure is subjected to 2 times design pressure for one minute.
— Pressure test on complete bushing with 1.5 × rated operating pressure during 15 minutes.
— Gas tightness test on complete bushing.
— Resistance measurement test as per the procedure in IEC 694.

(*f*) **Routine Tests on Circuit Breaker Unit**

— Check of correct wiring & visual inspection
— Measurement of coil resistance
— Mechanical operation & timing test
— Measurement of minimum operating voltage and pressure
— Measurement of motor current
— Stored energy test
— Oil leakage test
— Safety valve operation test
— Measurement of oil pressure switch operating pressure
— Measurement of gas density switch operating pressure
— Measurement of insulation resistance of main circuit, auxiliary circuit and control circuit
— Voltage test of auxiliary and control circuit
— Power frequency voltage withstand test on the main circuit

(*g*) **Routine tests on assembled/Transport Section**

— Visual Inspection
— Gas leakage test
— Operating Mechanism fluid leakage test
— Measurement of the resistance of the main circuit
— Power frequency voltage withstand test on the main circuit
— Partial discharge test
— Power frequency voltage withstand test on auxiliary and control circuit of Bay (Local) control cubicle
— Correct wiring & interlock test
— Measurement of gas density switch operating pressure
— Mechanical operation test
— Corrosion protection test

When testing according to IEEC 37.122, for pressure tests on enclosures, and for protection tests on circuit breakers (ANSI/IEEE C37.09-1979) some deviations may have to be taken into account. Also, following additional test will also have to be carried out.

— Current transformer and linear coupler transformer tests as per ANSI C 57.

A description of the procedure being following with regard to important tests as indicated above is briefly described hereunder:

1. **Visual Inspection.** The complete bays/shipping sections are visually inspected. Dimensional checks are made as per the layout drawings. The name plate markings are checked and compared with the drawings.

2. **Power frequency voltage tests on the main circuit, including partial discharge measurement.** They are made on complete apparatus including at least one insulator of each type transport units or complete bays in accordance with IEC 694, IEC 517 & IEC 60. It has to be ensured that the place of testing is dry, clean with adequate ventilation. The test voltages are supplied normally by metal clad test transformers directly flanged to the tested apparatus. During the test, the SF_6 gas pressure is maintained at its minimum value, test voltages are generally as per the following table.

Max. Voltage, (kV)	145	245	420	800
Applied Voltage at 50 Hz, (kV)	325	440	680	960

The test values do vary, *e.g.* for 420 kV, 520 kV test voltage is also used. The test voltage is applied for 60 to 72 seconds depending on nominal voltage frequency 50 Hz or 60 Hz.

The measurement of partial discharge as per IEC requirement is $1.1 \times$ Max. voltage/3. However, some manufacturers perform with descending voltage at $1.05 \times U_m/\sqrt{3}$. The acceptable value of partial discharge is less than 10 pc; The actual values are even less than 3 pc. When testing with a coupling capacitor, a minimum capacitance of 1000 F is provided.

Di-electric Tests on auxiliary and Control Circuits

The test, as per IEC-694, involves application of 2.0 kV, 50Hz voltage for one-minute between the auxiliary and control circuits connected together as a whole and the base of the switching device.

Measurement of the resistance of the main circuits

The test involves measurement of resistance on bus-joints, circuit breaker, disconnectors, earthing switch contacts so as to verify proper contact alignment.

This test is made in accordance with IEC:694; A d.c. current is passed across the said contacts & voltage drop measured to calculate the contact resistance.

Resistance value of close and trip solenoid coils and their series resistors are measured by digital multi meters and value obtained compared with the specified limits.

Gas density Test

This is an important test to determine the dielectric integrity of the switchgear, gas density is measured at rated pressure and ambient temperature.

Pressure Tests

These tests are undertaken on GIS enclosures and barrier insulators.

Enclosures : The tests are done as per IEC 517. However, the general practice is to subject the enclosure to 2 times design pressure for 1 minute.

Barrier Insulators : These insulators are routine tested with water pressure at 1200 kpa for 1 minute.

Gas leakage tests

This test is performed as per IEC-517 and is intended to verify that the leakage of the gas is within the permissible limits *i.e.* less 1-percent per annum.

In the above test, vessels are checked on porosity by filling with Helium gas and detecting the leakage of the gas by appropriate detectors; Subsequently, the vessel or transport unit is evacuated to less than 100 Pa pressure, then the vacuum pump is disconnected and pressure rise observed; The equipment is then filled with SF6 gas at rated pressure and sniffing tests are made on each joint, flanges, screw joints, gas fittings, welded seam etc. to verify/smell any leakages. Other method, called the accumulation method involves wrapping of plastic sheets around the mutually agreed locations of flanges, screw joints, gas fittings and notice any accumulation of gas in the plastic wraps which are left wrapped for 12 to 15 hours. The gas contents, if any, are measured by gas leakage detector.

Mechanical Operation Test

The intent of the above tests is to ensure that the switching devices comply with the stipulated operating conditions and that the mechanical interlocks and switching devices operate, open/close properly within the specified limits of auxiliary voltage, pressure etc.

Each switching device is subjected to a minimum of 50 operating cycles with the interlocks placed as per the requirement; for each switching devices details are as under:

Circuit-breaker

The tests are performed as per IEC 60056. A minimum of 50 close/open operations are made at ambient room temperature and at different operating mechanism pressures.

Switching times are measured and the time travel diagram is recorded, smoothness of the circuit open/close operation at different pressures of the operating mechanism is also checked.

Timing Test of Circuit Breaker

Closing time, opening time, asynchronisation time of the three poles and operating system pressure drop after each operation at different pressures & control voltages are measured. Also, recharging time of the hydraulic mechanism after one closing and opening operation at rated pressure are measured and compared with the permissible limits.

Also, minimum DC control voltage at which the gas circuit breaker can be electrically operated is measured to see that the CB operates at minimum DC auxiliary voltage. This operation test shall preferably be carried at minimum pressure of the operating mechanism (Hydraulic of Pneumatic).

The CB shall also be tested for stored energy under the specified operating sequence without oil pump operation. The operating system has also to be tested for leakage test by setting it at the rated pressure and other pumps switched off. The drop in pressure shall be measured after one hour. Then the pump shall be run continuously and operating pressure of the safety valves checked.

Disconnector and earthing switch

The intention is to verify that the disconnectors and earthing switches open and close correctly. Switches and their respective drive mechanisms are normally tested separately and subsequently together after complete assembly. Ten number operations each at minimum and maximum auxiliary voltage and 50 Nos. at rated voltage are performed for closing as well as opening; closing time of disconnector is also measured.

Tests on main circuit components

Normally 70 close/open operations are made. The torque of the motor as well as main circuit resistance are measured after completion of 70 operations.

Motor currents drawn at rated voltage, maximum and minimum voltage are also measured.

Tests on drives : The drives are tested under specified torque on simulators :

In this test, 50 close/open cycles each at rated supply voltage and rated pressure of compressed gas; 10 close/open cycles at specified minimum aux. supply voltage, 10-close/open cycles at max. supply voltage are employed.

After, completion of above close/open cycles, travel times and resistance of electrical parts are measured.

Tests on Switches

These tests are made either in the factory in case of complete bays as well as site to check their correct operations.

Tests of Auxiliary Electrical and Hydraulic Devices

The purpose is to verify that the electrical, hydraulic and other interlocks together with control devices operate satisfactorily and in the pre-determined sequence of operation under all conditions of use/operation and under the limits as specified for auxiliary supply.

The test is made in accordance with IEC-517.

Corrosion Protection Test

The dry film thickness (microns) of the paint (wherever applicable) is measured and compared with the stipulated values.

Verification of the correct wiring

The purpose is to verify that the wiring conforms with the diagram and prescribed requirements.

Wiring of complete bays and integrated control panels is checked which include:

— Correctness of all apparatus and of their installation
— Wiring check
— Dielectric Tests on aux. & control circuits
— Check of main circuits
— Completeness check
— Safety check while handling/transport

Checks/Tests on CTs

Polarity of the CTs is checked by inductive method; For power frequency withstand test on secondary windings, a voltage of 3000 volts, 50 Hz is applied for 60 seconds between secondary windings and earth as per IEC-60044-1, 60185; To verify the inter-turn voltage requirements, rms value equal to rated primary current at rated frequency is applied for one minute to the primary winding of the CT, with secondary open circuited so as to produce stipulated value (4.5 kV peak) of voltage at secondary terminal.

With primary winding open circuited, a voltage equal to ten times the r.m.s. value of the specified e.m.f. is applied for one minute to the secondary terminal provided that the r.m.s. value of the secondary current does not exceed the rated current and CT is checked for withstanding the applied test voltage (Applicable to PS-class CTs).

Determination of errors

Rated Current is passed through the CT to be tested and a standard (authenticated & calibrated CT), the secondary winding current is then compared with the Standard CT & current error and phase displacement measured and compared with the limits given in IEC 60044-1 & 60185.

Measurement of excitation characteristics

Excitation current is injected to the secondary circuit, with primary winding open circuited; Excitation current and voltage are measured at typical three points upto excitation current of 1 Amp/5 Amp, as the case may be.

Secondary Winding Resistance Measurement

Resistance values of the secondary winding are measured by digital multi-meters and compared with the design/specified values.

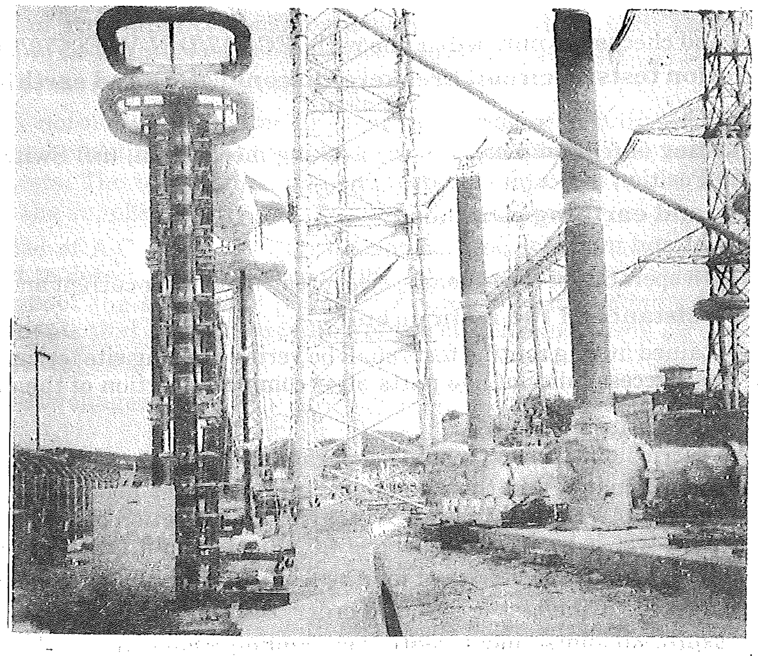


Fig. 7A.1. Site Test (Oscillating Impulse Test).

Turn Ratio and Composite Error Test

Difference between the rated and actual turns ratio expressed as percentage is checked and turns ratio errors obtained as such are compared with the specified limits.

The composite error at rated accuracy limit in terms of the percentage of primary currents for different accuracy class of CTs is checked and compared with the specified limits.

Lightning Impulse, Switching Impulse and Accuracy Tests for Voltage Transformers (VTs)

Three positive and three negative pulses of specified lightning impulse test voltage (1425 kV for 400 kV) are injected maintaining the SF6 gas pressure at its minimum value.

For switching impulse test, fifteen positive and fifteen negative pulses of the specified switching impulse test voltage (1050 kV for 400 kV) are injected keeping the SF_6 gas pressure at its minimum value.

Voltage error and phase displacement values are measured by comparing the same with a standard VT.

7.23. SITE/FIELD TESTING OF GIS (Refer Fig. 7A.1)

Purpose : Immediately after erection and physical check up of various assemblies, GIS is subjected to various tests to check the di-electric strength of the complete switchgear and also to detect any damage during transportation, storage or handling, presence of foreign particles, moisture content etc. to avoid the possibility of difficulty in charging the system to its rated max. voltage or to detect the possibility of likely reason of internal fault on commissioning. The site tests are supplementary to the routine tests.

The various main site tests include:

— Mechanical operation on circuit breakers, disconnectors and earthing switches.

— Measurement of the resistance of the main circuits.

— SF_6 gas leakage tests

— Moisture content tests

— Checks for correct wiring, proper functioning of the interlocks, control, measuring protective and regulating equipment including heating and lighting.

— High voltage tests on the main circuit.

Earthing Test

The aforesaid tests and checks are pursued in line with IEC-517/DIN-VDE0670/IEEEC37, 122.

Mechanical operation tests on circuit breakers, disconnectors and earthing switches.

For circuit breakers

— Checking and testing of (*i*) Pump control, (*ii*) Locking mechanism, (*iii*) Switching times of main circuit, (*iv*) Position indicator

For disconnectors and earthing switches

— Correct adjustment and indicator position check

— 5 number close/open operation of drive motors, measurement of motor current and running time.

Measurement of the resistance of the main circuits

Resistance values obtained during routine tests shall be verified during site testing to the extent practicable in view of the inaccessibility of live parts after complete erection of the switchgear.

SF_6 gas leakage test

These tests shall be carried out on each module separately.

In this test, the gas is evacuated and the rise of pressure noted for about one hour after the shutting off of the vacuum pump; Very fast pressure rise gives an indication of leak or higher moisture content; If the vacuum test is satisfactory, SF_6 is filled in to about 50% of the rated filling pressure, the joints made at site are then checked for any leakage with SF_6 gas detector or sniffer. The pressure is also monitored. If the test is found in order, the equipment is filled with SF_6 gas to achieve the rated pressure. All joints, inlets, vents, gas coupling piping etc. are then again checked by using gas sniffers.

Moisture content testing/dew point measurement of SF_6 gas

SF_6 gas used in GIS shall meet the requirement of IEC 376 (1974) - "Specification and acceptance of new sulphur hexaflouride".

The GIS sealed assembly is evacuated and the gas is filled up to the rated pressure. The assembly has to be then tested for moisture content as specified by the manufacturer, in line with IEC-376.

The tests for detection of moisture content are generally confined to ten percent of the gas compartments of different modules selected at random. The tests are done generally after 3-4 weeks after filling the compartments with the gas to allow for stabilization of the moisture.

In case moisture content in any of the compartments is found to be more than the admissible limits, it is advisable to go for testing of all other compartments.

Checks and verifications

Other checks and verifications are made to examine the proper functioning of the measuring, protective, regulating equipment, heating & lighting, interlocks and grounding.

First the individual bays are checked/tested vis-a-vis the above mentioned aspects. This is followed by checking of interconnection of the bays. It is important to check that the switching and motor operating devices operate satisfactorily under the maximum and minimum specified limits of auxiliary and control voltage and operating system works satisfactory under minimum operating pressure.

The interlocks are placed in position as per the approved relevant drawings to examine the operation of the switching devices which is repeated 5 times.

Current transformers are checked by current impulses to check the correctness of the polarity and by buzzer for correct and intact wiring. This check has to be made immediately before mounting the current transformers.

Some purchasers, also check and measure the CT ratio and its magnetization characteristic. For this a special testing facility is required and, therefore, purchaser has to consult the supplier in advance. This test is done with CT in mounted position and the current is injected through earthing switches.

Continuity of grounding connections is very important for GIS. The grounding connections, therefore, have to be scrupulously checked for electrical continuity.

High voltage tests on the main circuits

This test is normally made after the switchgear has been fully erected and gas filled at the rated density and moisture content found within the specified limits and successful completion of all other site tests. The test method and the tested voltage need to be agreed upon between the purchaser and the supplier.

The purpose of A.C. HV test is to detect the presence of conducting particles within the switchgear and to detect, to some large extent, abnormal dielectric strength. A successful test in an assurance about the absence of potentially damaging conducting particles, contamination or floating components that may cause failure of the switchgear during service.

Type of test voltages :

Types of test voltages are :-

— AC voltage

— Oscillating lightning impulse

— Oscillating Switching Impulse

— DC voltage

Switching Impulse Voltage

Test with switching impulse voltages are useful to detect the presence of contaminations as well as abnormal field configurations. This involves simple test equipment but oscillating switching impulse voltage is not as sensitive as AC voltage test. Some manufacturers, based on their experience employ switching impulses with oscillating wave forms with a time crest in the range of **150 μs to 10 ms.**

Oscillating Lightning Impulse

Tests with lightning impulse voltages are especially effective for detection of sharp protrusions; However, due to risk of flashover, the amplitude of the wave form must be choosen in consultation with the manufacturer. Based on the recommendations of the manufacturers, oscillating impulse voltages with front time upto about 10 μs are suitable.

DC voltages

DC voltages affect the insulator dielectric strength; However, manufacturer have recommended DC voltage tests only in case where cone insulators also come under the testing zone during the testing of adjacent cables. Not more than one core insulator is included.

Based on the recommendations made by experts, following observations are to be noted.

— For lower voltages upto 400 kV, AC voltage may be preferred for field testing; In addition, in case complete bays have been transported and assembled on site, a partial discharge measurement may also be pursued. The second choice may be to use oscillating switching impulse voltage. For this, no partial discharge measurement has been suggested.

— For extra high voltage (EHV), an additional impulse testing may be considered as back up to a.c. testing. For EHV, Oscillating lightning impulse testing (10 μs) is generally preferable to PD measurement as it provides clear evidence of whether any minor defect is potentially dangerous or not.

— For voltages upto 420 kV, AC voltage test (80% of rated voltage peak for one minute) followed by PD-measurement has been largely recommended. Another method is to use 80 percent of rated switching impulse level with a peak of 150 μs.

No partial discharge measurement is required in such case.

For voltage of 800 kV, the preferable procedure is to use AC voltage testing and oscillating lightning impulse voltage.

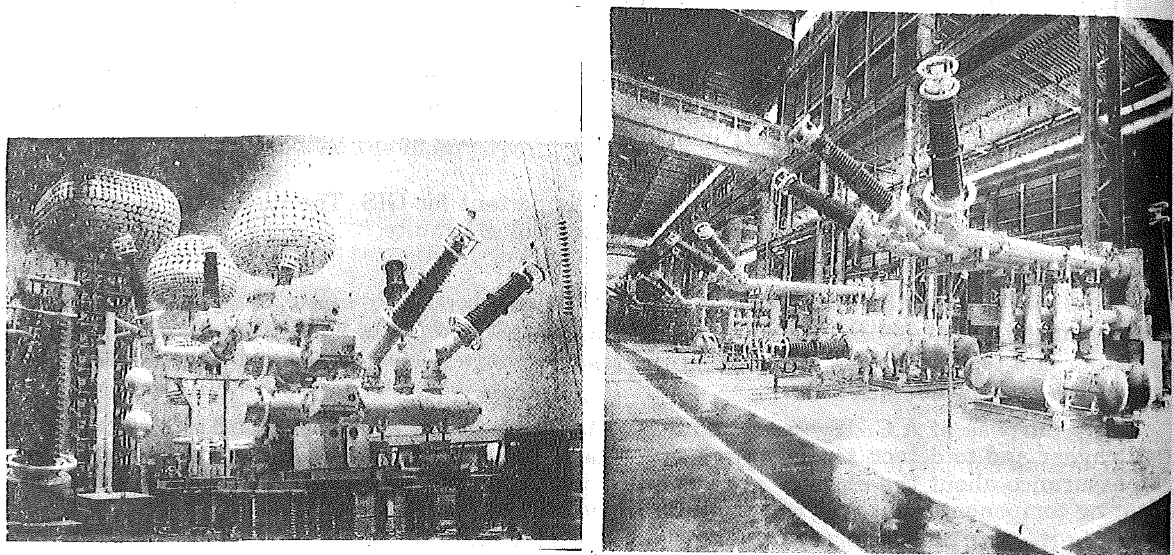


Fig. 7A.2. Factory testing process.

QUESTIONS

1. The function of SF_6 in GIS is

   (*a*) to act as dielectric medium (*b*) to act as arc quenching medium (*c*) to act as cooling medium (*d*) to act as Dielectric medium as well as arc quenching medium. (Ans. *d*)
2. What are the main difference between High speed and slow moving earthing switches in GIS ?
3. Name common type of interfuse required in GIS.
4. What is the function of partial Discharge monitoring (PDM) system in GIS ?
5. Name five field Acceptance Tests of GIS.

8

Minimum Oil Circuit-Breaker and Bulk Oil Circuit-Breaker

Bulk Oil or Tank type OCB—MOCB—Arc quenching in oil—Internal Source of Extinguishing Energy —Pre-arcing—Description of a 145 kV, MOCB—Modular Construction—Summary

8.1. INTRODUCTION

In minimum oil circuit-breakers, dielectric oil is used as an arc quenching medium and dielectric medium.

For voltages upto 12 kV, minimum oil circuit-breakers are generally enclosed in draw-out type metal-clad switchgear (Refer Ch. 15—Fig. 15.1 b).

For 36 kV, 72 kV and 145 kV ratings MOCB's are outdoor type, with one interrupter per pole and single opening mechanism for three poles (Refer Sec. 2.7).

For 245 kV and above, modular construction is necessary. In such a construction, the twin interrupter units are connected in series in T or Y formation.

Bulk oil circuit-breakers (tank type circuit-breakers) have become obsolete and have been described here in brief.

Minimum oil circuit-breakers have the following demerits:

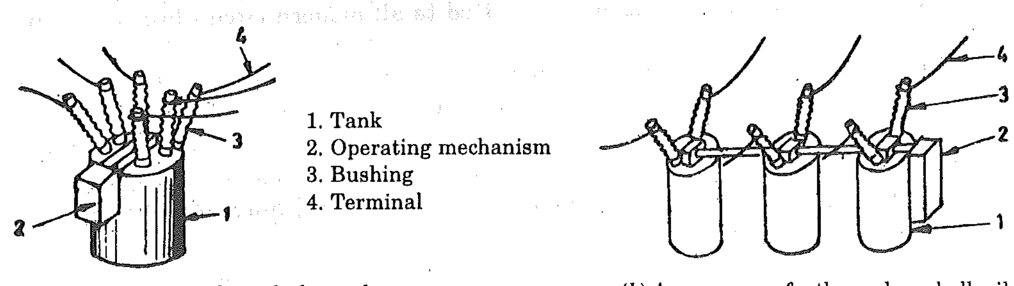
(1) Short Contact Life, (2) Frequent Maintenance (3) Possibility of Explosion. (4) Larger arcing time for small currents (5) Prone to restrikes.

They are being superseded by SF_6 circuit-breakers in all ranges.

8.2. TANK TYPE BULK OIL CIRCUIT-BREAKER (NOW OBSOLETE)

Oil circuit-breakers were widely used for rated upto 72.5 kV before 1960.

However the popularity of this breaker is decreasing and it is no more favoured in modern installation. The tank type circuit-breakers have 3 separate tanks for 72.5 kV and above. For 36 kV and below single tank construction is popular. In single tank construction phase barriers are provided between phases. This type of circuit-breaker is used for indoor metal-clad draw out type switchgear upto 12 kV (Fig. 15.1a). Above 12 kV, it is usually of outdoor type. Dielectric oil is used in circuit-breakers as an arc extinction medium as well as insulating medium. It is also called transformer oil.



(*a*) Appearance of a single tank three-phase bulk oil circuit breaker

(*b*) Appearance of a three phase bulk oil circuit breaker with three tanks.

Fig. 8.1. Bulk oil circuit-breaker.

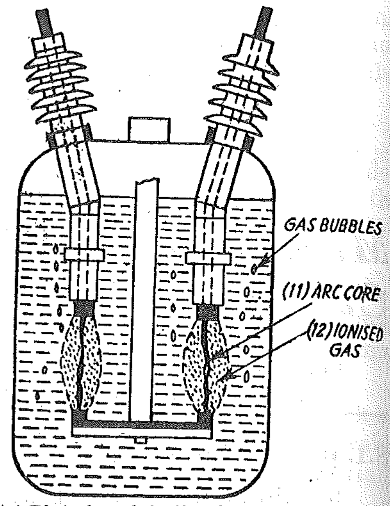
The contact separation takes place in steel tanks filled with oil. The gases formed due to the heat of the arc expand and set the turbulent flow in the oil.

To assist of arc extinction process, arc control devices are fitted to the contact assembly. These are semi-enclosed chamber of dielectric materials. The performance of oil circuit-breaker depends on the effectiveness of arc control devices.

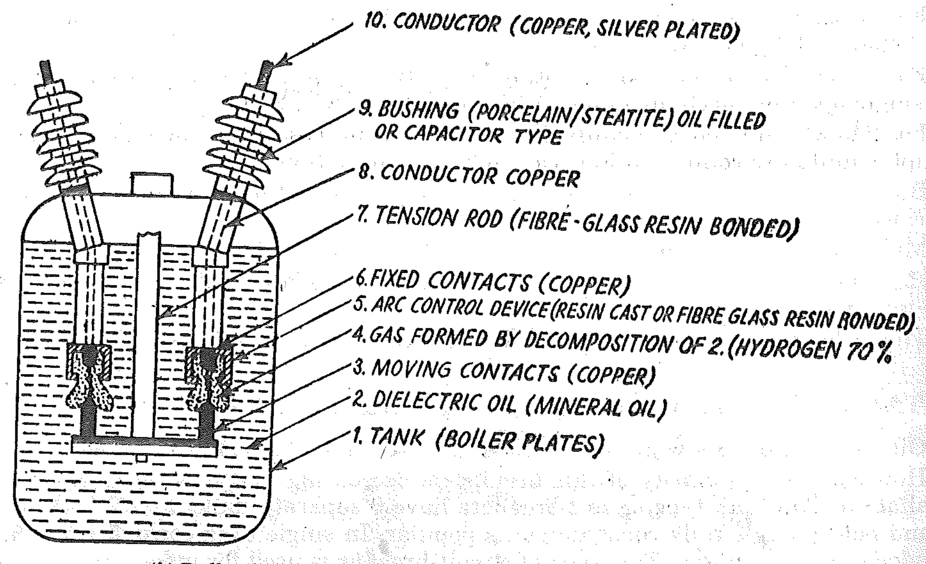
Fig. 8.2 illustrates the tank type will circuit-breaker, in open positions with the arc not yet extinguished.

The tension rod (7) is raised by operating mechanism (not shown in the figure) while closing the circuit-breaker. The opening and closing is obtained by lowering and raising the tension rod. As the contacts separate, and arc is drawn. This arc is extinguished by the oil and by the gases formed by the decomposition of oil.

The arc control devices (5) are normally connected to the fixed contact assembly, such that contact separation takes place inside this semi-enclosed devices. The gas produced in the device (4) produces high pressures in it. Thereby the arc extinction is quick. As the moving contacts leave the arc control devices, the trapped gas gets released from the arc control device, while doing so, the arc is extinguished by blast effect. Arc control devices are fitted to all modern circuit-breakers rated 3.6 kV and above.



(*a*) Plain break bulk oil circuit-breaker.



(*b*) Bulk oil circuit-breaker with arc control device.
Fig. 8.2. Explaining BOCB.

The construction and venting or arc-control devices is such that the gases flow *axially or radially* with respect to arc. The major disadvantages of tank type-circuit-breaker are :

1. Large quantity of oil is necessary in oil circuit-breakers through only a small quantity is necessary for arc extinction. The large quantity is necessary to provide insulation between the live parts and earthed steel tank. If the container is made of ceramic material, the size of container could be made small.

2. The entire oil in the tank is likely to get deteriorated duo to sludge formation in the proximity of arc. Then the entire oil needs replacement.

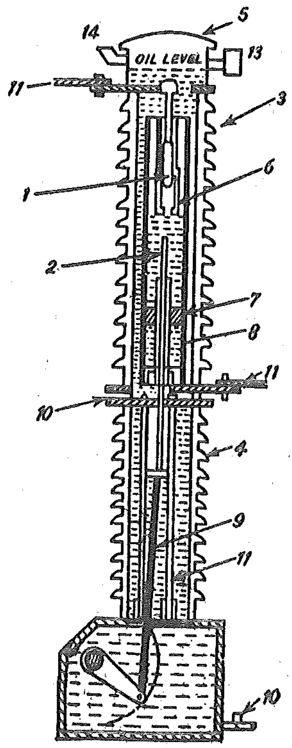
3. The tanks are too big, at 36 kV and above the tank type oil circuit-breaker loses its simplicity.

These causes led to the development of *Minimum oil circuit-breaker.* As the name itself signifies the minimum oil circuit-breaker requires less oil. The arc extinction medium is dielectric oil, the same as that used in tank type circuit-breaker. There is no steel tank but the arc extinction takes place in porcelain containers.

8.3. MINIMUM OIL CIRCUIT-BREAKER

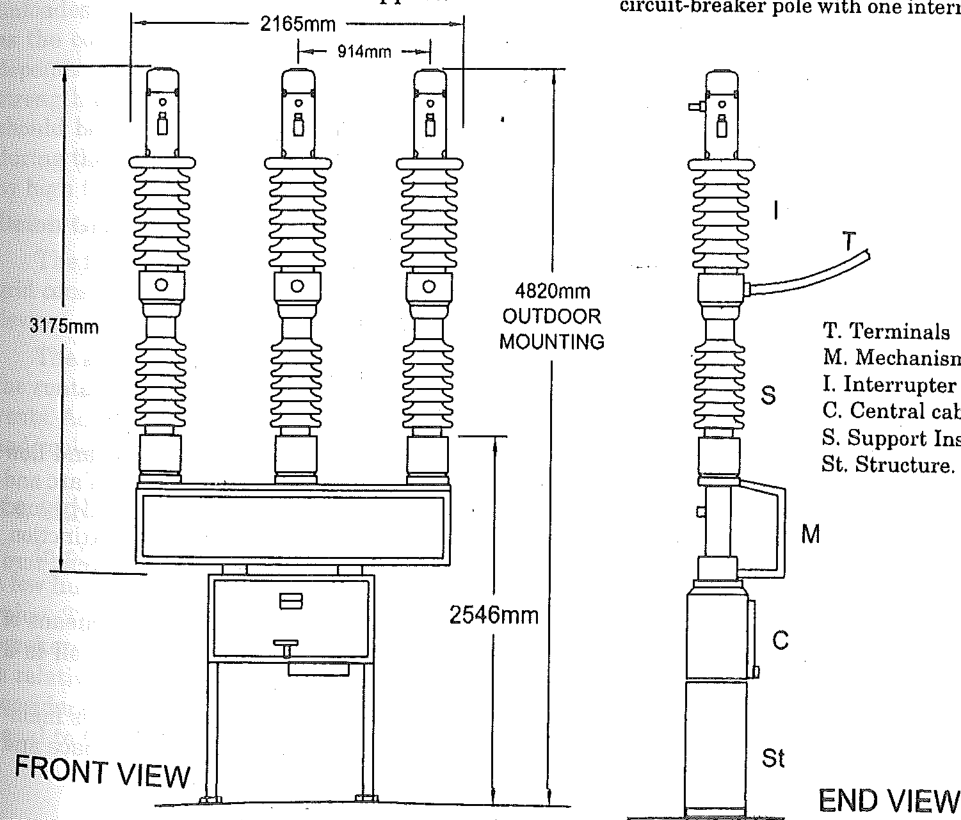
This type is also known as poor oil or small oil circuit-breaker. In minimum oil circuit-breakers the current interruption takes place inside 'interrupter'. The enclosure of the interrupter is made of insulating material like procelain. Hence the clearance between the live parts and the enclosure can be reduced and lesser quantity of oil require for internal insulation. One pole of a 3 pole outdoor minimum oil circuit-breaker is illustrated in Fig. 8.3.

There are two chambers (3) and (4) separated from each other, but both filled with oil. The upper chamber (3) is arc extinction chamber. The oil from this chamber does not mix with that in the lower chamber. Lower chamber acts like a dielectric support.



1. Fixed Contact
2. Moving Contact
3. Current Interruption Chamber
4. Supporting Chamber
5. Top Chamber
6. Arc Extinction Device
7. Lower Fixed Contact
8. Glass-Fibre Enclosure
9. Operating Rod
10. Drain valve
11. Terminals
12. Relief valve
13. Gas vent
14. Operating mechanism (not shown)

Fig. 8.3. Simplified diagram of an outdoor minimum oil circuit-breaker pole with one interrupter pole.



T. Terminals
M. Mechanism housing
I. Interrupter (one per phase)
C. Central cabinet
S. Support Insulator
St. Structure.

Fig. 8.4. A typical 145 kV out-door minimum oil circuit-breaker.

Arc extinction device (6) is fitted to the upper fixed contact. The lower fixed contact (7) is ring shaped. The moving contact (2) makes a sliding contact with the lower fixed contacts. A resin bounded glass-fibre cylinder (8) encloses the contact assembly. This cylinder (8) is also filled with oil. Porcelain cylinder (3) encloses the fibre-glass cylinder (8). Other provisions are similar to the bulk oil circuit-breaker.

The operating rod is operated by operating mechanism. The three poles operate simultaneously.

8.4. PRINCIPLE OF ARC-EXTINCTION ON OIL BREAKERS

As the current carrying contacts are separated under oil, the heat of the arc causes decomposition of the oil. The gases formed due to the decomposition expand, causing increase in pressure. The pressure built-up and the flow of gases is influenced by the design of arc-control device speed of contact travel, the energy liberated by the arc, etc. The gas flowing near the contact zone causing cooling and splitting of the arc. The contact space is filled with fresh dielectric oil after the final arc interruption at a current zero.

Arc control devices are fitted to the fixed contact of minimum oil circuit-breaker.

Arc control devices modify the behaviour of circuit-breakers. These are enclosures of dielectric material fitted to contacts of the circuit-breaker such that the actual contacts are separated inside the cavity of the device. At current zero of the wave, the arc diameter is very small and the gas

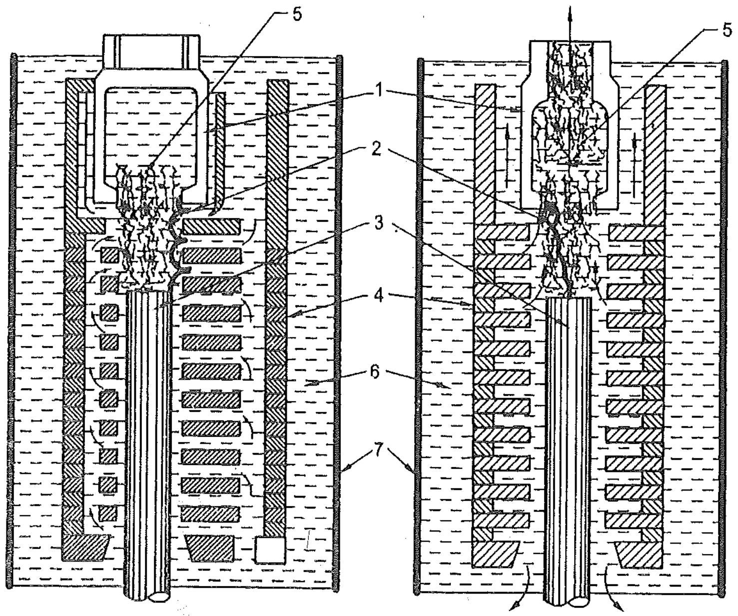
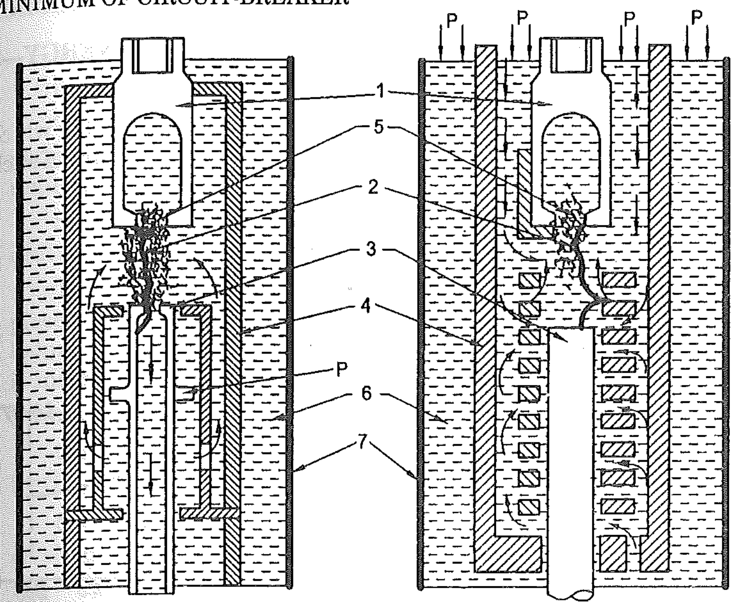


Fig. 8.5. (*a*) Techniques of arc Quenching in minimum oil circuit-breakers.

flow is able to interrupt the arc. The interruption of the arc stops the generation of gas and flow of oil. The contact space contains hot gases during the brief period after the interruption of arc and high rate of rise of TRV can cause a restrike. To avoid this the contact travel is extended well beyond the arc control devices so the fresh dielectric oil filled the contact space after the arc extinction. The techniques adopted to increase the rate of gain of dielectric strength after final current zero are :

— Flushing the contact space by fresh dielectric oil forced into the contact space by means of piston-action. A piston attached to the moving contact compresses the dielectric oil in a cylinder. The oil at a high pressure in the cylinder flows into the contact space.

— Maintaining the pressure on the oil in the interrupter. If the oil in the interrupter is maintained at higher pressure by means of an inert gas, the oil flow into the contact space and the hot gases travel upwards. Pressure reduces the size of gas bubbles.



1. Fixed constactor assembly.
2. Arc
3. Moving contact with Tungsten-Copper Tip
4. Fibre Reinforced Tube
5. Gases envolved by decomposition of oil
6. Dielectric oil
7. Outer Enclosure (Porecelain or Fibre reinforced Epoxy)

P — Piston
P — Pressure

Fig. 8.5. (*b*).

These techniques are used in minimum oil circuit-breakers to avoid restrikes during switching (Sec. 3.14.1).

8.5. PRE-ARCING PHENOMENON

The pre-arcing phenomenon is of significance in high voltage circuit-breakers used for closing unloaded transmission lines and capacitors. While closing a circuit-breaker, the arc is established as the contacts come near each other, before the final contact touch. The duration of pre-arcing depends upon the voltage across the interrupter, speed of travel while closing and the dielectric strength of the medium. The pre-arcing causes generation of heat and gases. The circuit-breakers should be capable of withstanding the temperature stresses and the internal pressures arising during the pre-arcing. While closing on the capacitor banks, the prearcing current is characterised by high frequency and the energy converted into heat during the pre-arcing is significant.

Deion Grid

The further development adopted for bulk oil circuit-breakers was that of deion grid. The deion grid consists of insulated iron discs of various shapes placed one above the other in the arc control device.

The shapes are such that narrow space is available for tear and there are side vents too. During the contact separation the magnetic material of discs gets magnetized and pulls the arc into the vents. Additional magnetic field is also provided separately. The arc is thus lengthened, constrained and cooled. Magnetic type Deion grids interrupter fault currents rapidly and efficiently.

8.6. SENSITIVITY TO TRV

In plain break circuit-breaker the posts zero resistance is generally fairly low (of the order of a few hundreds of ohm) so that the rate of rise of restriking voltage is damped down to a fairly low value. The inherent rate of rise of restriking voltage has little effect on behaviour of oil circuit-breakers. In oil circuit-breakers with arc control devices the post zero resistance of contact space is relatively high so that there is less damping effect. At low currents, the performance may be considerably improved by adopting *Resistance Switching*. The value of resistance is approximately equal to 0.5 $\sqrt{LC}$ ohms which is of the order of few hundred ohms.

8.7. CIRCUIT-BREAKERS WITH INTERNAL SOURCES OF EXTINGUISHING ENERGY—CRITICAL CURRENT (Refer Sec. 6.4)

In oil current-breaker the energy for arc extinction is provided by the short circuit itself, which decomposes oil and thereby pressure inside the tank is increased. The characteristic feature of such breakers is that the amount of extinguishing energy depend on the magnitude of current to be interrupted. For larger currents (upto a certain limit) the breaking time is less. For too small currents, the arc extinction is rapid because the arc simply breaks on its own; in oil. Between these limits, there is a range of small currents called "Critical Range" in which the breaking of currents is difficult and arc duration time is high. In this critical range of current the current is not in a position to build up enough pressure so as to cause rapid arc extinction. The characteristic of breaking current *vs.* arc duration in Fig. 8.6 explains the phenomenon. The range of critical current varies with the design of oil circuit-breaker (Refer Sec. 6.4)

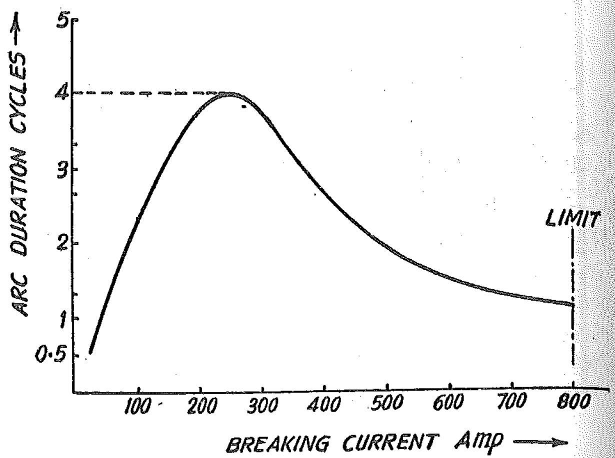


Fig. 8.6. Arc duration characteristic, an example (Refer Fig. 6.4).

The typical ranges of critical current are between 10 to 20% of rated short circuit-breaker current. Higher arcing time for smaller breaking current is a particular disadvantage of oil circuit-breaker.

8.8. CONTACT ASSEMBLY (Refer Sec. 2.18)

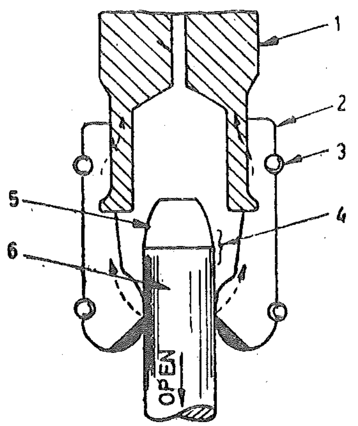
As this stage, we will discuss some aspects of contact design. The contact, design is influenced by the type of arc control device.

1. The main contacts should have low contact resistance.

2. Resistance being inversely proportional to the pressure. The contact pressure should be appropriate.

3. The contacts should be self-cleaning type, *i.e.* the layer of copper oxide should be cleaned by rubbing of contacts.

4. Contact area (true) should be well defined.



1. Contact support
2. Main contacts (Electrolytic-copper with tungsten copper tips)
3. Coiled spring (Phosphor-bronze)
4. Moving contact
5. Arcing tip of (4) brazed to (6) (Tungsten-copper)
6. Moving contact stem (Electrolytic copper)
   Arrow indicates current path.

Fig. 8.7. Typical finger contact assembly in oil circuit-breakers.

5. Springs used for contacts should have gradually rising characteristic *i.e.* they should be soft.

6. The contact tips should be replaceable without the need to replace the entire contact.

7. The contact should not provide what is called "Contact-Grip". In some contacts the electromagnetic forces grip the contacts and oppose the opening process. Hence the opening speed is reduced.

8. It is desirable to have separate main contacts and arcing contacts. The resistance of main contacts is low because of silver plating, the arcing contacts have longer life.

The moving contact is invariably a copper rod of cylindrical shape with specially tipped contact pieces. The fixed contacts fitted with arc control device, are normally in four or six pieces with spring behind them. These pieces are arranged symmetrically to form a central cavity. The moving contact is inserted in this cavity (Refer Fig. 8.7).

Summary

Oil circuit breakers were used for voltage upto 145 kV. This type of breaker has been replaced by SF_6 breakers.

Oil circuit-breakers use Dielectric oil (Transformer oil) for the purpose of arc extinction. In bulk-oil circuit breakers the arc-extinction takes place in a tank; whereas in minimum oil circuit-breakers the arc-extinction takes place in insulating housing enclosed in ceramic enclosures.

For MOCB, rated upto 145 kV single break designs prevail, for higher voltages multibreak designs were common.

Modular construction was adopted for minimum oil circuit-breakers of 245 kV and above. However SF_6 Circuit Breakers are now preferred for entire range of breakers.

9

Vacuum Interrupter and Vaccum Circuit-Breaker

Introduction—Historical review—Electrical Breakdown in High Vacuum—Arc Extinction in Vaccum—Construction of Vacuum Interrupter—Summary.

9.1. INTRODUCTION

When two current carrying contacts are sparated in a vacuum module, an arc is drawn between them. An intensely hot spot is created at the instant of contact separation from which metal vapour shoot off, constituting plasma. The amount of vapour in the plasma is proportional to the rate of vapour emission from the electrodes, hence to the arc current. With alternating current arc, the current decreases during a portion of wave, and tends to zero. Thereby the rate of vapour emission tends to zero and the amount of plasma tends to zero. Soon after natural current zero, the remaining metal vapour condenses and the dielectric strength builds up rapidly, and restriking of arc is prevented.

This principle is used in vacuum circuit-breakers.

The vacuum circuit-breaker comprises one or more sealed vacuum-interrupter units per pole. The moving contact in the interrupter is connected to insulating operating rod linked with the operating-mechanism. The contact travel is of the order of a few millimetres only. The movement of the contacts within the sealed interrupter unit is permitted by metal-bellows.

The range of vacuum switching devices includes :

— Vacuum interrupters rated 3.6/7.2/12/36 kV for indoor metalclad switchgear (Ch. 15).
— Vacuum interrupters rated 1.2/3.6/7.2 kV for indoor metal enclosed control gear (Ch. 15).
— Vacuum interrupters rated 3.6/7.2/36 kV for outdoor procelain housed, single interrupter per pole, circuit-breaker (Fig. 9.8).
— Multi-interrupter outdoor porcelain-housed circuit-breakers for 72.5 kV and above, (Now obsolete). For 72.5 kV and above vacuum Circuit breakers are not used for Voltages above 36 kV.

The structural configuration of the switchgear mentioned above is quite different, through the basic interrupter unit is based on same principle of operation.

For voltages upto 36 kV, vacuum circuit breakers employing is single interrupter unit have become extremely popular for metal-enclosed switchgear arc-furnace installations, auxiliary switchgear in generating stations and other industrial applications.

Single Phase 25 kV, 25 kA Vacuum Circuit-breaker having two interrupters per pole are used for railway track-side 25 kV Single Phase substations. Vacuum switching devices have several merits such as high speed of dielectric recovery after rapid and silent operations, suitability for repeated operations, simple operating mechanisms, freedom from explosion, flexibility design, long of life etc.

The unique merits of vacuum interrupters are small contact travel and less weight of moving parts. The vacuum interrupters have a very long life of the order of several thousand operations

on rated normal current. However for outdoor installations the external insulation requirements must be fulfilled and the advantages of high dielectric strength of vacuum cannot be fully utilised. Some recently developed 36 kV-GIS utilize SF_6 gas as an insulation and vacuum-interrupters for arc-interruption. Such GIS are commercially manufactured in India (1995). Vacuum Switchgear has been described in Sec. 15.5.

9.2. ELECTRICAL BREAKDOWN IN HIGH VACUUM

The pressures below about 10^{-5} mm of mercury are considered to be high vaccum. The charged particles from one electrode moving towards the other electrode at such a pressure are unlikely to cause collision with residual gas molecules. Hence ionization by collosion of particles with atoms and molecules is less in vacuum relative to that in gas.

Keeping a small gap (0.5 mm) between electrodes in vacuum if the voltage is gradually, increased at a certain voltages the gap breaks down and current increases suddenly, this phenomenon is called Vacuum Breakdown or Vacuum Spark.

Pressure remaining constant, the nature of the characteristic depends on the surface condition, material of electrodes.

Secondary emission takes place by bombardment of high energy on the surface of electrodes. Next, the electron emission takes place from the surface of the electrodes by virtue of intense heat. The current leaves the electrodes from a few spots. The current densities are high at these spots. The arc consists of a thin column of plasma. The core of the arc has high temperatures of the order of 6000°K to 15,000°K. At such temperatures the emission takes place from the surface of the electrodes, called Thermal Emission Summarising electron emission from the contact is the cause for arc formation in a vacuum switching device. The electron emission takes place in various ways such as Field Emission. Thermal Emission, Secondary Emission etc.

Table 9.1. Voltage Withstand values of 24 kV Vacuum Interrupters

Contact Gap mm	2	5	10
Power frequency withstand kV rms	40	80	100
Impulse withstand kV*	80	150	200

*Limit of impulse withstand by external flashover.

(*a*) **Conditioning of Electrodes**

If vacuum gap is continuously sparking over, the breakdown voltage increases and then reaches a value when the gap is conditional. Thereafter the spark-over voltage remains consistent.

(*b*) **Material of Contact and Surface Finish**

The creep of material, occluded gases in the material and the chamber create special problems in vacuum circuit breakers.

(*c*) **Dielectric Recovery after Sparking**

The vacuum gap regains its dielectric strength at a rate of about 20 $kV/\mu s$ after a spark over. The rate of recovery depends upon design features of the interrupter.

(*d*) **Effect of Contact Material**

The breakdown alternating voltages for the same vacuum pressure and the same contact gap vary with the contact materials.

(*f*) **Insulation strength**

The insulation strength of vacuum can be determined by applying the d.c. voltage till breakdown occurs. The insulation strength is given by the average of the highest voltage at which no spark occurs and the first value of voltage at which spark does occur. The insulation strength depends on the material of contact surface.

The dielectric strength of vacuum is relatively high and therefore, a small contact travel is usually enough to withstand the recovery voltage.

9.3. ARC EXTINCTION IN VACUUM INTERRUPTERS

The arc interruption process in vacuum interrupters is quite diferent from that in other types of circuit-breakers. The vacuum as such is a dielectric medium and arc cannot persist in ideal vacuum. However, the separation of current carrying contacts causes the vapour to be released from the contacts giving rise to plasma. Thus, as the contacts separate, the contact space is filled with vapour of positive ions liberated from the contact material. The vapour density depends on the current in the arc. During the decreasing mode of the current wave the rate of release of the vapour reduces and after the current zero, the medium regains the dielectric strength provided vapour density around contacts has substantially reduced.

While interrupting a current of the order of a few hundred amperes by separating flat contacts under high vacuum. The arc generally has several parallel paths, each arc-path originating and sinking in a hot spot of current. Thus the total current is divided in several parallel arcs. The parallel arcs repel each other so that the arc tends to spread over the contact surface. Such an arc is called diffused arc. The diffused arc can get interrupted easily.

At higher values of currents of the order of a few thousand amperes, the arc gets concentrated on a small region and becomes self-substained arc. The concentrated arc around a small area causes rapid vaporisation of the contact surface.

The transition from diffused arc to be concentrated arc depends upon the material and shape of contact the magnitude of current and the condition of electrodes. The interruption of arc is possible when the vapour density varies in phase with the current and the arc remains in the diffused state. The arc does not strike again if the metal vapour is quickly removed from the contact zone.

Thus the arc-extinction process in vacuum circuit-breaker is related to a great extent to the material and shape of the contacts and the technique adopted in condensing the metal vapour. The contact geometry is so designed that the root of the arc keeps on moving so that the temperature at one point on the contact does not reach a very high value.

The rapid building up of dielectric strength after final arc extinction is a unique advantage of vacuum circuit-breaker. They are ideally suitable for capacitor switching as they can give restrike free performance.

The vacuum circuit-breakers interrupt the small currents before natural current zero causing current chopping. However the chopping level depends on material of contact.

9.4. CONSTRUCTION OF A VACUUM INTERRUPTER

— 'Interrupter' is the sub-assembly a complete pole in which the arc interruption takes place.

There are two basic forms of vacuum interrupters.

— Interrupter suitable for a single unit per pole.

— Interrupter suitable for multi-unit per pole.

The interrupter is general consists of the following parts :

1. Enclosure (Ref. Fig. 9.3)

The enclosure is made of impermeable insulating material like glass. The enclosure must not be porous and should retain high vacuum of the order of 10^{-10} torr.

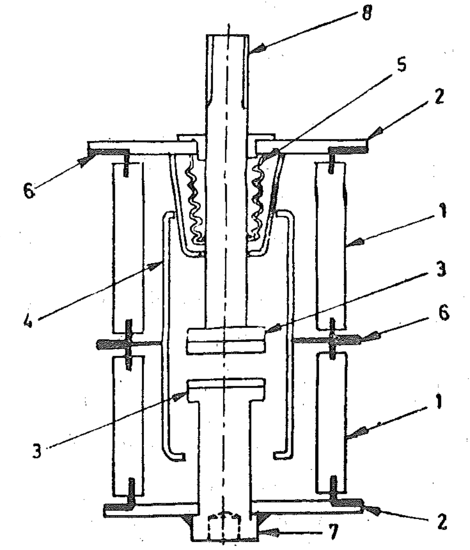
2. End Flanges

The two end-flanges are made of non-magnetic metal.

The end-flanges support the enclosure fixed contact, vapour condensing shields, bellows, and the protective-cover for the bellows :

3. Contacts

The contacts are made of large stem with large disc-shaped faces. The disc is provided with symmetrical groovers in such a way that the segments of the two contacts are not in the same line.



1. Enclosure Glass.
2. Eng Flanges. Non-magnetic metal.
3. Contacts.
4. Vapour condensing shield.
5. Metallic Bellows.
6. Seals.
7. Fixed contact stem.
8. Moving contact stem

Fig. 9.1. Cross-section of a typical 15 kV vacuum interrupter.

The magnetic field set-up by the components of currents with such a geometry causes the plasma of the arc to move rapidly over the contacts instead of remaining stable at one point. The concentration of the arc is thus prevented and the arc remain in diffused state. The sintered material used for contact tip is generally copper—chromium or bismuth alloy.

4. Vapour Condensing Shields

These metallic shields are supported on insulating housing such that they cover the contact region. The metal vapour released from the contact surface during arcing is condensed on these shields and is preveted from condensing on the insulating enclosure.

5. Metallic Bellows

One end of the bellows is welded to the metal-flange. The other end is welded to the moving contact. The bellows permit the sealed construction of the interrupter and yet permit movement of the contact. Stainless steel bellows are generally used in vacuum interrupters.

The bellows are covered by a protective shield.

6. Seals

The sealing techniques are similar to those used by electronic valve and power-tube manufacturers. These are like metal-glass, or metal ceramic seals.

In the swithgear installation, the interrupter is housed inside a sheet metal enclosure and the metal flanges are supported on porcelain or epoxy insulators. The moving contact is connected to the operating mechanism by means of a glass-fibre rod.

Vacuum interrupters are being increasingly used in metal-clad swithgear of voltage range 3.6 to 15 kV. The typical ratings of such vacuum interrupters are as follows :

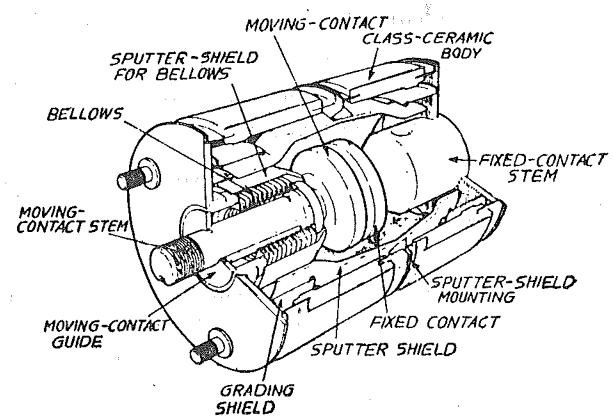


Fig. 9.2. Section of a vacuum interrupter.
[*Courtesy* : G.E.C. Switchgear Ltd. England]

Table 9.2 Typical Ratings of Vacuum Interrupters

Rated current (Amp)	*Rated breaking current (kA), rms*		
	at 7.5 kV	*12 kV*	*36 kV*
800—1600			
—2500	25	25	25
—3150	50	40	31.5

Vacuum switchgear includes vacuum iterrupters, operating mechanism, operating links enclosure etc. (Ref. Sec. 15.5).

9.5. ARC INTERRUPTION IN HIGH VACUUM

In vacuum interrupters, the arc extinction process is related with the following :

— Degree of Vacuum
— di/dt of Arc current
— dv/dt or TRV
— Plasma of the arc (liberated from contact surface)
— Im of Arc current
— Energy dissipated from the arc
— Peak of TRV

9.6. DEGREE OF VACUUM IN INTERRUPTERS

The vacuum level is expressed in Torr. (1 Torr is equivalent to a pressure represented by a barometric 'head' of 1 mm mercury). The breakdown voltage of certain contact gap varies with the absolute pressure in the vacuum interrupters as shown in Fig. 9.3. As the absolute pressure is reduced from 10^{-1} Torr, to 10^{-3} the dielectric strength (kV/mm) goes on increasing. Above 10° Torr, the characteristic in almost flat. And the dielectric strength in this region is above 12 kV peak/mm. In vacuum interrupters vacuum level of the order of 10^{-6} to 10^{-10} Torr is used. This is called high vacuum range. During the passage of time and after arc interruptions, the vacuum level goes on reducing. However it remains in the range of 10^{-5} Torr and 10^{-8} Torr. Vacuum in the range of 10^{-3} to 10^{-4} is sufficient for interruption and for withstanding impulse test voltage.

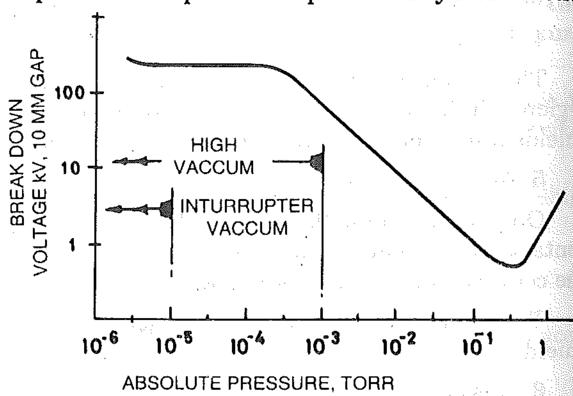


Fig. 9.3. Breakdown characteristic of a vacuum gap. (10 mm) for different vacuum levels.

9.6.1. Construction of a vacuum interrupter (Fig. 9.4)

(*Courtesy :* Siemens, West Germany)

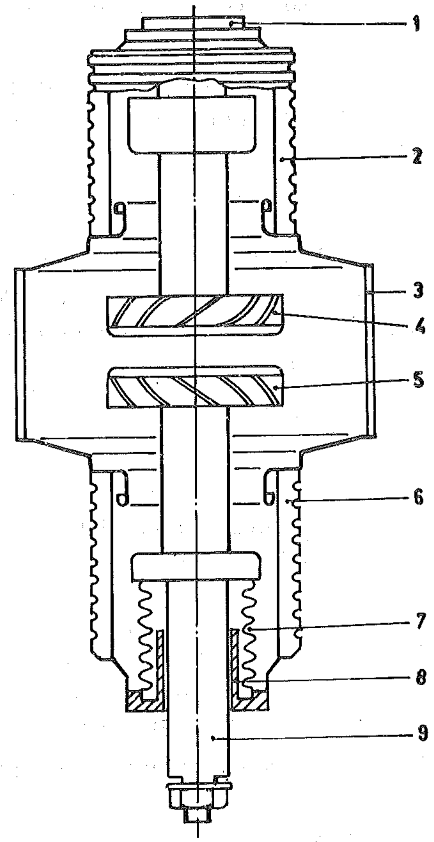
The basic design of vacuum interrupters for contactors and circuit-breakers is similar. The arcing chamber with the two stem-connected contact pieces is located between two ceramic insulators. The fixed contact piece is connected to the housing and the other (moving contact piece) is connected to the housing *via* vacuum tight metal bellow (7).

The arcing chamber (3) acts as a vapour shield. On opening a metal vapour arc is drawn between the contact pieces (4, 5) and is extinguished at current zero. The small amount of metal vapour that is not redistributed over the contact pieces condenses on the arcing chamber well. The protects the inside of the ceramic insulators against condensed metal vapour, which would reduce

the internal insulation. The metal bellow enables the moving contact stem to carry out its stroke. The stroke varies according to the rated voltage of the vacuum interrupter and is only 16 mm for 24 kV. A metal bellow must be able to withstand the movement corresponding to 30,000 make/break operations without falling. This is confirmed a long term no load tests. Fractures should not occur until after more than 200,000 such operations.

The insulators (2, 6) are made of *metallized aluminium oxide* ceramics, which permits them to be brazed to metal. There are no replaceable seals and the interrupter has a permanently sealed construction.

Vacuum tightness. All parts are either brazed or welded. Joints made in his way are not subject to ageing and the interrupter therefore remains vacuum tight throughout its working life.



One vacuum interrupter used for on pole. Refer Fig. 9.8 for end delevation of a vacuum Circuit-breaker indicating location of the Vacuum Interrupter
1. Terminal Plate
2. Insulator (Ceramic)
3. Arc Chamber (Metallic) (Condensing shield)
4. Fixed contact piece
5. Moving contact piece
6. Insulator (Ceramic)
7. Metal bellow
8. Moving contact Guide
9. Moving contact stem

Fig. 9.4. Cross-Sectional View of Vacuum Interrupter
Courtesy : Siemens, West Germany.

9.7. INTERRUPTION OF SHORT-CIRCUIT CURRENTS IN VACUUM INTERRUPTERS

There are two different interrupting ability limits of each vacuum interrupters.

1. **Ability to Interrupt of power frequency current (50 Hz).** This ability of vacuum interrupters is related with the contact shape, contact materials, vacuum level. Plain butt contacts are capable of interrupting power frequency currents up to about 6 kA rms. Above this value, *constricted arc* is formed and the arc is not quenched by plain butt contacts. To overcome this limitation, contact geometry is modified by providing curved grooves in the contact surface disc. Such contacts are called *spiral petal contacts, contrate (segmented) contacts.*

2. **Ultimate Interrupting ability (Commutating ability)**

This is related with ability to extinguish the last cathode spot in the arc root. Till the last arc root cathode spot is not extinguished, interruption cannot takes place in vacuum and the arc may continue to burn, cycle after cycle. The *ultimate interrupting ability* (commutating ability) is expressed in terms of

$$UIA = \frac{-di}{dt} \times \frac{dt}{dt}$$

where $\frac{di}{dt}$ = rate of reduction of current in arc (– ve)

$\frac{du}{dt}$ = rate of rise of TRV

UIA depends on contact material, contact shape, contact speed, degree of vacuum etc.

UIA also depend on di/dt, du/dt, I_m.

In various switching duties, severity of di/dt is different than severity of du/dt. Hence each switching duty is evaluated separately. The limit of vacuum interrupters is not due to du/dt but is due to di/dt for given du/dt.

Vacuum interrupters can withstand highest du/dt of the order of 10 kV/μs.

9.8. DESIGN ASPECTS OF VACUUM INTERRUPTERS

The complete vacuum switchtgear for voltages between 3.6 kV and 36 kV is in the form of the *Metal Enclosed Switchgear* (Ref. 15.4, 15.5, 15.19). *Vacuum Interrupters are* the 'hearts' of a vacuum switchgear. As a rule vacuum interrupters are single phase units. One vacuum interrupter is provided in each pole and the three poles with a common mechanism, linkages, frame etc. form one complete circuit-breaker unit.

9.8.1. Length of Interrupter

Ref. Fig. 9.7 cross section of a vacuum interrupter. The contact gap between fixed and moving contact (4, 5) is small (8 to 20 mm). Because of high dielectric strength of vacuum small contact travel is sufficient. The minimum length of contact gap is decided by required *impulse voltage withstand level* of the interrupter.

The length of the vacuum interrupter includes the length of the chamber and length of insultation. The total external creepage distance and clearance requirements in air (or in SF_6 gas) (Ref. Fig. 12.1 for an outdoor circuit-breaker). The definitions of creepage distance and clearances given in Sec. 12.7 apply equally to vacuum switchgear and vacuum interrupter.

The length of vacuum interrupter depends on minimum requirement of external clearance and creepage.

9.8.2. Contact Travel (Contact (Gap))

Because of high dielectrical strength of the medium, smaller contact gap is enough for withstanding TRV and impulse withstand test voltage. Typical value are :

	Minimum	In Practice
12 kV Interrupter	6—10 mm	8—20 mm
3.6 kV Contractor	2—3 mm	3—5 mm

The impulse withstand voltage requirements are considered while deciding the required contact gap.

9.8.3. Contact Shape

The dimensions and shape of the contacts are related both to the breaking current and to the normal full load current. The contact area depends on an acceptable power dissipation on full load current.

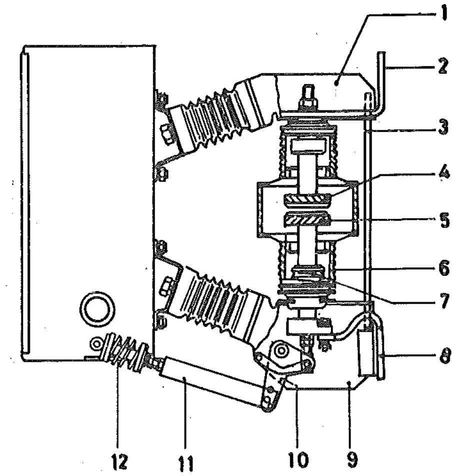
The limit of impulse voltage withstand level of vacuum interrupters is given by external flashover. *i.e.*, during the impulse test on a vacuum interrupter with open contacts flashover should occur externally.

On opening of the contact the current to be interrupted produces a metal vapour arc discharge and continues flowing through the plasma until the next current zero. The arc is extinguished and the conductive metal vapour condenses on the contact piece surfaces within a few microseconds. The dielectric strength of the break is thus reestablished very rapidly. The steady-state pressure in a vacuum interrupter is less than 10^{-9} bar. Contacts gap clearance of between 8 and 20 mm is adequate to give a high dielectric strength.

Contact size for normal Rated Current

Contact shape is selected for required and rated current. For rated current, the temperature rise should be within permissible limits. For this purpose contact stems should have sufficiently large diameter to dissipate the heat by conduction to the external heat sinks.

Because of the good thermal insulation of the vacuum medium between the contacts and the enclosure, all the heat at the contacts and in the contact stems must be removed by conduction along the stem. About 50% of the contact heat dissipation must be from each terminal of the interrupter, while maintaining the terminal below the specified temperature limits. Hence the heat sinks are provided at each terminal of the interrupter (Fig. 9.5).



1. Upper support and heat sink (copper)
2. Terminal of pole (Copper)
3. Insulator support rod
4. Fixed contact piece
5. Moving contact piece
6. Insulator
7. Metallic bellow
8. Lower terminal (copper)
9. Lower heat sink
10. Mechanism linkage
11. Glass fibre rod for the breaker pole
12. Opening spring

Fig. 9.5. Cross sectional view of a typical Vacuum Circuit-breaker (Side View)
Courtesy : Siemens (West Germany)

The temperature of contacts will be a few degree above that of the terminals, depending on the thermal resistivity of the contact stems, however the contacts are completely protected from oxidation due to surrounding high vacuum.

9.8.4. Contact size and shape for required short-circuit breaking current

The arc quenching in the vacuum interrupters depends on the contact shape and contact material. For higher rated currents the arc should be diffused. Arc should not be allowed to turn into a constricted arc. A *diffused arc* has several arc roots on contact surface. A constricted arc has a single arc root of a higher diameter and temperature (Ref. Sec. 9.3).

The diffused vacuum arc can be interrupted easily, due to the extremely short thermal lag (less than 1. μ.s) in metal vapour emission from cathode spots. If magnetic constriction of the diffuse arc into a constricted discharge occurs, large heated regions with very long thermal and vapour emission time constants (greater than 100 μ.s.) may be formed. Such large heated areas will cause emission of vapour persist beyond the current zero. This causes the arc to continue after current zero and thereby causing failure of the interrupter.

The formation of *constricted* arc is prevented special design of contact discs.

Plain butt contacts give diffused arc above the breaking currents of the order of 5 kA rms. Hence the use of plain butt contacts is limited to rated short-circuit breaking currents of 4 kA.

For short-circuit breaking currents above 4 kA, the butt contacts are in the form of either *spiral contacts* or *contrate contacts* (Fig. 9.6). *Both the design of depend for their operation on the interaction of the arc and a magnetic field to keep the arc in rapid motion, and maintain diffused arc.*

Small chopping current. Below a certain minimum current, the metal vapour arc is interrupted. Before a certain zero. *In inductive circuits, this chopping current must therefore be as small as possible to prevent the build-up unduly high voltage surges. It depends essentially on the material used contact. With optimized chromium copper contact material it is below 5 A.*

High breaking currents. At breaking currents of between 10 and 50 kA, its self-magnetic field causes the diffused arc root covering the entire contact piece surface. In order to avoid local overheating of the contact pieces the arc must not remain stationary. A radial (additional) magnetic field caused by slotting of the contact pieces produces a force which drives the arc round the arcing rings. This is the purpose of using 'petal contacts' or 'contrate contacts'.

Minimum contacts piece erosion. The metal vapour plasma of an arc drawn in vacuum is highly conductive. As the arc voltage is only between 20 and 200 V, energy conversion in the break is also minimal. The high conductivity in conjunction with the small energy conversion and short arcing times (below 15 ms for the last-poles-to-clear) are the reasons for the insignificant contact piece erosion and long electrical life of the vacuum interrupters.

Small contact resistance. In vaccum, the contact surfaces are free of impurities and pollution layers. Materials of high conductivity are used. Consequently the contact resistance between the two outer terminations of an interrupter is about 10 micro-ohms and the heat loss is correspondingly small.

The spiral contacts, petal contacts, contrate contacts etc. are patented names of the contact shapes developed by GE (USA) and AEI (UK) and other organisation during 1960-1980.

Spiral Petal Contacts (Fig. 9.6)

These type of contacts have been developed by GE (USA). The contact tips are of flat disc shape with spiral grooves, as shown in the figure.

For smaller arc currents the arc is diffused. Due to peculiar petals in the contact, the arc roots move towards the edges. The cathode spots tend to spread towards the edge of the contact disc instead of farming single constricted arc.

For higher arc currents, the arc roots tend to move from central zone to the edges due to blow out effect of petals. Because of spiral shape of grooves, the movement of arc roots has radial and circumferential components. Thereby the arc roots are blown out of the disc. This helps in diffusing the arc.

Segmented Contact (Contrate Contact)

This contact shape is shown in Fig. 9.6. The contact tips are of cupshape with inclined segments. Because of several segments the arc roots are formed and the arc is split up in several parallel paths. These arc paths repel each other and the arc roots are pushed away from the contact face.

Arc quenching makes heavy demands on the interrupter contact pieces, since they must be designed for

— high short-circuit breaking capacity
— small chopping current
— small contact resistance
— high dielectric strength
— minimal contact piece erosion

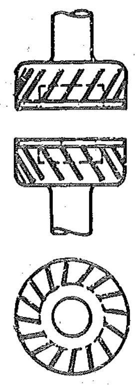


Fig. 9.6 (*a*) Contrate (segmented) contacts

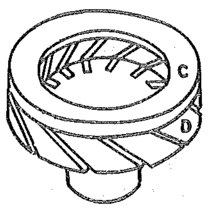


Fig. 9.6 (*b*) Contrate (segmented) contact

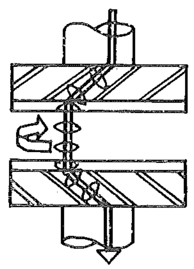


Fig. 9.6 (*c*) Spining of arc due to electromagnetic forces in contrate contacts

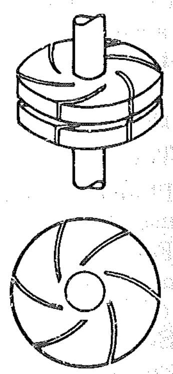


Fig. 9.6 (*d*) Petal contacts

These requirements have all been met to optimum effect, both technically and economically by basic research carried out in laboratories and development of suitable materials contact shapes and interrupter geometry, in conjunction with the most modern production methods.

This helps in diffusing the arc. Because of the cup shape of contact tip, the arc forms a ring instead of a cylinder. The contact tip material is especially selected such that the contact has low current chopping properties and non welding properties.

9.8.5. Contact Material

The contacts material for vacuum interrupters should have the following properties.

(1) High electrical conductivity.
(2) Low contact resistance
(3) High thermal conductivity
(4) Low current chopping level
(5) High arc withstand ability
(6) High melting point
(7) Low tendency to weld
(8) Easy to manufacture and economical

Some of these properties are of opposite nature. For example, low contact resistance and high arc withstand ability are rarely found in the same material. In other type of breakers, the main contacts and arcing contacts are of different materials. But in vacuum interrupters, the same contact face is used for main contact and arcing contact.

Several materials have been tried by different manufacturers. The following three materials are commonly used for vacuum interrupters :

(1) Copper-Bismuth Alloy
(2) Copper-Chromium Alloy
(3) Copper-Berrylium Alloy

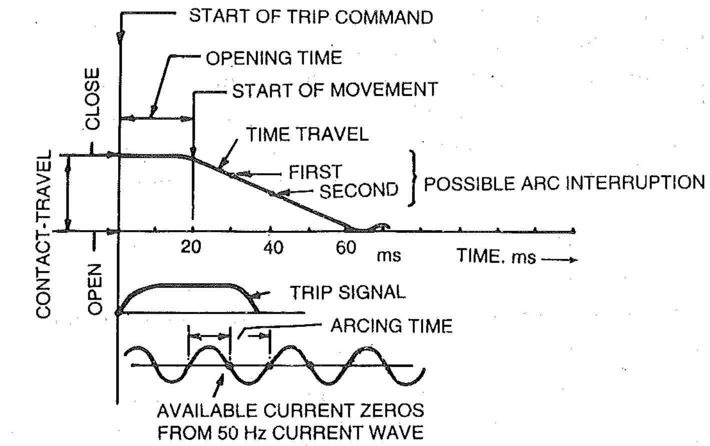


Fig. 9.7. Time-travel characteristic of moving contact of VCB. for Opening Stroke. Number of current zeros available.

9.9. Time/Travel Characteristics

The vacuum interrupters are designed for giving several thousand laod operations.

Typical values of contact travel characteristics for vacuum interrupters are given in Table 9.2.

Table 9.2. Reference Values of Contact Travel Characteristics of 12 kV Vacuum Interrupter

Contact Gap	8 to 12 mm
Contact Speed :	
—Opening	0.5 to 0.8 mm/ms
—Closing	0.5 to mm/ms

The time/travel characteristic during opening stroke is selected for a particular interrupter by considering :

— Total number of current zeros of 50 cycles wave form, required during the active opening stroke (Ref. Fig. 9.11).

The slope of the contact travel characteristic gives the contact speed. For higher contact speed, the slope is higher. The contact reaches final open position earlier.

Opening Speed

Assuming total travel 10 mm, assuming 50% contact travel for half cycle period (10 ms), the average opening speed will be 5/10 = 0.5 mm/ms.

Assuming 70% contact travel for half cycle period (10 ms), and half cycle period, average opening speed will be 7/10 = 0.7 mm/ms.

The choice of opening speed is based on the following conditions :

(1) The arcing time should be reasonably short. The maximum arcing time should not be greater than about half cycle of 50 Hz wave.

(2) Vacuum interrupter should be restrike free for capacitance switching. If current zero occurs near the instant of contact separation the electric strength of the interrupter in the open position is sufficiently great after half a cycle of the power frequency wave *i.e.* contact should travel fully in 10 ms to its open position.

Generally some 50-70% of full travel normally be attained in 10 ms.

Closing speed

Contact speeds in closing must fulfill two opposite conditions. Low speeds reduce mechanical stresses and shocks. A low speed of closing also reduces the mechanical stresses of the bellows and increases bellows life. A low impact velocity reduces the problems of contact bounce during closing.

On the other hand a higher speed of closing reduces the duration of prearcing and thus the amount of contact wear, the tendency to weld, and possible generation of voltage escallation due to sparking during the prearcing period. Typical speed at contact touch are 0.5 mm/ms.

9.10. CONTACT PRESSURE

Due to butt contacts high electromagnetic repulsive forces are established at the instant of prearcing period and contact will have to close against such repulsive forces. These forces are proportional to I_m^2 where I_m is peak making current.

The contact pressure in a vacuum interrupter must be sufficient (1) to give low contact resistance (2) to close effectively on to fault current and (3) to remain closed during the passage of fault current (4) it should satisfactory normal current carrying capacity.

9.11. CONTACT ACCELERATION DURING OPENING

The vacuum interrupter contacts weld to a very slight degree, and the suitable contact material having low welding tendency is selected for contact tips. The moving contact is accelerated with impact force to break the small welds.

A typical arrangement for opening the contacts of vacuum interrupters is to arrange the mechanism to accelerate as mass (which should be larger than moving contact mass) to a velocity more than of the opening velocity required. The mass then pulls off the contact, the severity of the pull being controlled by the coupling between 'hammer' and contact. This coupling sometimes has elastic material.

9.12. CONTACT EROSION

Contact erosion is caused by arcing. Erosion rate is expressed in terms of grams/coulomb is not a constant but increases with increasing current. The interrupters interrupt their full short-circuit current some hundreds of times, and can give many thousands of operations on normal full load current.

Material is lost from the contacts in three ways: (1) melting globules (2) metal vapour evaporated from the cathode spots (3) liquid droplets thrown out of a molten metal film on the surface of the electrodes at high currents—these droplets are usually ejected by the electromagnetic forces caused by the interaction of the arc current and its own magnetic field.

Bellows

Bellows used in Vacuum Interrupters are of stainless steel. The stainless steel plate of desired composition is either rolled or hydraulically formed to get the convolutes of the bellow. Alternatively rings cut from stainless steel plates are arranged in V formation and the edges are welded-Bellow permits movement of moving contact without loss of Vacuum.

9.13. VACUUM LEVEL AND SHELF LIFE OF INTERRUPTERS

Vacuum pressure in interrupters is in the range $10^{-5} - 10^{-9}$ torr, variation occurs during the life of an interrupter. Vacuum of the order of 10^{-3} torr is sufficient for interruption.

The shelf life of vacuum interrupters is minimum 20 years and possibly much longer. When interrupters are operated the metal vapour film is deposited on the shield and contacts.

Vacuum testing may be done on sub-assemblies during manufacture by normal mass spectrometer methods or the complete interrupter may be vacuum checked during or after evacuating.

A standard procedure used by manufacture is to measure the pressure after the interrupter is sealed at intervals of about one month. The pressure can be measured using the axial magnetic field and radial electric field. The current that flow between contact and main shields gives a measure of pressure within the interrupter.

9.14. CHECKING OF VACUUM

Simple method for checking vacuum in the interrupter at site is to check the force required for pulling the moving contact. If vacuum is higher, higher force is required to pull the contact. Simple spring balance may be used to measure the pulling force. Another method is to supply power frequency test voltage to terminals of open vacuum interrupter.

Following test voltages are recommended :

— 12 kV interrupter : 15 kV to 50 kV rms.

— 36 kV interrupter 45 kV to 90 kV rms.

If vacuum is lost, the open interrupter will flashover internally on application of the test voltage.

9.15. RANGE OF VACUUM SWITCHGEAR, VACUUM CONTROLGEAR AND VACUUM CIRCUIT-BREAKERS

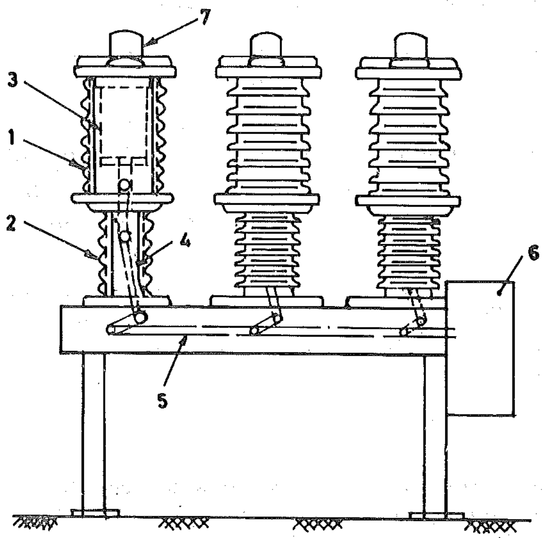
In the introduction (Sec. 9.1), the range of vacuum switching devices was mentioned. Vacuum switching device may be one of the following six types :

1. Vacuum Contactor : This is capable of several million operations on load and overload. The short-circuit interruption capability is limited. Back-up HRC fuse gives the short-circuit protection. Vacuum contactors are used in Vacuum Controlgear in the voltage range of 1.2 kV/3.6 kV/7.2 kV. It is not economical for LV controlgear in which simple air-break contactors are preferred. Vacuum controlgear uses vacuum contactors as the main switching device for normal load switching and overload switching. It may have a limited short-circuit breaking and full short-circuit making capability (Ref. Sec. 15.47 for further details).

2. Vacuum Circuit-breakers for medium voltage metal clad switchgear or metal enclosed switchgear. This type of switchgear is used mainly in industrial applications and distribution applications in the range 3.6 kV/7.2 kV/12 kV/36 kV. The vacuum circuit-breaker is the main switching device in the indoor metal-enclosed switchgear. The complete VCB has a three phase subassembly having one common mechanism housing, linkages, and three vacuum interrupters mounted on the frame by means of epoxy-resin support insulators.

3. Outdoor Vacuum, Circuit-breakers in the Kiosks. The complete vacuum circuit-breaker unit may be installed in a outdoor Kiosk. The kiosk (outdoor sheet-metal room with inclined roof)

1. Enclosure-Porcelain
2. Support procelain
3. Vacuum interrupter
4. Insulating rod
5. Linkages
6. Mechanism housing
7. Interrupter Support



1. Enclosure
2. Support procelain
3. Interrupters
4. Insulating rod
5. linkages
7. Support

Fig. 9.8. Front View of a 36 kV Porcelain-Enclosed 3 Ph. Vacuum Circuit-breaker.

Complete kiosk incorporates the vacuum circuit-breaker, kiosk, bushings, busbars, CTs, VTs, some measuring instruments. The Kiosk may be installed outdoor. Vacuum Kiosks are generally preferred for outdoor switchyard rated 12 kV and 36 kV.

They are also preferred for 25 kV track-side substations for 1-phase traction system.

4. Outdoor Procelain-housed Vacuum circuit-breakers.

Here the circuit-breaker is a three phase self-contained device having a support-structure mechanism, three poles linkages. The vacuum interrupter is housed in the upper procelain housing (Ref. Fig. 9.8). Such a circuit-breaker is preferred for 12 kV, 36 kV outdoor switchyards.

5. Single phase Roof-top Railway Circuit-breaker.

Earlier, air-blast circuit-breakers were used for such an application. Now vacuum circuit-breakers are preferred. The CB is single phase unit of low weight. It is installed on the roof of railway carriage.

6. EHV Vacuum Circuit-breakers with multiple-interrupters per pole.

Such circuit-breakers have been successfully developed and installed.

Vaccum circuit-breaker needs several interrupters connected per pole. Whereas SF_6 circuit-breakers requires only one or two interrupters per pole SF_6 circuit-breakers are less costly and have superior performance. Hence for EHV range VCB has not succeeded commercially.

9.16. MERITS OF VCBs

1. VCB is self contained does not need filling of gas or oil. They do not need auxiliary air system, oil handling system etc. No need of periodic refilling.

2. No emission of gases, Pollution free.

3. Modest maintenance of the breaker, no maintenance of interrupters. Hence economical over long period.

4. Breaker forms a unit which can be installed at any required orientation. Breaker unit is compact and self contained.

5. Non explosive.

6. Silent operation

7. Large number of operations on load: or short circuit. Suitable for repeated operating duty. Long life.

8. Suitable for capacitor switching, cable switching, industrial load switching.

9. **Constant dielectric.** There are no gas decomposition products in vacuum and the hermetically sealed vacuum interrupter keeps out all environmental effects.

10. **Constant contact resistance.** In vacuum the contacts cannot oxidize, a ract which ensures that their very small resistance is maintained throughout their life.

11. **High total current switched.** Since contact piece erosion is small, rated normal current can be interrupted up to 30,000 times and rated short-circuit breaking current on average a hundred times.

These reasons together with the economic advantages offered-have boosted acceptance of the vacuum circuit-breakers.

9.17. DEMERITS

1. The vacuum interrupter is more expensive than the interrupting devices in other types of circuit-breakers and its cost is affected by production volume. It is uneconomical to manufacture vacuum interrupters in small quantities.

2. Rated voltage of single interrupter is limited to about $36/\sqrt{3} = 20$ kV. Above 36 kV, two interrupters are required to be connected in series. This makes the breaker uneconomical for rated voltage about 36 kV.

3. Vacuum interrupters require high technology for production.

4. In the event of loss of vacuum due to transit damage or failure, the entire interrupter is rendered useless. It cannot be repaired at site.

5. For interruption of low magnetising currents in certain range, additional surge suppressors are required in parallel with each phase of a VCB.

9.18. SWITCHING PHENOMENA WITH VCB

The application details about Electrical switching phenomena associated with medium voltage vacuum circuit breakers is given in Sec. 15.22 to 15.26.

9.18.1. Reignition in Vacuum Circuit-breakers

As the contacts open, a small contact travel may interrupt the arc if the wave is passing through early period after current zero (Fig. 9.9). In such event, full TRV appears across small contact gap. The small gap (fraction of mm) cannot withstand high TRV and the arc reignites. The reignition causes high frequency oscillation in LC circuit. Such oscillations have several current zeroes with a period of few microseconds. But the cannot gap is increasing in the meanwhile. After a few mm

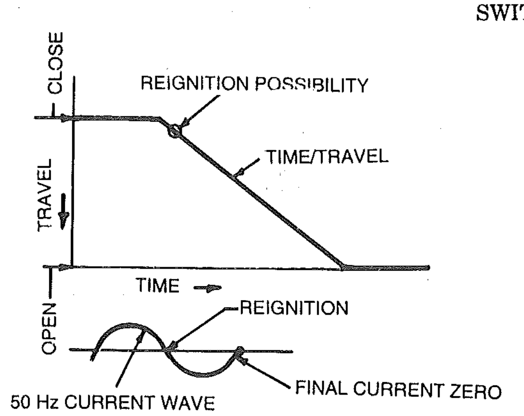


Fig. 9.9. Time-travel characteristic of Vacuum circuit-breaker contact during opening stroke, indicating reignition possibility in current wave.

gap, the reignition of high frequency wave stops and arc is quenched. Multiple reignition lasts for a period of few microseconds. Such multiple reignition may give undesirable transient overvoltages of high frequency. This problem is overcome in vacuum interrupters by selecting suitable contact material. Instead of using tungsten-copper, other materials like copper bismuth alloy, copper chromium alloy are used.

9.18.2. Capabilities of Modern Circuit breakers for Medium Voltages

— Short circuit current interruption. Upto 50 kA at 12 kV with 15 ms arcing time

— Operating duty 0—0.3 Sec—CO—1.5 Sec—CO

— Capacitive current breaking : 1000 A at 36 kV

— Parallel bank switching Inrush currents 40 kA peak, 1250 A/μs

— Repeated load switching 30,000 Switching operations on full load.

9.18.3. Switching Over-voltage Problem with VCB for Motor Switching Duty, RC Surge suppressors

While using vacuum Circuit-breakers for motor switching, over-voltages can be generated due to (*a*) Current Chopping (*b*) Multiple Reignition. Suitable RC Surge suppressors should be incorporated with vacuum switchgear to limit switching over voltages.

Current Chopping occurs at low value of current (0.1 to 20 ampere) as the vacuum gap chops the current (Ref. Sec. 3.12). Each vacuum interrupter has certain chopping level (say, 5 A).

Multiple Reignition occurs when the contact gap is too small while opening a low power factor load such as magnetising currents of transformers and also while switching off locked- rotor motors connected through long cables. The gap quenches the arc but is too small to withstand the TRV, hence breaks down again. The gap again recovers and re-ignites again. Such repeated multiple reignition gives rise to over-voltages which are harmful to the insulation of motors and transformers.

RC Surge Suppressors comprising resistance of 100 ohms and series capacitance of 0.1 μF are connected across phase and earth for each phase on load side of vacuum interrupter. The combination is called RC Surge Suppressor. This is provided with vacuum switchgear to limit switching over-voltages during low inductive current switching (Ref. Sec. 18.12). R.C. Surge Suppressor reduce the rate of rise and peak of Switching overvoltage.

Summary

Vacuum interrupters are sealed units comprising a pair of fixed and moving contact, metallic bellows, vapour condensing shield, insulating enclosure etc. Vacuum interrupters are compact and give very long operational life without any maintenance. They are popular for ratings upto 36 kV, 25 kA and are being widely used for indoor metal-clad switchgear, trackside sub-station etc.

Surge suppressors comprising non-linear resistors or resistance capacitor combination are connected on load side of vacuum circuit-breakers for limiting switching over-voltage. These are necessary for low-power factor load switching.

QUESTIONS

1. Describe the behaviour of electric arc in high vacuum.
2. Describe the construction of a vacuum interrupter and vacuum circuit-breaker.
3. State the merits of vacuum interrupter and discuss the problems involved.
4. What are the possible applications of vacuum interrupters ?
5. Explain the process of arc extinction in high vacuum.
6. With the help of neat sketches, explain the construction of a vacuum interrupter.
7. Explain current chopping in VCB. Explain the function of RC surge suppressors used with vacuum switchgear for motor switching.

10

Testing of High Voltage A.C. Circuit-Breaker

Classification—Type tests/Routine test/Development test/Reliability test—Mechanical Tests—Temperature rise Tests—Dielectric Tests—Short time Current Tests—Basic Short-Circuit. Test Duties—Routine Tests—Special Tests—on EHV Circuit-breakers—Commissioning Tests—Summary

10.1. CLASSIFICATION OF THE TEST

The tests on high-voltage a.c. circuit-breakers can be classified as follows :

Development Tests

These are carried out on components, sub-assemblies and complete circuit-breaker during and after the development of the circuit-breaker. The designers and research scientist verify the effect of various parameters on the behaviour of circuit-breakers, by conducting development tests. Development tests are not specified in the standards.

Type Tests (Ref. Sec. 3.19)

These are conducted on first few prototype circuit-breakers of each type to prove the capabilities and to confirm the rated characteristics of the circuit-breaker of that design. Type tests are not conducted on every circuit-breaker. The tests are conducted in specially built testing laboratories. Type tests are performed as per recommendations of standards (IEC) or (IS).

Routine Tests

Routine tests are also performed as per the recommendations of the standards (IEC/IS).

Routine tests are conducted on each circuit-breaker. These are performed in the manufacturer's premises. Routine tests confirm the proper functioning of the circuit-breaker.

Reliability Tests

Type tests and Routine tests are conducted on new-circuits breakers under larboratory conditions. The performance of circuit breakers installed at site is affected by additional stresses such as variation in ambient temperature variations dust, humidity repeated operations, maintenance schedules etc.

Reliability tests are conducted to verify the reliability of the circuit-breakers under various stresses occurring in actual applications. Reliability tests can be conducted in specially built laboratories and also at site.

Commissioning Tests

These are conducted on the circuit-breaker after installation at site to verify the operational readiness and proper functioning.

The tests on low-voltage a.c. circuit-breakers are in Sec. 15.7.

Table 10.1

Summary of Type Tests on High Voltage A.C. Circuit-Breakers

	Test	*Remarks*	*Ref. Sec*
1.	No load mechanical operation test	No load operations to verify speed of travel, opening time, closing time. Carried out at 85% and 110% rated voltage of shunt trip release.	10.2.5
2.	Mechanical performance tests (Endurance tests)	1000 close-open operations.	10.2.1
3.	Temperature rise test.	Steady temperature of conducting parts and insulating parts measured for rated continuous alternating current.	10.2.2
4.	Dielectric test—1.2/50 μs lightning impulse withstand—1 mm power frequency voltage withstand Dry and Wet.	Five consecutive shots of positive and then negative polarity. One minute p.f. withstand	12.6
5.	Short-time current test.	Rated short-circuit current passed through closed breaker for 1 sec or 3 sec.	11.6
6.	Short-circuit breaking and making, Basic. Short circuit test duties.	At 10%, 30%, 60% and 100% rated short circuit breaking current with specified operating sequence, and specified TRV.	11.7
7.	Line charging current breaking tests.	Applicable for circuit breakers rated 72.5 kV. and above to be used for over head lines.	11.10
8.	Cable charging current breaking tests.	Applicable to circuit-breaker intended for long cable network.	11.13
9.	Single capacitor-Bank Breaking Tests.	Applicable or circuit-breaker to be used for capacitor switching.	11.12
10.	Small inductive current breaking tests. Reactor Switching.	Applicable for circuit-breaker with shunt reactors, transformers, reactors, motors.	13.1 11.14
11.	Out-of-phase switching.	Applicable to circuit breakers which may connect two parts made out-of-phase conditions.	11.11
12.	Short-line Fault test.	Applicable to circuit-breakers rated above 52 kV and for overhead lines. These are in addition to basic short-circuit test duties.	11.9

10.2. TYPE TESTS

Type tests are the tests of one circuit-breaker on a first few circuit-breakers of each type made to the same specifications and having same essential details and would pass the identical tests. Type tests are conducted for the purpose of proving the rated characteristics of circuit-breakers. (Ref. Sec. 3.19)

Type test can be broadly classified in the following groups :

(*a*) Mechanical tests*

(*b*) Tests of temperature rise, millivolt drop test.*

(*c*) High voltage test (Dielectric tests).*

(*d*) Basic short circuit test duties.*

— Making test.

— Breaking tests.

— Operating sequence tests at 10%, 30%, 60%, 100% of rated breaking current with specified TRV conditions.

(*e*) Critical current tests.

(*f*) Single phase short-circuit test.*

(*g*) Short time current test.

* These are essential for certification of a.c. circuit breakers rated 145 kV and above in all cases.

In addition to these the following tests are recommended on circuit-breakers to be used in specific applications.

(*h*) Short line fault tests*
(*i*) Out-of-phase switching tests.
(*j*) Line-charging current-switching test.*
(*k*) Cable-charging current switching tests.
(*l*) Capacitive current switching tests.
(*m*) Small inductive current breaking tests.
(*n*) Reactor current switching tests.

Type tests are conducted on new circuit-breaker. Before conducting the type tests, sufficient information should be furnished to the testing authorities for identifying the circuit-breaker.

This information includes : assigned ratings, design principle drawings, reference standards, rated operating pressure/voltage of auxiliaries, support-structure etc. These details are included in the type tests report. After certifying the circuit-breaker by conducing type-tests, there should be no change in the design.

10.2.1. Mechanical Test (Endurance Tests)

The breaker should be in a position to open and close satisfactorily. In mechanical tests, the circuit-breaker is opened and closed several times (1000). Some operations (50) are by energizing the relay, remaining are by closing the trip circuit by other means. Mechanical tests on high voltage a.c. circuit breakers are conducted without current and voltage in the main circuit. Out of the 1000 operations, about 100 operations are mady by connecting the main circuit (contacts) in series with trip circuit.

No adjustment or replacement of parts is permitted during the mechanical tests. However, lubrication is permitted as per manufacturers instructions.

After the tests, the contacts, linkages and all the other parts should be in good condition and should not show any permanent deformation or distortion. The dimensions should be within original limits. During repeated operations of the circuit- breaker, the weaker parts in the assembly may fail. The circuit-breaker is then considered to have failed in the mechanical test. The tests are then to be repeated after improvement in the design and manufacture. Successful performance in Mechanical Endurance tests prove the adequacy of design and also good quality of materials and manufacture.

Though 1000 close-open cycles are specified in the standards, the manufacturer may conduct 10,000 or more operations to ascertain the reliability and for getting design data.

10.2.2. Temperature-Rise Tests

These are type tests to assign the normal current rating to the circuit-breaker (Ref. Sec. 31.9.4). Similar tests are conducted on other switchgear equipment such as isolators, bus-bars.

Alternating current of rated value and rated frequency is passed through a closed circuit-breaker, continuously till a steady temperature is attained. Readings of temperature of various conducting, insulating and structural parts are taken at an interval of one or half-an hour. When the steady temperature is reached, the maximum temperature rise of each part should be less than the permissible limit (Ref. Table 3.4). When a circuit-breaker in closed condition carries normal current the heat is generated in current-carrying parts due to $I^2 Rt$ loss. This heat is dissipated by conduction, convection and radiation. To maintain the temperature rise within specified limits, the $I^2 Rt$ losses should be reduced by increasing conductor cross-section using suitable low resistivity material, improving convection, conduction and radiation of heat.

The test set-up is illustrated in Fig 10.1. The current is obtained from special transformer which gives required continuous current at a low voltage (5 to 15 V a.c.) current is adjusted by regulation on primary voltage (240 or 440 V). The tests are either single phase or three phase. Single phase tests are permissible for outdoor circuit-breakers.

* These are essential for certification of a.c. circuit breakers rated 145 kV and above in all cases.

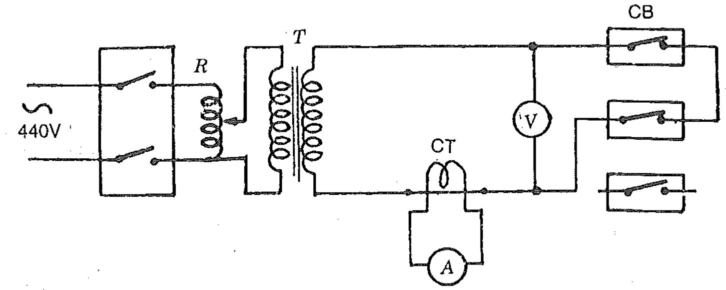


Fig. 10.1. (*a*) Test circuit—Temperature Rise Test (Single Phase)

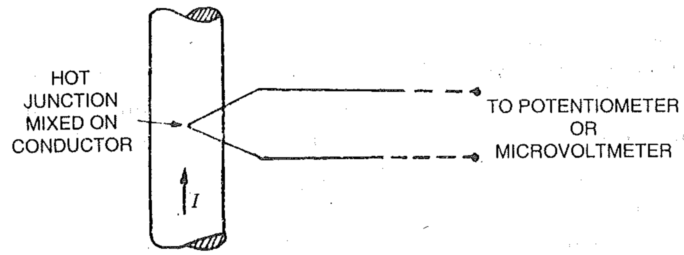


Fig. 10.1. (*b*) Measurement of Temperature.

The temperature is measured by means of Thermocouples. Thermocouple comprises a junctions of two dissimilar materials. The e.m.f. induced depends upon temperature difference between the hot junction and cold end. The hot junctions are fixed on the parts of circuit-breakers (Contacts, conductors, terminals, insulators etc.). The output of the thermocouples is measured by potentiometer or digital voltmeter. The temperature is calculated for the calibrated value (°C per millivolt).

Alternatively, temperature can be measured by self-resistance method or thermometers.

10.2.3. Measurement of D.C. Resistance

The D.C. resistance of main circuit of each pole of a circuit-breaker is of the order of a few tens of micro-ohms. The resistance of the pole tested for temperature rise provides the basis of comparison for all other poles of the same type. The resistance is measured by measuring d.c. voltage drop or by measuring resistance across terminals of each pole by means of a micro-ohm-meter.

10.2.4. Millivolt Drop Tests

The voltage drop across the breaker pole is measured for different values of d.c. currents. The voltage drop gives a measure of resistance of current carrying part and contacts.

The d.c. current should be more than 100 A and less than rated current of circuit-breaker. The resistance of breaker pole should be measured at ambient air temperature. The resistance is of the order of a few tens of micro-ohms.

10.2.5. No-load Operation Tests and Oscillographic and other records

The no-load operation tests include the following operations :

— Closing (C)
— Opening (O)
— Operating sequence (Ref. Sec. 3.19.8)

O—0.3 sec.—CO—3 min—CO (For rapid Auto-reclosure) and

O—3 min—CO—3 min—CO or

CO—15 sec.—CO. (For non-rapid autoreclosure).

No load tests are conducted prior to short-circuit tests. The following quantities are recorded on Oscillographs taken during the no-load test :

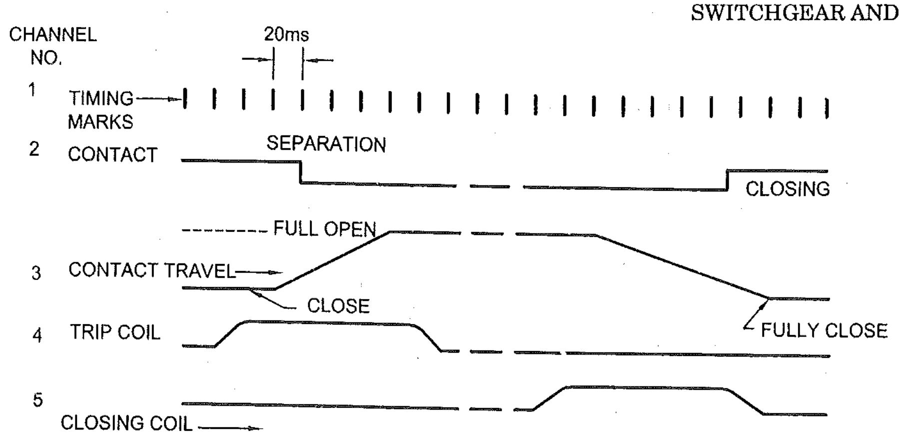


Fig 10.2 Typical oscillogram of no-load O.C. test taken on ultra-violet recorder.

— Travel of moving contact.
— Timing Scale.
— Pressure of Quenching medium (*e.g.* SF_6 Gas)
— Current in trip coil.
— Instant of contact separation..............Ch. 2., Fig. 10.2
— Closing coil current.............Ch. 5.
— Contact touch.............Ch. 2.

The no-load tests are carried out with following conditions :

With solenoid operated mechanisms tests are made with closing solenoid energized at both 105% and 85% of rated supply voltage of closing coil.

With spring mechanism, pneumatic mechanism and hydraulic mechanism, the shunt release (trip coil) should operate at 85% and 110% of rated supply voltage. The no-load tests indicate the functional readiness of circuit-breakers. The no-load characteristics should be indentical to the required characteristic.

The oscillographic records are generally obtained on multi-channel ultra-violet recorders (U.V. recorders). One channel is required for each quantity. The contact-travel is recorded by means of rectilinear potentiometer (travel recorder) connected suitably to the moving contact system.

10.2.6. Dielectric Tests

These are conducted to confirm the rated level of the circuit—breaker. The dielectric tests include power frequency voltage withstand tests and impulse voltage withstand tests (Further details in Ch. 12).

10.2.7. Basic Short-Circuit test Duties

These are performed in specially built short-circuit testing stations. These tests confirm the rated making capacity and rated breaking capacity of the circuit-breaker with reference to rated operating sequence. The basic short-circuit tests consists of the following five test duties :

Test duty 1	:	at 10% rated breaking current with d.c. component less than 20% with rated operating sequence for opening operation only.
Test duty 2	:	at 30% rated breaking current, with d.c. component less than 20% with rated operating sequence for opening operation only.
Test duty 3	:	at 60% rated breaking current with d.c. component less than 20% with rated operating sequence for opening operation only.
Test duty 4	:	at 10% rated breaking current with rated operating sequence.
Test duty 5	:	That is applicable for fast circuit breakers whose contact separation time is less than about 70 ms. This duty consists of rated operating sequence at 10% rated breaking current with specified d.c. component.

Details about Basic Short Circuit-Test duties are given in Ch. 11, Sec. 11.7.

10.3. ROUTINE TESTS (Ref. Sec. 10.9)

Routine tests are conducted on each circuit-breakers before dispatch. A routine test is defined as a test of every circuit-breaker made to the same specifications. The routine tests include the following tests :

(*a*) Mechanical operation tests
(*b*) Millivolt drop test, measurement of resistance
(*c*) Power frequency voltage tests at manufacturers premises
(*d*) Voltage tests on auxiliary circuits, control circuits.

Routine tests reveal the defects in the materials and construction of circuit-breaker. The result of routine tests confirm the quality of the circuit-breaker.

Mechanical Operation Tests

During routine testings five opening and five closing operations should be carried out at (*a*) minimum supply voltage and pressure (*b*) maximum supply voltage and pressure.

10.4. DEVELOPMENT TESTS

The circuit-breaker development and manufacture involves a very large number and variety of tests on individual items, materials sub-assemblies, units, poles and complete assemblies. Extensive testing is employed to ensure reliable equipment.

Development tests (Design tests) are necessary to verify the effect of various parameters on the performance. For example, to ascertain the effect of contact speed on breaking capacity, the circuit-breaker is tested repeatedly with change in contact speed. Before, the development of a circuit-breaker the arc-quenching principle is identified. The various parameters and their influence is theoretically predicated. Some special tests rigs are made for testing and measurement. Full scale prototypes are then manufactured. In this process, the designers use useful data available with the company. For example for design of the procelain, the necessary data are available from the catalogues of the manufactures of porcelain. For design of contacts the configuration can be derived from available designs of contact assemblies.

Each sub-assembly has certain functional requirement. For example, the contacts should give low resistance in closed condition, should not get deforming during mechanical operations, should not get welded during short-time current tests etc. Hence, to verify the capability of contact configurations, necessary development tests are conducted depending upon these functional requirements. Necessary modifications are made on the basis of test results. Pressure tests are conducted on porcelains, glassfibre tubes, etc. to test the leakage and the withstand pressure (Ref. Table 10.2).

10.5. RELIABILITY TESTS*

Type tests and routine test specified in the standards are conducted on new circuit breakers in clean and healthy condition. However the circuit-breaker installed at site is subjected to various stresses such as

— alternate variation of ambient temperatures
— extremely low temperatures
— extremely high temperatures
— rain moisture
— vibrations due to earthquakes
— dust, chemical fumes etc.
— frequent, switching in some cases
— overloads, over voltages etc.

Moreover, the circuit-breaker may not be maintained by skilled personnel at times. The reliability of circuit breakers is verified by conducting special reliability tests.* For example the

* New standards are under publication.

circuit-breaker is subjected to extremely low temperatures created in climatic test chambers. After the tests the sealing rings and other parts are critically examined.

Based on large number of mechanical operation tests, short-circuit tests etc., the manufacturer recommends the maintenance practice to the followed for the circuit-breaker. Tables 10.2, 10.3 and 10.4 give a list about the variety of tests performed on the items, sub-assemblies and full assemblies of SF_6 circuit-breaker during and after the development.

10.6. COMMISSIONING TESTS

After the installation the circuit-breakers and protective gear are subjected to commissioning tests, are conducted on site to ensure proper assembly and operational readiness of the equipment. High accuracy is generally not expected in such tests. The tests facility available on site is also a deciding factor.

The commissioning tests include.

— mechanical operation tests.
— measurement of travel, simultaneous touching of contacts.
— measurement of insulation resistance, measurement of DC resistance of poles.
— pre-commissioning checks, SF_6 gas pressure, Vacuum Integrity.
— operation open the close
— checking of operation by energising the manual operating signal
— checking the operation by energising of relays etc.

Table 10.2 Unit Test on Single Sub-assemblies of SF_6 Circuit-breakers

	Pole	*Insulators*	*Castings*	*Gaskets*	*Spring*	*Capacitance*	*Control rods*
Pressure test	*	*	*				
Dimensional control	*	*	*	*	*		*
Visual check	*	*	*	*	*	*	*
Hardness			*	*	*		*
Dielectric strength	*	*					*
Tensile strength							*
Special tests	*	*	*	*	*		*
Test certifications	*	*	*	*	*	*	*

Table 10.3. Units Test on Sub-assemblies

	Control Unit	*Arc. Ext. chamber*	*Pole*	*Switch cubicle*	*SF_6 Gas system*	*Accessories*
Mech. operations	*	*	*	*		
Excess pressure		*	*	*	*	
Switching time	*	*	*	*		
Gas pressure		*	*		*	*
Minimum operating pressure		*		*		
Voltage drop		*	*			
Gas leakage		*		*	*	
Insulation test		*				
Operational control	*	*		*	*	*
Completeness	*	*	*	*	*	*
Leakage test		*	*		*	

Table 10.4. Test on Components of SF_6 Circuit Breaker

	Gas system	*Insulators*	*Sub-Assemblies*	*Arc Extinction chamber*	*Breaker pole*	*Complete Breaker*	*Cubicle*
Switching times				*	*	*	*
Travel measurement				*	*	*	
Min. Control voltage					*	*	*
Pressure test	*	*	*	*	*	*	*
Leakage	*		*	*	*	*	
Life expectancy			*	*	*		*
Durability		*	*	*	*	*	*
Climate tests		*	*	*	*	*	*
Icing tests				*	*	*	*
Current path resistance				*	*		
Noise measurement					*	*	
Earthquake effects					*	*	
Tensile strength		*					
Bending strength		*					
Sharp temperature drop		*					
Impulse voltage		*			*	*	
Power frequency voltage		*			*	*	
Switching over voltage					*	*	
Bias test					*	*	
Corona inception						*	
Radio interface voltage						*	
Terminal short circuit					*	*	
Short-time current					*	*	
Small inductive current					*	*	
Unloaded lines					*	*	
Phase opposition					*	*	

10.7. INSULATION RESISTANCE MEASUREMENT AT SITE

Insulation resistance is measured by means of Megohm-meter (Megger). The megger comprises a megohm—meter, and built-in d.c. generator. The minimum reading is zero and maximum is infinity. The scale is in megohms. The two terminals of megger arc connected across the insulation *i.e.* on the conductor and other to earthed body. The handle is rotated by hand or motor. The insulation resistance indicated by the pointer in megohms.

For h.v. switchgear, 1000 V or 5000 V (d.c.) megger is preferred. The insulation resistance of h.v. circuit-breaker is very high (above 1000 megohms). Refer Appendix E4)

Insulation resistance of control circuit trip circuit, relay circuit secondary circuit, etc., is a measured by means of 500 V megger. Value obtained should not be less than 1 megohm.

10.8. HIGH VOLTAGE POWER FREQUENCY WITHSTAND TEST (ROUTINE TEST)

Power frequency voltage withstand tests are routine tests. High voltage tests (as per the recommendation of standards) are conducted on each circuit-breaker. By such tests, the defective insulation or small creapage if any are brought to notice. Test Voltages are applied as follows : Aa, Bb, Cc, are terminals of poles and F is the Frame.

Test Condition No.	*Circuit-breaker Condition*	*Voltage applied to*	*Earthed connection to*
1.	Close	Aa Cc	BbF
2.	Close	Bb	Aa Cc F
3.	Open	ABC	abcf
4.	Open	abc	ABCF

10.9. ROUTINE TESTS OR CIRCUIT-BREAKERS

Routine Tests include the following :

1. Mechanical operation tests.
2. Measurement of resistance of main circuit of each pole.
3. Power frequency voltage withstand test on main circuit of each pole and the combination of poles and breaker-frame.
4. Voltage withstand test on auxiliary circuits.
5. Measurement of Insulation resistance of main circuits.
6. Measurement of Insulation resistance of auxiliary circuits.
7. Tests and checks after mechanical operation tests.

Routine tests are conducted on each circuit-breakers before dispatch. A routine test is defined as a test of every circuit-breaker made to the same specifications.

Routine tests reveal the defects in the materials and construction of circuit-breaker. The results of routine tests confirm the quality of the circuit-breaker.

On complete Circuit-breaker or Part of it.

Circuit breaker upto 132 kV may be tested with all the 3 poles assembled on frame and with mechanism assembled for the complete 3 phase circuit-breaker.

Mechanical operating tests should preferably be made on the complete circuit-breaker. However when circuit-breakers are assembled and shipped as separate units routine tests may be performed on components. Operating mechanisms and control cubicles shall be tested together with the circuit-breaker or with an appropriate dummy load.

10.9.1. Mechanical operating tests (Routine Test)

Mechanical operating tests are performed on 3 phase breaker on a part of it.

(*a*) at specified maximum supply voltages and pressure (if applicable)
  1. five closing operations
  2. five opening operations

(*b*) At specified minimum supply voltages and pressure (if applicable)
  1. five closing operations
  2. five opening operations

(*c*) At rated supply voltages and pressure (if applicable)
  1. five close-open operating cycles with the tripping mechanisms energized by the closing of the main contacts.
  2. moreover for circuit-breakers intended for rapid autoreclosing, five open-close sequences O—i—C where -i shall be not more than the interval specified for the rated operating sequence.

Measurements during mechanical Operation Tests.

For each required operating sequences the following measurements are :

— measurement of operating times :

— measurement of fluid consumption (if applicable)

If possible the time-travel diagram should be recorded.

Mechanically stressed auxiliary equipment should function correctly during and after the tests.

QUESTIONS

1. Distinguish between type tests, routine tests, development tests.
2. State the various type tests necessary or high voltage a.c. circuit breaker.
3. Fill in the gaps.
   (*a*) The contact resistance of circuit-breakers is of the order of............
   (*b*) High voltages test include :
      (1) ....
      (2) ....
      (3) ....
   (*c*) Insulation resistance of H.V. circuit-breakers is more than.........
   (*d*) Routine tests are conducted on.........circuit-breaker.
   (*e*) Short circuit tests of current carrying parts for normal current should be less than..........
4. Describe the following (any two) :
   (*a*) Temperature rise test. (*b*) Millivolt resistance measurement.
   (*c*) Insulation endurance tests. (*d*) Mechanical endurance tests.
   (*e*) No load Mechanical tests. (*f*) Routine tests.
   (*g*) Type tests.
5. What is the difference between power frequency test and impulse voltage test ?
6. Explain the term Insulation Resistance and the procedure of measurement of the same.
7. Describe the procedure of conducting temperature rise test on a high voltage ac. circuit breaker. Draw a neat sketch of the test circuit. Explain the procedure of measurement of temperature rise.
8. State the various routine tests on High Voltage AC Circuit-breakers.
9. Describe the mechanical Operation tests on high voltage AC circuit-breakers for routine testing.
10. State the application of voltage under various breaker position during the routine power frequency voltage withstand tests on High Voltage AC Circuit breakers.

11

Short Circuit Testing of Circuit-Breakers

Introduction—Short Circuit Test Plants—Field Testing—Laboratory Testing—Layout—Short Circuit Generators—Transformer—Reactors—Master Circuit Breaker—Making Device—Capacitors—Sequence Switch—Direct Testing—Short Time Current Test—Indirect Testing—Unit Testing—Synthetic Testing—Substitution Test—Compensation Test—Capacitance Test—The Switching Phenomena for Tests—Tests on EHV Breaker—Summary—Questions.

11.1. INTRODUCTION

In Chapter 9, we studied the difference between type tests and routine tests. The various tests performed on circuit-breakers according to Standard Specifications were briefly reviewed. The short-circuit tests come under Type Tests. The short-circuit tests and switching duty tests on circuit-breaker include :

(*a*) Breaking current tests.

(*b*) Making current tests.

(*c*) Short time current tests.

(*d*) Operating duty tests, Basic short-circuit Test Duties.

(*e*) Tests for small inductive currents.

(*f*) Test for short line faults (SLF).

(*g*) Tests for breaking capacitive currents.

(*h*) Capacitor switching.

(*i*) Out-of phase switching.

(*j*) Line charging current breaking tests.

(*k*) Cable charging current breaking test.

(*l*) Critical current tests (m) Inductive current tests.

Short-circuit test mentioned above are conducted to prove the ratings of the circuit-breaker. In addition, short circuit tests are performed for research and development. The modern EHV circuit-breakers are developed through experimental investigation of the problems of circuit-breaking *e.g.* arc extinction, current chopping, breaking of inductive current etc.

11.2. STRESSES ON CIRCUIT-BREAKER DURING SHORT-CIRCUIT TESTS

The short-circuits produce a severe stress on circuit-breakers. The circuit-breaker should be capable of withstanding the stresses. Short-time current test verify the capacity of the circuit-breaker to carry the specified short-circuit current for a duration of 1 sec or 3 sec. When short-circuit current is passed through the circuit-breakers, the contacts and current carrying parts are subjected to thermal stresses. The insulation in the vicinity of conductors is severly stressed. The poles and terminals experience electro-dynamic forces. The short time current tests verify the ability of the circuit-breaker to withstand temperature stresses and electrodynamic forces.

The making capacity test verify the ability of the circuit-breaker to close on short-circuit. As the circuit breaker closes on existing short-circuit, the current reaches a high value during the peak

of the first current loop. The electrodynamic forces between contacts and between poles reach a high value. The circuit-breaker should be capable of closing effectively contact welding and contact bouncing.

The breaking capacity tests verify ability the of the circuit-breaker to clear short-circuits. The operating mechanism and the interrupter should be able to perform their functions effectively. During the breaking operation, the operating mechanism is subjected to mechanical stresses. The contacts and current carrying parts are subjected to thermal stresses. The insulating and metallic materials in the neighbourhood of the arc are subjected to high thermal stresses. The part of the interrupter may be subjected to high pressure due to increase in pressure in the interrupter.

These stresses depend on the magnitude of fault current and the design of the circuit-breaker itself. In the post current zero period the contact gap is subject to transient recovery voltage. The severity of the voltage stresses depends upon the system configuration and the type of switching duty. *Short circuit testing is an experimental method for proving the ratings of the circuit-breaker and investigating the behaviour of circuit-breaker for research and development.*

The chapter is divided into three sections as follows :

Part A-Short Current Testing Plants.

Part B-Basic short-circuit Test Duties and Special Tests.

Part C-Indirect Tests.

The short-circuit testing plants are built specially and they provide the facility of short circuit testing. In Direct texts the breaker is subjected to direct short-circuit and results are analysed. In Indirect Testing, the capacity of complete breaker is ascertained by indirect test procedures.

Tests are conducted as per relevant standards.

PART A

11.3. SHORT-CIRCUIT TESTING PLANTS

There are three types of testing station :

1. Field type testing station.
2. Laboratory type testing station.
3. Composite testing station.

In field type testing power required for testing is directly taken from a large power system, the breaker under tests is connected in the system.

In laboratory type of testing the short-circuit generators provides the power for testing. In laboratory testing the breaker is tested directly or indirectly. When the capacity of the test plant is inadequate to test the breaker, indirect tests are performed to assess the behaviour of the circuit-breaker. There are several indirect methods of testing such a subsitution method, unit testing synthetic testing etc. A composite testing station is a combination of field type testing station and laboratory type testing station.

Layout of a Simple Short-circuit Testing Station*

The layout of a test plant for testing 11 kV/33 breakers up to 750 MVA is simpler and different from that of a large test plant for testing breakers up to, say 220 kV, 7500 MVA.

(*a*) **Description of a simple Test Plant** (Fig. 11.1)

The short-circuit power is supplied by speciality built *Short-cicuit Generators.* There are normally two or more generators though only one is shown in the figure. The short circuit generators

* Switchgear, testing and development station (STDS). Bhopal belonging to CPRI has a capacity of 1250 MVA can test circuit-breakers upto 12 kV. A very high capacity composite short-circuit testing station has been built a CRRI, Bangalore 1989. Breakers up to 420 kV, 62.5 kA can be tested.

are driven by three phase induction motor and the special type of excitation called impulse excitation is provided.

Series resistor and reactors are provided for adjusting the magnitude of short-circuit current and power factor.

The Master Circuit-Breaker has higher capacity than circuit breaker under test. In the event of failure of the circuit-breaker under test, the Master Circuit-Breaker opens and protects the circuit.

Making switch is a specially designed circuit closing device which can close at the desired moment and can withstand the making currents.

Transformers are used to get test voltages other than the generator voltage. The transformers are single phase units which can be connected in different ways to get several test voltages.

In addition to the above equipment there is equipment for

1. Measurement, record, control;
2. Sequence switch to obtain sequential operation;
3. Auxiliaries etc.

(*b*) **Short-circuit Generator and Drive Motor**

Short-circuit generators provide power to the circuit-breakers under test. The short-circuit generators must be capable of withstanding extremely high reactive power surges lasting for a short

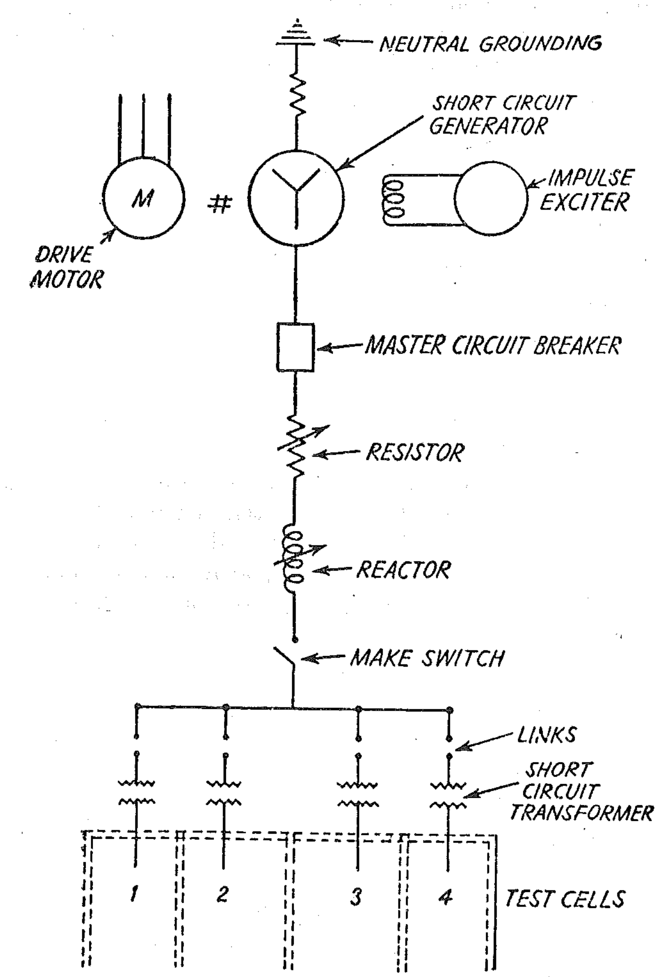
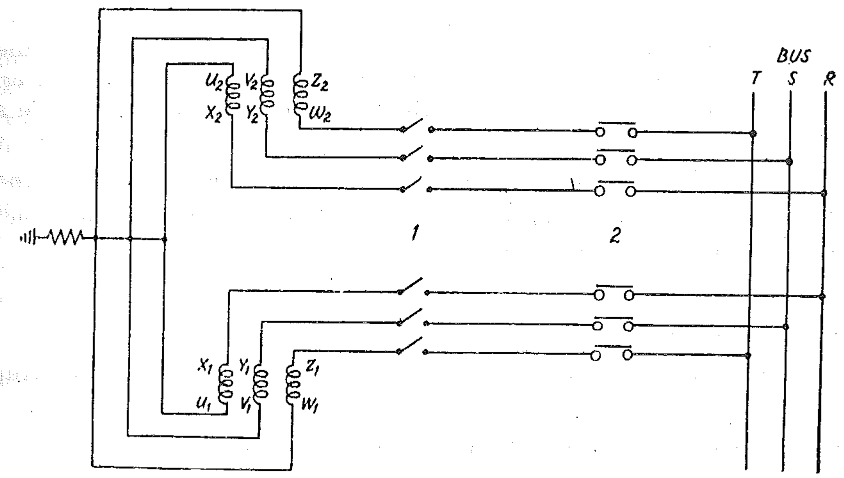


Fig. 11.1. Schematic diagram of short-circuit test plant.

duration. Therefore, their design is different from that of the conventional alternators for power generation.

The generator is driven by a three phase induction motor connected through a resilient shaft. Shortly before the short-circuit, the motor is disconnect from the supply and idles with the generator rotor.

A separate d.c. converter set with a high speak output provides the "Impulse Excitation". The short circuit current which are at lagging power factor have a demagnetising effect. This results in reduction in total field hence in reduced e.m.f. As a results the recovery voltage is less than the voltage before short circuit. The effect is reduced by boosting the generator field current by means of Impulse Excitation. The converter set used for excitation is fitted with a large flywheel. The motor is disconnected from supply before the application of excitation. The field current is increased shortly to about 10 times its normal value at the time of short circuit. This takes care of the demagnetising effect of short-circuit and gives desired recovery voltage.



$X_1\ Y\ Z_1$, $U_1\ V_1\ W_1$	Part 1 of generator winding	1-Making circuit breaker
$X_2\ Y_2\ Z_2$, $U_2\ V_2\ W_2$	Part 2 of generator winding	2-Making switch.

Fig. 11.2. Arrangement of circuit it a short-circuit plant.

Short-circuit generator is a 3-phase alternator. Each winding is made in two or more parts which can be connected in series, parallel combinations of star or delta to get voltages.

(*c*) **Short-circuit Transformers**

For tests at voltages other than the generator voltage, transformers are used. To step down the voltage to lower values a three-phase transformer is normally used. For voltage higher than generator voltage, usually banks of single phase transformers are employee. These transformers are designed to withstand repeated short-circuit and their windings have several parts which can be connected to series parallel combinations to get several voltages.

The leakage reactance of the short-circuit transformer is kept low. Transformer winding is mechanically strong and provided with extra-turn insulation. Three phase units are not used because a single 3-phase unit becomes too big. There is no special problem about cooling these transformers because they are in the circuit for a short time. The tank is normally smooth without any tubes for circulating oil. For 3-phase tests, the transformers are connected in delta on alternator side. The four windings of each phase on secondary side can be connected in series/parallel combinations and the three phases can be connected in star or delta.

Another three-phase transformer is used for testing low voltage breaker, H.R.C. fuses and for conducting short-time current tests on circuit-breakers.

(*d*) **Reactors**

For controlling the short-circuit current reactors are employed. These are normally air cored and air-cooled. Iron parts are avoided in their construction. These are single phase units or three phase banks. Each reactor is designed to withstand electrodynamic stresses. The coils are securedly placed to avoid distortion.

(*e*) **Master Circuit-breaker**

These are air blast circuit-breakers of capacity more than the breakers under test. In case of failure of the test circuit-breakers, the master circuit-breaker opens. In addition after every test, it isolates the specimen under test from the supply source and must be able to handle the full short-circuit power of the test circuit.

(*f*) **Making Device**

The making switch or making device, as the name implies, is used to ensure that the short-circuit current are applied correctly at the desired moment. This equipment is characterized by close making time, high making capacity. However, the breaking capacity is negligible and the making device is not used for circuit interruption.

The basic construction of making device is as follows. It is usually air blast making switch with an air pressure of 14-16 kgf/cm^2. Contact clearance of only a few mm is sufficient because the contact device is fast, sure and without chapter. In recent stations SF_6 make switches are used.

(*g*) **Capacitor**

Capacitor banks are useful for two purposes :

(1) Provide leading current for testing the performance of circuit-breaker in interruption of charging currents.

(2) Regulating the frequency of transient recovery voltage given by

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

In synthetic testing and other indirect tests, capacitors are important items in the test circuit.

The capacitor banks provide charging currents, regulate natural frequency of transient recovery voltage and are used for synthetic testing. These are single phase banks. These banks can be connected in series or parallel, as desired, both individually and in any combination of the three.

(*h*) **Resistors**

The variation of short-circuit power factor is obtained by using resistors in series with the reactors. The p.f. can be increased from 0.1 to 0.3.

(*i*) **Test Cubicles.**

The test cubicles are constructions of reinforced cement concrete or strong brick work. In these cubicles the breakers are tested. There is provision for observation. Supply of compressed air and oil purification system is given to the test cells to facilitate testing of air blast circuit-breaker and oil circuit-breakers respectively. Separate cubicles are provided for testing L.V., H.V., E.H.V. equipment, fuses.

(*j*) **Sequence Switch**

During the short-circuit testing several operations are performed in a sequence and the total time is too short to perform manual operation. The sequential switching of equipment measurements and control circuits is accomplished by sequence switch. This is a drum switch with several pairs of contacts. The drum is rotated by a motor. Once the drum is rotated, it closes and opens

several control circuits according to a certain sequence. For example, the sequences for Breaking Capacity Test in one test were as follows :

1. Drive motor of short-circuit generator made off.
2. Impulse excitation switched on.
3. Master circuit-breaker closed.
4. Oscillograph circuit connected.
5. Make-switch closed.
6. Circuit-breaker under test opened.
7. Master circuit-breaker opened.
8. Exciter switched off and its field suppressed.

The above operations take a very short time of the order of 0.2 second.

(*k*) **Measurements**

The test events mentioned above cover a very short time of the order of a few hundredth of a second. All the measurements must, therefore, be recorded by means of oscillographs.

Light beam oscillograph which are simple to operate are used for relatively slow varying quantities like current, voltage and also for mechanical quantities such as contact travel, trip signal etc. High frequency transient phenomenon of TRV covers a very short time interval of the order of 1 msec. For recording such fast varying quantities cathode ray oscilloscope are used. Processes which last a few half waves are recorded on barrel type camera. If time is too short, around current zero, Polaroid Oscilloscope camera is convenient. Normally one light beam oscillograph and several cathode ray oscillographs are simultaneously used. High speed photography techniques are being employed for investigating arc extinction phenomenon, movement of part etc. Films are taken at 400 to 800 frames per second.

The following quantities can be recorded during the tests :

(*a*) Short-Circuit current in each phase.

(*b*) Voltage across each pole before, during and after the short-circuit.

(*c*) Fluid (Air, SF_6 or oil) pressure.

(*d*) Contact travel-speed.

(*e*) Generator voltage.

(*f*) Transient Recovery voltage.

(*g*) Current in trip circuit etc.

PART B. DIRECT TESTING

11.4. DIRECT TESTING

Direct testing involves subjecting a complete breaker or breaker pole to full power or stress during the test.

The circuit for direct test is shown in Fig. 11.3.

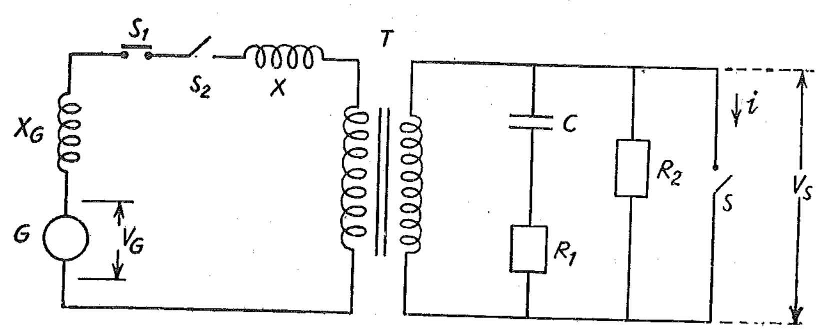
The preliminary preparation of circuit-breaker testing include connecting the equipment adjusting the magnitude of reactors, connecting transformers to get desired test voltages etc. The contacts on sequence switch are adjusted to get desired timings. The oscillographs are adjusted and calibrated. The operations of test follow automatically by means of sequence switch, as mentioned earlier.

While testing breaking capacity; Master circuit-breaker and circuit-breaker under test are closed firts. Short circuit is applied by closing the making switch. The breaker under test is opened at moment. The breaking current determined from the oscillograph as explained in Chapter 3, Sec. 3.19.5.

Making capacity test is necessary type test. All circuit-breakers are tested for their ability to make on to a short-circuit. The master circuit-breaker and the make switch are closed first. The breaker under test is closed on a three phase short-circuit. The making current is determined as explained in chapter 3. Operating duty test are performed according to the Standard Specifications or client's instructions.

11.5. RULES FOR TYPE TESTS

(*i*) **Breaking Current.** The short-circuit current broken by the circuit breaker should be measured at the instant of contact separation as described in chapter 3 and should be stated in terms of two values : Breaking current and d.c. component (Ref. Sec. 3.19.5.)



V_G = Generator voltage
i = Short circuit current
X = Current control reactance
S_2 = Making Switch
S = Breaker under test.
C, R_1, R_2 = Capacitance, resistance for adjusting the transient recovery voltage
G = Short circuit generator.
G_S = Voltage across test breaker
X_s = Generator reactance
S_1 = Back-up (Master) circuit-breaker
T = Transformer

Fig. 11.3. Short-circuit test arrangement (single line representation).

(*ii*) **Breaking Capacity.** The breaking capacity test should be performed with specified TRV of test circuit.

(*iii*) **Peak Making Current.** The peak making current made by the circuit-breaker during the test should be expressed by maximum current in any pole. It is measured as described in chapter 3, Sec. 3.19.6.

(*iv*) Conditions of severity for Making Capacity and Breaking capacity tests are specified as under the following clauses :

1. Conditions of breaker before test.
2. Conditions during the test.
3. Conditions of breaker after test.
4. Applied voltage before test.
5. Transient recovery voltage.
6. Short-circuit power factor.
7. Test frequency.
8. Earthing of test circuit.
9. Test duties.

11.6. SHORT-TIME CURRENT TESTS ON CIRCUIT-BREAKERS, ISOLATORS, BUSBARS, CTs ETC.

(*a*) **Requirement.** Short time current tests are Type Tests for confirming Rated Duration of Short-circuit current (1 sec or 3 sec) assigned by the manufacturer (Ref. Sec. 3.19.7).

Rated short time current is defined as the r.m.s. value of a.c. current which the circuit-breaker can carry for a specified short duration (1 sec or 3 sec) without mechanical damage and without contact welding.

Short-time current tests are necessary type tests for circuit-breakers, bus bars, metal-clad switchgear, current transformers, bushings, isolators etc. The procedure described here is applicable in all cases.

(*b*) **Test voltage.** Short-time current tests may be carried out at any suitable test voltage. The voltage is selected by testing station authorities depending upon the reactance of the equipment and required value of short-time current.

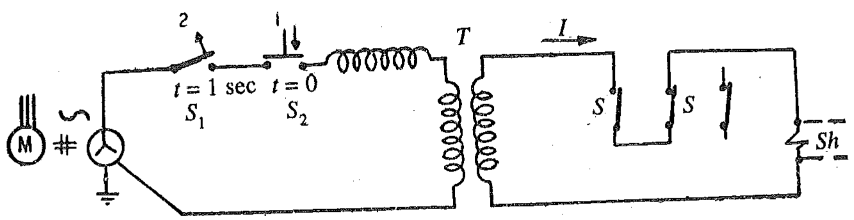
(*c*) **Single-phase Tests or Three-Phase Tests.** Both single phase tests and three phase tests are permitted by the standard. However a complete triple pole breaker is installed in the test bay for the purpose of tests. The single phase tests are carried out by connecting two adjacent poles in series.

In case only single pole is to be tested, a rigid return conductor is installed at the centre-line of adjacent pole to simulate the electrodynamic forces between adjacent poles. For circuit-breakers above 72.5 kV the return conductor is not necessary because of the large clearance and reduced electrodynamic forces.

(*d*) **Test Circuit** (Ref. Fig. 11.4 *a*, *b*). The circuit-breaker is connected on the low-voltage side of short-circuit transformer for testing station. The short-circuit is applied beyond the circuit-breaker *via* a shunt of measurement.

In single-phase test, the two adjacent poles are connected in series. The short-circuit current is passed through the closed series circuit and the shunt.

In three-phase test, the three terminals of the circuit breaker on one side are connected to low-voltage side to short-circuit transformer of testing station. The other three terminals of poles are connected in star *via* shunt in each phase for measurement of current.



S, S = Adjacent poles of circuit-breakers under test (kept closed)
S_1 = master circuit-breaker opened at $t = 1$ sec
S_2 = Make switch, open before $t = 0$, closed at $t = 0$
I = Rated short-time current
T = Low secondary voltage transformer
Sh = Shunt for measurement of current I

Fig. 11.4. (*a*) Explaining single-phase short time current test on a circuit-breaker or isolator.

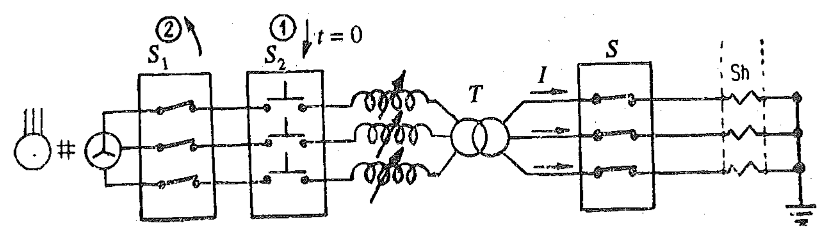


Fig. 11.4. (*b*) Three phase Test circuit.

(*e*) **Procedure.** The magnitude of short-circuit current is achieved by selecting appropriate voltage and reactance by the testing authorities depending upon the reactance of the circuit-breaker under test and the required value of current. Trial shots are taken at reduced voltage and current to check the calibration.

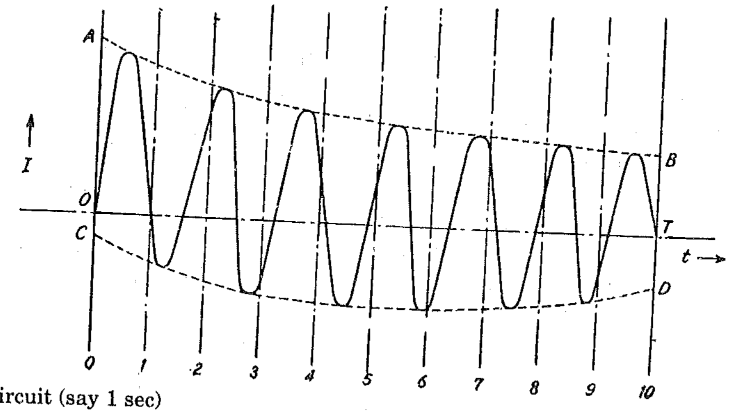
For this test, the circuit-breaker under test (S) is kept in closed condition throughout the test.

Short circuit current is initiated by closing the station make switch (S_2) at $t = 0$ sec and current is interrupted opening master circuit breaker (S_1) at $t = 1$ sec or 3 sec. The peak of first major current loop should be 2.5 times rated short time current (Ref. Sec. 3.19.6).

The record is obtained on the oscillograph on the sheets of ultraviolet recorder automatically.

(*f*) **Observations.** Visual inspection and no-load operation of the circuit-breaker immediately after the short-time current test are usually sufficient. The parts of the circuit-breaker should not get damaged during the test. The circuit-breaker should not emit any flame or smoke. The contacts should not get welded. The circuit-breaker should be capable of opening and closing after the short-time current test.

(*g*) **Short-Time Current Test, Evaluation of Test Results.** Fig. 11.5 shows an example of oscillogram taken during the short-time current test. The current is passed the breaker for a short-time (1 sec) and the oscillogram is taken.



OT duration of short-circuit (say 1 sec)

AB, CD] Envelope of short-circuit wave

$I_0, I_1, I_2, \ldots\ldots I_{10}$ r.m.s. value of asymmetrical current at each instant.

Fig. 11.5. Oscillogram of short-circuit of short time current test.

The r.m.s. value of current during the time interval 0 to T of such a wave is given by the expression.

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2\, dt}$$

where i is the current (variable)

t time (variable) (seconds)

T duration of current in seconds.

Procedure of determining equivalent r.m.s. value of short-time current is as follows. The time interval $0T$ is divided into 10 equal parts marked by 0, 1, 2,....etc. upto 10. The r.m.s. values at these instants are I_0, I_1, I_2.....etc. upto I_{10}

$$I_{rms} \text{ at this instant} = \sqrt{(I_{sym})^2 + (I_{d.c.})^2}$$

where I_{sym} = r.m.s. value of a.c. component at this instant

$I_{d.c.}$ = component at this instant.

It is r.m.s. value of current at this instant. This way I_0, I_1, I_2......etc. upto I_{10} are calculated. From these values the r.m.s. value of short time current is calculated with sufficient accuracy by *Simson Formula :*

$$I = \sqrt{\frac{1}{30}\,[I_0^2 + 4\,(I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_9^2) + 2\,(I_2^2 + I_4^2 + I_6^2 + I_8^2 + I_{10}^2)]}$$

Temperature rise limits are not specified for short-time current tests. It is very difficult to record the transient temperature during 1 sec. duration.

(*h*) **Stresses during Short-time Current Test.** The electrodynamic forces between adjacent poles and adjacent phase conductors are proportional to square of current and inversely proportional to phase spacing. During short-time current, the insulator supports experience impact cantilever force due to electrodynamic forces.

The contacts experience temperature stresses proportional to I^2 Rt. The resistance depends on contact pressure and surface condition.

11.7. BASIC SHORT-CIRCUIT TEST DUTIES (Ref. Sec. 10.27.3.15)

(*a*) **Requirements.** *The circuit-breaker should be capable of performing the opening and closing operations as per rated operating sequence for all values of short-circuit currents upto its rated short-circuit breaking current at specified test voltage and relevant conidtions of TRV for terminal short-circuits.*

The requirements are verified by conducting Basic short circuit. Test Duties. These requirements are discussed below :

(*i*) **Breaking Capacity** (Ref. Sec. 3.19.5. (Ref. Fig. 11.12)

The Circuit-breaker should have rated short-circuit current breaking capacity. It should be capable of breaking all currents upto its rated short-circuit breaking currents. Since it is difficult to carry out tests at every value, the basic short-circuit tests are made at 10%, 30%, 60% and 100% of rated short-circuit breaking current (a.c. component) and specified d.c. component.

(*ii*) **TRV Conditions**

The circuit-breaker should have rated TRV for terminal faults (Ref. Sec. 3.19). During Breaker operations, the TRV should be as per specified TRV condition for the respective test duty.

TRV for test Duty 1 (10%) and Test Duty 2 (30%) are more severe than those for Test Duty 3 (60%) and Test Duty 4 (100%)

(*iii*) **Making Capacity.** (Ref. Sec. 3.19.6.) (Ref. Fig. 11.12)

The circuit-breaker should be able to close on short-circuit, *i.e.*, it should have rated short-circuit making capacity. This is tested by closing the circuit-breaker on short-circuit.

(*iv*) **Operating Sequence.** (Ref. Sec. 3.19.8) (Fig 12.11)

The circuit-breaker should be able to perform the opening and closing duties as per rated operating sequence. The requirement is verified by conducting the Basic Short-Circuit Test Duties with rated operating sequence.

(*b*) **Procedure.** For breaking capacity tests (TD 1, TD 2, TD 3 and TD 5), the short-circuit currents are initiated by closing the make switch of the testing station and the current is interrupted by opening the circuit-breaker under test. The circuit-breaker under test is not closed on short-circuit (Ref. Fig. 11.12)

For making capacity tests (TD 4a) the short-circuit is initiated by closing the circuit-breaker under test. The opening of short circuit current is by master-breaker of the testing station. The circuit-breaker under test need not to open the short-circuit.

The sequence of circuit-breaker under test, master circuit-breaker and make switch is pre-arranged to get desired duty cycle.

(*c*) Test circuit (Ref. Fig. 11.3) The basic short-circuit tests are carried by out on complete three pole circuit-breaker. However, when capacity of the testing station is inadequate for testing a complete three phase circuit-breaker the test may be carried out on one pole of a three phase circuit-breaker. Even then, a complete circuit-breaker is usually installed in the test bay and only one pole is connected in the circuit. In case of EHV circuit-breakers with modular construction, the tests may be carried out on pole. The test voltage is selected such that rated power frequency recovery voltage is obtained. The test voltage is selected such that rated power frequency recovery voltage is obtained.

The parameters L and C in the station are arranged such that the required current and TRV conditions are achieved L and C are changed for each test duty.

(*d*) **Severity.** Basic short-circuit test duty produces severe electromechanical, thermal and dielectric stress on circuit-breaker. The severity of these components varies with Test Duty 1, 2, 3, 4*a*/4*b* and 5 depending upon type of circuit-breaker. For circuit-breakers with internal source of energy, the smaller breaking currents generate less pressure. Hence TD 1 and 2 may be more severe. When arcing time for Test Duty 1 and 2 is more by 1/2 cycle than Test Duty 3 and 4, the Critical Current Tests are necessary.

11.8. CRITICAL CURRENT TESTS (Ref. Sec. 8.7)

In circuit-breaker with internal source of extinguishing energy *i.e.*, oil circuit-breakers, the arc duration depends upon design of cross-jet pot and speed of contacts. The arcing time for Test Duty 1 (10%) may exceed that of Test Duty 2 by more than one-half cycle. In such cases, additional 'Critical Current Tests' are required.

Critical current test duties are similar to Test Duty 1 except for following changes.

— The breaking currents are in the range of 4 to 6% and 1 to 2% of rated short-circuit breaking current.

— TRV conditions are modified.

11.9. SHORT-LINE FAULT TESTS (Ref. Sec. 3.14.1)

(*a*) **Requirements.** These tests are applicable to three pole circuit-breakers intended for direct connection to overhead transmission lines having rated voltage of 72.5 kV and above.

These are not applicable to 36 kV and 12 kV circuit-breakers. The theory of short-line faults has been discussed in Sec. 3.16. The capability of the circuit-breakers to perform the short-line fault clearing duty is tested by conducting these tests. In high power testing station, the transmission line is generally represented by an artificial transmission line comprising R, L, C parameters or by specially built transmission line.

For purpose of short line fault simulation, the system can be considered in two sides (Ref. Sec. 3.16)

— Source side having rated voltage and equivalent inductance corresponding to 10% rated short-circuit breaking current.

— Line side impedance.

To represent different lengths of lines and corresponding short-line fault current, these values of line side impedances are recommended. These are selected to get 90%, 75% and 60% of rated short-circuit breaking current respectively.

(*b*) **Test Circuit.**. The short line fault tests are single phase tests. The circuit consists of a supply circuit and line side circuit. The parameters are so selected that required TRV conditions are obtained.

(*c*) **Short line Fault Test Duties.** The standard test duties L90, L75, L60 consist of rated operating sequence for opening operation only as follows :

Test Duty L90 : At 90% rated breaking current and appropriate TRV.

Test Duty L75 : At 75% rated breaking current and appropriate TRV.

Test Duty L60 : At 60% rated breaking current and appropriate TRV.

(*d*) **Severity.** After opening a short-line fault, voltage waves originating in the circuit-breaker travel to source side and line side. The line wave gest reflected from the fault point and thus within a few tens of microsecond, the wave travels to-and-fro between the open circuit breaker and the

fault point giving rise to damped saw-tooth oscillations of voltage at line side terminal of circuit-breaker. The result and TRV across the circuit breaker is characterised by high rate of during initial portion of TRV (Ref. Sec. 3.16). Different types of circuit-breakers have different sensitivity of TRV. The grading capacitors dampen the TRV.

Value $V_p = V\sqrt{3}$

I_L = Short line fault current.

C_B = Circuit-breaker under test.

X_L = Reactance on line side.

X_S = Reactance on source side.

Z = Surge impedance of line.

L = Length of line upto fault.

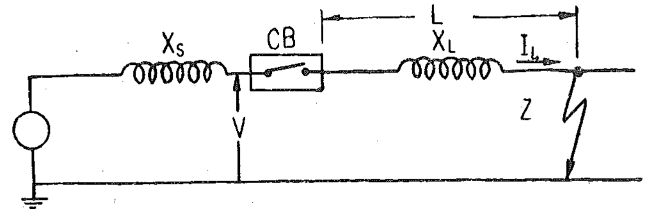


Fig. 11.6. Circuit representing Short Line Fault condition.

11.10. LINE CHARGING BREAKING CURRENT TESTS

(*a*) **Rated line charging breaking current.** It is the value of line charging current taken by the line no load. The circuit-breaker is capable of interrupting with over-voltage within permissible limits. Breaker should not restrike.

Rated Voltage (V)	*Rated line charging current*
KV	*A*
72.5	10
145	50
245	125
420	400
525	500

(*b*) **Requirement.** These test are conducted of h.v.a.c. circuit-breakers rated 72.5 kV and above to prove their assigned rated line charging breaking current.

(*c*) **Test Circuit.** The tests are either single phase or three phase with either overhead line on on-load or with artifical line with R, L, C.

The supply circuit has two types :

Supply Circuit 1 : Which can give short-circuit current less than 10%.

Supply Circuit 2 : Which can give short-circuit current more than rated short-circuit current.

(*d*) **Test voltage.** In single phase tests, the test voltage V_t is given by

$$V_t = 1.2 \times \frac{V}{\sqrt{3}}$$

where V is rated voltage of circuit-breaker.

(*e*) **Test Duties.** Test 3 is applicable only if the circuit-breaker restrikes during test duty 1 or 2. The test consists of 10 to 12 operations for each duty.

Test Duty No.	*Supply Circuit*	*Test current as percentage of rated line charging current*
1	1	10 to 30
2	1	100 to 120
3	2	100 to 110

11.11. OUT-OF-PHASE SWITCHING TESTS

(*a*) **Requirements.** When a circuit-breaker is connected between two circuit supplied from different sources, the circuit-breaker may have to open or close during out-of-phase condition [Fig. 11.7 (*a*) or phase opposition [Fig. 11.7 (*b*)]. The phase angle between rotating vectors on either sides of the circuit-breaker may exceed normal value (0°) and may be as much as 180° (Phase opposition). The circuit-breakers which are required to inter-connect two systems or to synchronise the units with the busbars need rated out-of-phase breaking capacity. The circuit-breaker should be capable of breaking out-of-phase currents upto its assigned ratings with specified conditions of TRV. (Ref. Sec. 3.17)

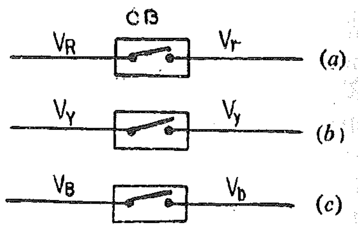


Fig. 11.7.

(*b*) **Test Conditions.** The out-of-phase breaking are either single phase or three phase. The performance out-of-phase breaking capacity in a test is specified in terms of the following :

— Value of out-of-phase breaking current

— Value of out of phase recovery voltage

— Characteristics of inherent TRV for out-of-phase switching.

Test Voltages

For single phase test, the test voltage (V_1) given by the following expressions :

$V_t = 2 \times \frac{V}{\sqrt{3}}$ For effectively earthed system.

$V_t = 2.5 \times \frac{V}{\sqrt{3}}$ For non-effectively earth system.

Where V is rated voltage of Circuit-breaker.

(*a*) **Out-of-phase Test Duties**

Test Duty 1 : 0 and 0 at 20 to 40% I_{op}

Test Duty 2 : 0 and 0 at 100 to 110% I_{op}

where I_{op} is rated out-of-phase breaking current, O is opening.

The rated out of phase breaking current is generally 25% of rated breaking current of circuit-breaker.

11.12. CAPACITIVE CURRENT SWITCHING TESTS

Capacitor current switching is a special switching duty for a circuit breaker (Ref. Sec. 3.14, Sec. 3.19.19). Capacitor current switching tests are applicable for circuit-breakers which are intended to be used for breaking capacitive currents. The breakers should be restrike free. The switching overvoltages while opening single capacitor banks should be within permissible limits.

Circuit breakers to be used for closing parallel capacitor banks should be tested for rated back-to-back capacitor bank breaking current and rated capacitor bank inrush making current. Ref Sec. 15.26 for capacitor switching applications for medium voltages.

Applicability

Capacitive current switching tests are applicable to all circuit-breakers to which one or more of the following ratings have been assigned.

— Rated line-charging breaking current (Sec. 11.10)

Line charging current switching tests are recommended circuit-breakers for rated voltages of 72.5 kV and above.

— Rated cable-charging breaking current (Sec. 11.13)

Cable-charging current switching tests are recommended for circuit-breakers of rated voltages of 24 kV and above to be used of switching cable currents.

— Rated single-capacitor bank breaking current.

Rated single capacitor bank current breaking tests are recommended for circuit-breaker to be used for switching capacitor banks. The breaker should be restrike free and switching overvoltages should be within specified limits.

— Rated back-to-back capacitor bank breaking current and

— Rated capacitor bank inrush making current.

These tests are intended for circuit-breakers which switch in or switch out *parallel capacitor banks*.

Supply Circuit A

Supply circuit A is a circuit having an impedance such that its short-circuit current does not exceed 10% of the rated short-circuit current of the circuit-breaker except that, if necessary, the impedance shall be reduced below the value given by this requirement so that power frequency voltage variation caused by switching the capacitive current does not exceed 10%.

Supply Circuit B

Supply circuit B is a circuit having impedance which is as low as possible, but not so low that its short-circuit current exceeds the rated short-circuit current of the circuit-breaker. The characteristics of the test circuit shall be such that the power frequency voltage variation when switching is as small as possible and is in any case less than 5% for Test-duty No. 4.

Test duties

Test conditions corresponding to normal service conditions.

The capacitive current switching tests shall consist of four test-duties as specified in Table below.

Test-duty	*Supply circuit*	*Test current as percentage of the rated capacitive breaking current*
1.	A	20 to 40
2.	A	Not less than 100
3.	B	20 to 40
4.	B	Not less than 100

The number of tests for each test-duty shall be :

—10 tests for three-phase tests :

—12 tests for single-phase tests with the contact separation distributed at intervals of approximately 30 electrical degrees.

Test duties for Capacitive current Switching tests

Test Duty	*1*	*2*	*3*	*4*
Test Circuit	A	A	B	B
Line Current Switching tests and cable charging current switching tests.	O	C, P	P	C, O
Capacitor bank Current switching tests	O	C, O	O	C, O

Last two shots of the test duty to be C, O

C = Close; O = open.

Criterion of Suitability of circuit breaker.

The capacitive current switching tests are performed to prove respective assigned ratings.

The breaker is considered to be suitable for respective capacitive current switching duty (Sec. 11.10.1) if the breaker is restrike free during opening and can withstand inrush currents of specified frequency and peak during closing. The switching overvoltages should be within specified limits.

11.12.1. Single Capacitor Bank Current Breaking Test

(*a*) **Requirement.** These tests are applicable to circuit-breakers which are intended for opening capacitive loads such as Capacitor banks. Capacitor banks are used for power factor improvement (reactive power compensation) at receiving end of transmission lines. The circuit-breakers used for switching such capacitor banks should have the rated capacitor breaking current.

(Ref. Sec. 3.14). These should be restrike free.

(*b*) **Rated Capacitor Breaking Current.** This is a assigned by the manufacturer on the basis of development and proving test. This current varies between a few tens of amperes and a few hundred amperes for circuit-breakers rated 12 kV, 36 kV and 72.5 kV. Alternatively, the capacity is expressed in terms of three phase MVAR given by

$$\text{MVAR} = \sqrt{3} \times \text{kV} \times \text{kA}$$

For example at 36 kV circuit-breaker with rated capacitor breaking current of 600. A will have a breaking capacity equal to

$$\sqrt{3} \times 36 \times \frac{600}{1000} = 37.4 \text{ MVAR}$$

(*c*) **Test Circuit.** The tests can be either single phase tests or three phase tests depending upon available test facilities. (Ref. 11.6). The tests are conducted with two types of supply circuits as follows :

Supply Circuit I. With higher inductance on supply side such that short-circuit current is less than 10% or rated short-circuit current.

Supply Circuit II. With low inductance on supply side such that short-circuit is more than 100% rated short-circuit current.

(*d*) **Test Duties.** The single capacitor breaking test comprises for test duties as mentioned below. For each test duty, 10 shots are taken for three phase tests or 12 to 30 shots for single phase tests.

Test Duty	*Supply Circuit (See clause C)*	*Test current as a percentage of rated capacitor breaking current*
1	1	20 to 40%
2	1	100 to 110%
3	2	20 to 40%
4	2	100 to 110%

The tests sequence in Test Duty 4 are make-break tests.

(*e*) **Severity and Performance Evaluation.** During closing on capacitor banks, the inrush currents have high frequency. The energy released in prearcing causes heating and pressure rise which depends on magnitude and frequency on inrush currents. Each circuit-breaker has a limit of closing duty with regard to frequency and magnitude of current.

During opening operations, the circuit-breaker should not restrike and should not produce over-voltage above permissible limits (Ref. Sec. 3.19, Table 3.4)

11.13. CABLE-CHARGING BREAKING CURRENT TEST

(*a*) **Requirement.** The circuit-breaker for opening high voltage cables or cable networks should be capable of interrupting the charging currents of cables successfully with the over voltage within specified limits. The recommended value of rated cable charging breaking current are as follows :

Rated Voltage	*Rated cable charging breaking current*
kV	*A*
3.6	10
7.6	10
12	25
36	50
72.5	125
145	160
245	250
420	400

(*b*) **Test Conditions.** These tests are either field tests or laboratory tests. Field tests are conducted on actual cable. Laboratory tests are conducted by employing cables or capacitors. Single phase tests are permitted for 36 kV and above.

Test Circuits

Test circuit 1 has such impendance that the S.C. current does not exceed 10% of rated short-circuit current of the breaker. Test circuit 2 has impedance that short-circuit current exceeds rated short circuit current of the circuit-breakers.

(*c*) **Test Duties.** For each of the duty 10 to 12 opening and at least two make-break operations are conducted.

Test Duty	*Supply Circuit*	*Test current as per cent of rated cable changing breaking current*
1	1	20 to 40
2	1	100 to 110
3	2	20 to 100
4	2	100 to 100

11.13.1. Small Inductive Current Breaking Tests

(*a*) **Requirements.** The circuit-breakers to be used in following cases should have assigned value of Rated Small Inductive Breaking Current.

— Steady magnetizing current of power transformers.

— Inrush currents of power transformers.

— Currents of shunt reactors or reactor loaded transformers.

— Currents of small high-voltage motors during starting periods.

The term 'small inductive current' refers to current having power factor less than 0.15 and which are usually lower than the rated normal current of circuit-breakers. In some cases (in-rush current of transformers or motors) the value of small inductive current may be more than the rated current of the circuit breakers.

The circuit-breaker should not produce over-voltage beyond the specified limits during breaking of small inductive currents.

(*b*) **Rated Small Inductive Breaking Current.** The Rated Small Inductive Breaking Current Capacity is the highest value of small inductive current which the circuit-breaker is capable of breaking with over-voltages within specified limits.

The frequencies of TRV are based on duration of first loop of voltage after final current zero. (Ref. Sec. 3.12).

(*c*) **The Test Circuit.** The Test circuit is illustrated in Fig. 11.8. Tests are either single phase or three depending upon the availability of load.

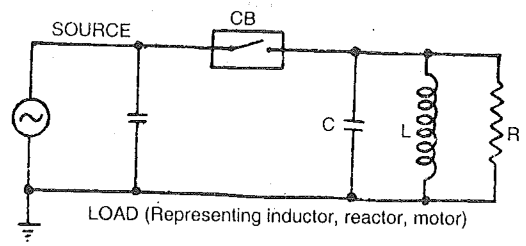


Fig. 11.8. Test Circuit for Small Inductive Current-Breaking.

(*d*) **Test Results.** The circuit-breaker should be capable of opening the circuit with overvoltages with specified limits. In case, overvoltages are beyond the limit, suitable surge suppressors (R-C) combination should be connected on load side and interrupter design may be modified. Switching resistors may be incorporated in the circuit-breaker. (Ref. Sec. 3.13.)

11.13.2. Recommendations for Small Inductive Current Switching Tests

The switching overvoltages produced by small inductive current switching are related with current chopping phenomena. The overvoltage waveform can have different shapes. It is difficult to assess the degree of effect of such wide range of wave shapes on insulations of loads and supply circuits.

Clean shopping overvoltage without reignitions may be compared with standard switching Impulse Wave (SIW) of 250/2500 μs in case of EHV circuit switching.

For medium voltage circuits standard Lighting Impulse voltage wave (LIW) of 1.2/50μs may serve as guideline. Recommendations of IEC 56 1987 for small inductive current switching tests are summarised below :

1. Transformer magnetizing current for circuit-breakers with rated voltages of 100 kV and above.

Experience indicates that when interrupting magnetizing currents of unloaded transformers under steady state conditions and at voltages not exceeding their rated voltage the over-voltages are small. Tests are therefore, not specified to simulate this switching condition.

Switching of the inrush magnetizing current of an unloaded transformer is not a normal service condition and no tests are specified.

2. Transformer magnetizing current for circuit-breakers with rated voltages below 100 kV.

Generally tests are not required but in cases of doubt they should be made on the system under actual service conditions. If this is not possible, three-phase tests may be made in a laboratory using the actual transformer to be switched in service. In either case, the source circuit should have as low a capacitance as possible subject to the rated TRV not being exceeded. Any means of voltage limiting to be used in service may be connected for the tests.

3. Transformer with a teritary winding loaded with reactors.

This shall be considered a special case and agreement reached between manufacturer and user.

4. High voltage motors.

A test circuit is under consideration of IEC (1988)

5. Shunt reactors.

A test circuit is under consideration if IEC (1988)

11.14. REACTOR SWITCHING TEST

The laboratory tests do not give true representation of actual network conditions. However, laboratory test has been proposed by CIGRE (1987) and is likely to be recommended in the next revision of IEC 56.

(*a*) **Test Duties**

CIGRE 1987 recommends the following test circuit for Medium Voltage and High Voltage Reactor switching.

Rated voltage of CB kV	*Test duty*	*Current**	*Natural frequency of Load" kHz.*	*Natural frequency of Loop Hz*
12-36	A	500	9-11	150—200
	B	1500	18—22	150—200
	A	2300	1.8—2.2	150—200
36-72.5	B	500	3.6—4.4	150—200
	A	100	0.9—1.1	150—200
72.5 and above	B	300	1.6—1.8	150—200

(*b*) **Purpose of Test.**

Reactor current breaking tests are performed with following purposes :

A1. To prove the interrupting ability of the CB or the switch to interrupt the reactor currents.

A2. To confirm that reignitions occurring during reignition are not harmful.

A3. Investigations of the breakers behaviour mainly in respect of overvoltages production with following respects.

— to determine maximum chopping current.
— to investigate statistical distribution of the chopping current.
— to investigate statistical distribution of the chopping current.
— to investigate reignition probability, to determine the range of point-of-wave settings with reignitions.
— to estimate the dielectric characteristic of contact gap.

Conclusions.

Interruptions of reactor currents may create overvoltage of the two types :

— Chopping overvoltages having high magnitudes of time duration approximately corresponding to switching impulses.
— Reignition overvoltages overvoltage having time duration similar to lightning impulses but lower crest values.

Expected over voltages.

Chopping overvoltages : below 2 p.u.

Reignition overvoltages : 2 p.u.

For circuit-breakers of rated voltages above 275 kV overvoltages above 2 p.u. may not be permitted.

Method to Limit Overvoltages during Reactor Switching.

— Use of opening resistors with current breakers

* Current of p.f. less than 0.15.

** For first pole-to-clear, the worst overvoltages occur due to current chopping at lower values of currents. Hence test duties A performed with lower value of current.

— Use of ZnO arresters near the circuit-breaker

— Use of high capacitance between breaker and reactor connected between phase to earth.

Means to Limit switching overvoltages during opening of small inductive currents and reactor currents include the following.

1. *Use of opening Resistors* (Resistor Switching)

To reduce the overvoltage amplitudes, two different ranges of opening resistors are used.

— Resistance values of the order 10 to 50 Kilo-ohms per phase.

— Resistance values of the order 1 to 5 Kilo-Ohms per phase.

The resistances used for damping TRV of short circuit currents interruption are several hundred ohms (for line CB) down to a few ohms for generator CB.

Resistance current is interrupted by auxiliary break.

2. *Use of ZnO Arresters in parallel with the circuit-breakers.*

This is an alternative to the use of opening resistors to reduce peak-to-peak excursion of overvoltage due to reignition.

The protective level of the ZnO arrester may be kept between 1.5 p.u. and 2.0 p.u. However additional surge arresters are essential for phase to ground between the CB and the reactor.

3. *Capacitor between breaker and reactor.*

This reduces steepness and amplitude of overvoltage. However it complicates the generation and limitation of overvoltage.

Special Note

Laboratory tests for reactor switching and low inductive current switching are for obtaining information about the influence of the CB on the overvoltages. For determination of overvoltages in actual installation, field testing is recommeded by CIGRE.

PART C—INDIRECT TESTING

The short-circuit power available in earlier testing stations (of the order of 4000 MVA in laboratory type testing station) is not sufficient to test a complete breaker (which is of rated breaking capacity of the order of 10,000 MVA at 245 kV). Even single pole of a EHV circuit-breaker cannot be tested by direct means. As all EHV circuit-breaker are with several arc interrupter units tested per pole each unit can be separately tested. This is called Unit Testing. From tests on one unit, the capacity of the complete pole and breaker is determined. This method of Unit Testing is adopted internationally. Synthetic testing is another popular method which permits testing of breaker of capacity 5, times that of the plant.

The important indirect Methods include the following :

1. *Unit Testing**. Which means testing one or more units separately.

2. *Synthetic Testing**. In which the current source providing short circuit current and voltage source supplying restriking and recovery voltage are different.

3. *Substitution Tests.* These are conducted for oil circuit-breaker, the characteristics of current versus time are obtained for different voltages. The performance beyond the tested values is determined by approximation.

4. *Compensation Tests.* Which are conducted on oil circuit-breakers in critical range of low current by a suitable compensation such as increased frequency, increase restriking voltages etc.

5. *Capacitance Tests.* The capacitor which is charged by a voltage source is discharged through the breaker. An oscillatory circuit provides restriking voltage.

* Most widely used indirect test used for Type Testing.

11.15. UNIT TESTING OR ELEMENT TESTING

Almost all modern EHV circuit-breakers, minimum oil, Air Blast, SF_6 etc. consist of two or more identical units (or interrupters) per pole. These interrupters operate (open or close) simultaneously and share the voltage across the pole almost equally. The breaking capacity in M.V.A. is also shared equally. Hence by testing one unit, the results can be applied to the capacity of the pole. This is known as Unit Testing or Element Testing. Element testing in an internationally accepted method.*

While applying unit test the voltage must be reduced by factor a and all the impedances should be reduced by factor a to get test voltage across the unit same at that following expressions :

$a = \frac{1}{n}$ when one unit is rested together.

$a = \frac{m}{n}$ when m units are tested together.

where n is number of units per pole.

For example consider 3 pole, 230 kV circuit-breaker with three units per pole. Test is to be conducted at normal voltage *i.e.* 230 kV between poles. Voltage across one pole is $230/\sqrt{3} = 133$ kV.

$$a = \frac{1}{n},\ n = 3$$

$\therefore$ Voltages required for testing one unit

$$= a \times 133 = \frac{1}{3} \times 133 = 44.33 \text{ kV}$$

Further : L and C of test circuit should be reduced to get same natural frequency as that direct testing, *i.e.*

$$f_n = \frac{1}{2\pi\sqrt{LC}} \text{ in Direct Testing}$$

$$f_n = \frac{1}{2\pi\sqrt{aL \times \frac{C}{a}}} = \frac{1}{2\pi\sqrt{LC}}$$

The natural frequency of transient restriking voltage remains unchanged. Time scale also remains unchanged.

With breakers in which the voltage distribution across the pole is not evenly distributed amongest the units, some units will be stressed more and the others less. The test should be performed so as to test the highest stress coming over the unit. Hence correction must be made in unit testing results. Statistically, unit testing has been established as a reliable method of testing.

11.16. SYNTHETIC TESTING

Fig. 11.9 illustrates the principle of synthetic testing.

The synthetic test employs two sources namely.

(1) Current source (of relatively low voltage)

(2) Voltage source (of relatively low current).

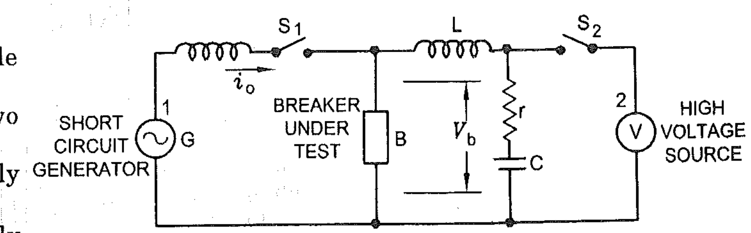


Fig. 11.9. Synthetic Testing Test Circuit (simplified).

* If two interrupters are coupled in series, the double-interrupter assembly should be tested together as a 'unit'. (Ref. Sec. 11.7 C).

If testing station has a capacity, complete breaker is tested instead of unit testing.

The current source provides short-circuit current. The voltage source provides restriking voltage plus recovery voltage. Other L, r, C etc. are used to get desired test conditions. The switch S_1 is closed to supply short-circuit current L_G. At near final current zero switch S_2 (which is usually a spark gap) is closed and V_3 is applied to the breaker at an appropriate moment. The voltage will have transient because of L and C of the circuit.

The advantages of this method are the following.

(1) The breaker can be tested for desired TRV and R.R.R.V.

(2) The short-circuit generator has to supply currents at a relatively less voltage (as compared to direct testing).

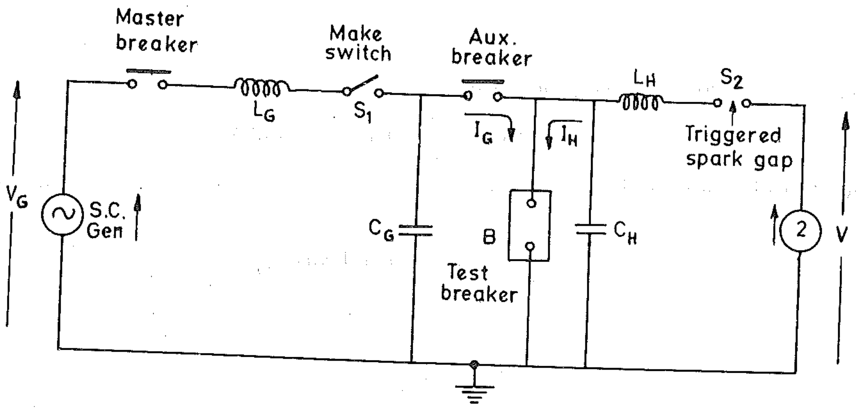
(3) Both test current and test voltage can be independently varied. This gives flexibility to the test.

(4) The method is simple. It can be applied to unit testing also.

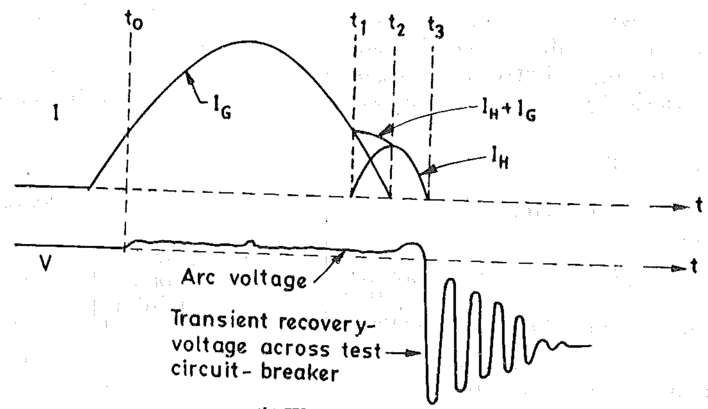
(5) With this method a breaker of capacity (MVA) of five time that of the capacity (MVA) of the test plan can be tested.

Types of Synthetic Test Circuits

There are two types of synthetic test circuit.



(*a*) Parallel current injection



(*b*) Waveforms

Fig. 11.10. Synthetic Test Circuit and waveform based on Parallel Current Injection Method.

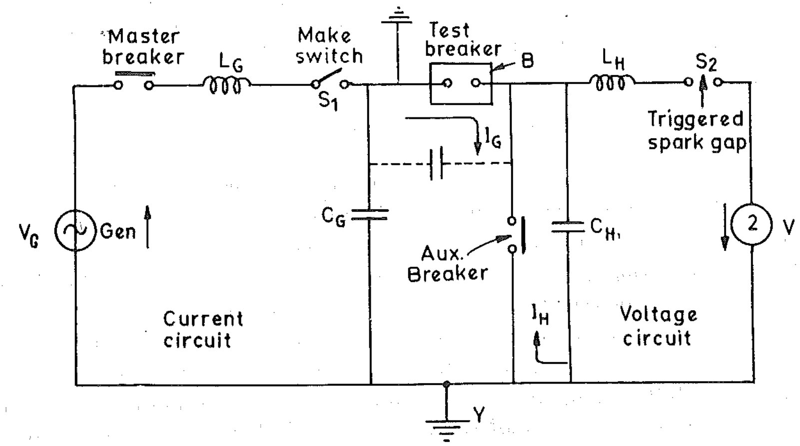
[In parallel current injection method, voltage circuit (2) is effectively connected in parallel with current (1) and the test breaker 'B' before the main current I_G reaches zero. This method is widely used for synthetic test circuits for getting frequencies of TRV]

— Parallel Current Injection Method (Fig. 11.10)

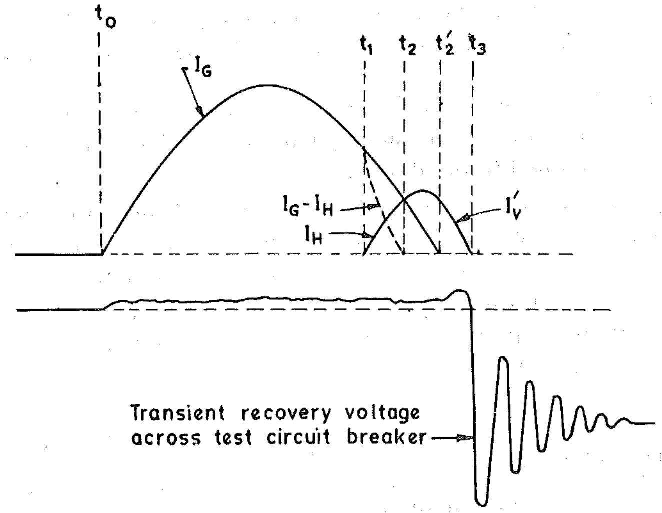
— Series Current Injection Method

Parallel Current Injection Method widely used for testing circuit-breakers because it can give high frequency transient voltages as required by standards.

Ref. 11.10 (*a*). In parallel current injection method, the voltage circuit (2) is effectively connected *in parallel* with current circuit (1) and the test breaker *before* the main current I_G in test breaker current is properly simulated.



(*c*) Series current injection



(*d*)

Fig. 11.10. Synthetic Test Circuit and waveform based on Series Current Injection Method.

Fig. 11.10 (*c*) represents series current injection method, in which the voltage circuit (2) is connected to current circuit in series before main current zero. As a result the I_H and I_G are in opposition in breaker circuit.

Stresses produced by synthetic test should correspond to those in actual network. This is difficult. Several factors influence the stresses during the test. These include.

— High current mode

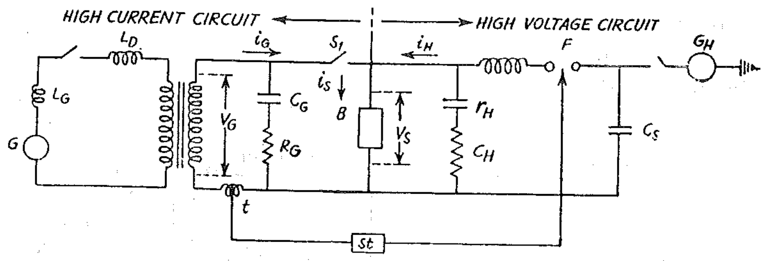
— High voltage mode

— instant of applying voltage

— t_1, t_2, t_3, t_2 (Ref. Fig. 11.10)

— frequencies of TRV etc.

Brown Boveri's Synthetic Testing Circuit. Synthetic test circuit shown in Fig. 11.11 is used by Brown Boveri, Switzerland. It is used in such a fashion that the short-circuit current is supplied from a circuit at a relatively low motive voltage while the restriking and recovery voltage is supplied by a separate H.V. circuit.



G_H = H.V. Generator
S_1 = Auxiliary breaker is high current circuit
L_G L_D = Inductance in high current circuit
S_t = Control unit for triggering sphere gas F
I_G V_G = Current and voltage in high circuit
C_2 = Supply capacitance of H.V. circuit
G = Short circuit generator
T = Transformer in high current
B = Breaker under test
i_H = Current h.v. circuit.
F = Spark Gap
I_B = Breaker current : V_s = Voltage
C_G R = Capacitance and resistance for regulating the natural frequency of high current circuit.

Fig. 11.11 Brown Boveri's Synthetic Testing Circuit.

The circuit on the left side of the breaker under test B is high current circuit which consists of short-circuit generator IG, short-circuit transformer and also capacitor C_G and resistor R_G C_G and R_G control the natural frequency of high current circuit. The short-circuit power is supplied at a voltages V_s which corresponds to about 30 kV, this voltages is smaller than recovery V_s required for testing the specimen. The recovery voltage is supplied by a separate voltage circuit on the right side of breaker B.

The auxiliary breaker S_1 is opened simultaneously with the tested breaker B and a few microseconds before the current interruption (i_G) in breaker B, the spark gap is triggered by control S_t and the voltage V, is applied to breaker B.

The current i_H has a natural frequency of 500 Hz and an amplitude of one-tenth of that of current i_G. The currents are superimposed in current zero zone in such a way that during final 100 micro-seconds only current i_H is flowing through breaker under test B. The auxiliary breaker S_1 interrupts high current circuit from H.V. circuit before current $i_S = i_G + i_H$ is interrupted by breaker B and breaker B has to interrupt only current i_H. The restriking voltage across breaker B is, therefore, given by that of H.V. circuit.

11.17. SUBSTITUTION TEST

In oil circuit-breaker the current to be interrupted provides the internal sources of extinguishing energy. Therefore the arc duration depends upon the current to be interrupted *i.e.* for lower currents breaking time is more and for higher currents the breaking time is less. In subsitution test a number of tests at closely graduated capacities are conducted on the breaker with internal source of extinguishing energy. Characteristics of arc duration and current to interrupted are plotted (Fig. 11.12).

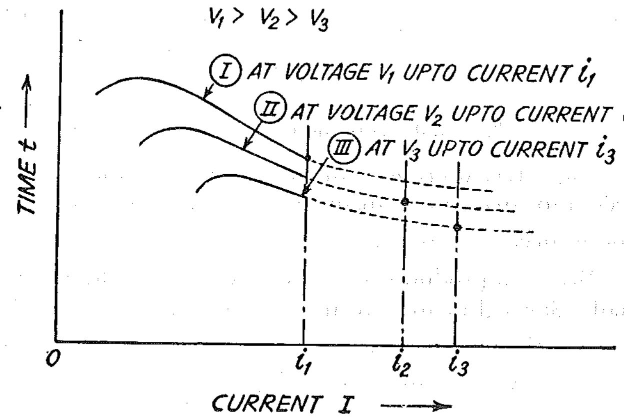


Fig. 11.12 Substitution test characteristics.

These are development tests.

The substitution test is conducted as follows :

(1) Test the breaker at full voltage and upto current permitted by the capacity of the plant, *i.e.* current i_1 of characteristic *I*.

(2) Test the breaker at reduced voltage upto current i_2 permitted by the test plant at reduced voltage V_2 obtain the time required for various current upto i_2 and plot characteristic *II*.

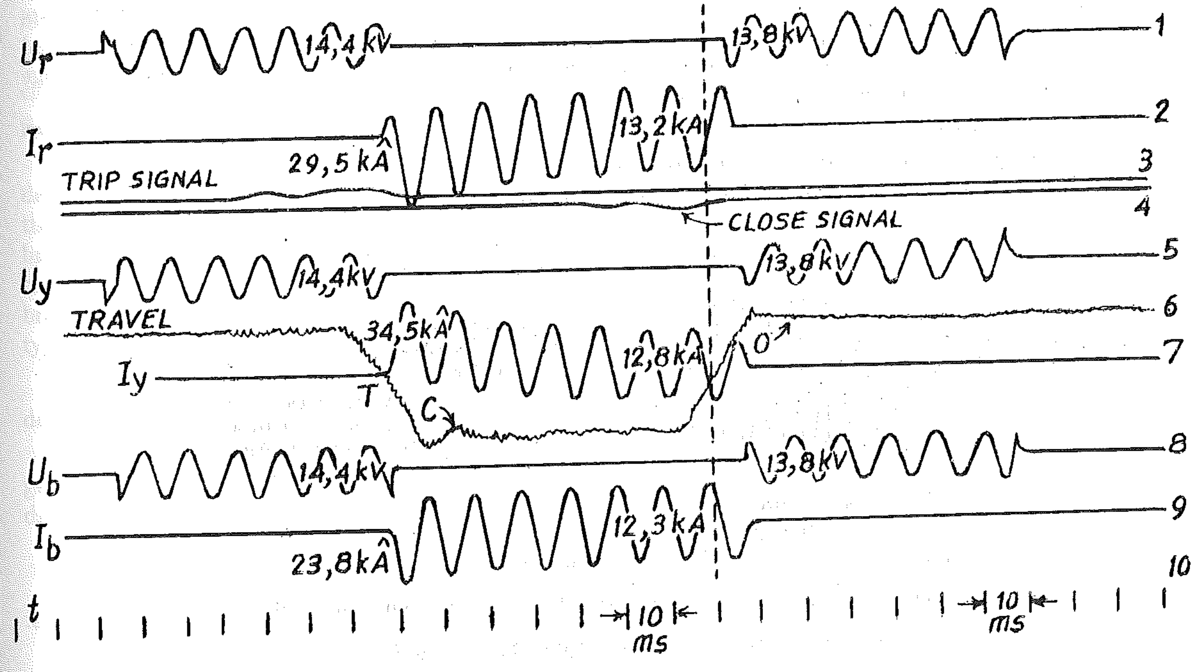


Fig 11.13. Record of 'C-O' operation during a short-circuit test on circuit-breaker.

Channels of U.V. Recorder :

U_r, U_y, U_b = Applied Voltages	3 = closing signal	I_r, I_y, I_b = Short-Circuit Current
4 = opening signal	T = Contact Travel	C = Closed
t = Timing marks	O = Open	

(3) Likewise, plot characteristics III at voltage V_3 upto current i_3, characteristic IV at voltage V_4 upto current i_1 etc where V_1 is the highest test voltage $V_1 > V_2 > V_3 > V_4$ etc. i_1 is the current at voltage V_1 permitted by test plant.

On plotting the characteristic I, II, III, etc, these are extended by approximation as shown by the dotted lines. Form the extended line the breaker performance can be predicated for values of current beyond range of testing station.*

11.18. CAPACITANCE TEST*

In this text a capacitor is charged by a d.c. voltage source. Capacitor is connected in series with an indcutor and making switch. The breaker is connected across the capacitor. C and L from oscillatory circuit. The circuit-breaker under test is opened and voltage across the capacitor is dis-

* These methods are used for development and research, and not for certification tests. These are not used by designers any more. The stresses occuring at full voltage and full current cannot be simulated by these tests.

Field Testing. The most convincing testing of circuit-breakers for proving capability of load switching without exceeding overvoltages is testing in actual installation. At least 30 switching operations should be carried out.

charged through the arc. The arc gets extinguished at a current zero. This test is used for investigating the behaviour of the breaker towards restriking voltage.

11.19. COMPENSATION TEST*

Oil circuit-breakers have internal source of extinguishing energy. For low currents extremely difficult extinguishing conditions may be experienced because of insufficient pressure build up. The characteristics of the breaker in critical range are ascertained by compensation test. These tests are conducted in critical range. In the test, the pressure in the arc extinction device, lengths and durations of arc etc. are recorded, test being conducted at reduced voltage. The reduction in voltage is compensated by some other factor such as :

(1) Increased frequency.

(2) Applying impulse voltage at current zero.

(3) The pressure in the tank of an oil circuit breaker is given by

$$p = kV^{0.5}I^{1.2}$$

The effect of reduced voltage can therefore be compensated by increasing current.

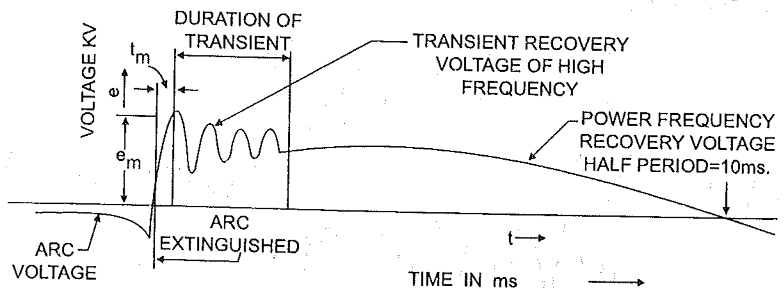


Fig. 11.14. Record of transient recovery voltage waveform on high speed CRO.

11.20. DEVELOPMENT TESTING OF CIRCUIT-BREAKERS

Table 10.2 to 10.4 gives a list of various development tests on a typical circuit-breaker.

Short-Circuit Development Tests : In earlier stages of circuit-breaker development the development tests were conducted on scaled models. Now, full scale prototype are subjected to development tests.

A complete programme of short-circuit development tests is drawn and adequate numbers of full scale prototypes are built. The important components in the interrupter such as contacts, nozzles etc. are made interchargeable.

The parameters which have a significant influence on the short-circuit performance of a circuit-breaker are identified. Their range is selected. For example, the diameters of contact may be in the range of 30 mm to 45 mm. In this case three to four contacts may be selected for development testing.

Three important parameters which determine the short-circuit performance of a circuit-breaker include.

1. Contact separation and the time-travel characteristic during opening operation.
2. Short-circuit current magnitude and its co-relation with the contact separation, speed and flow of quenching medium.
3. Arcing time and energy in arc. Parameters are varied and the performance of the circuit-breaker is analysed.

* These methods are used for development and research, and not for certification tests. These are not used by designers any more. The stresses occuring at full voltage and full current cannot be simulated by these tests. **Field Testing.** The most convincing testing of circuit-breakers for proving capability of load switching without exceeding overvoltages is testing in actual installation. At least 30 switching operations should be carried out.

Effect of Time-Travel Characteristic : The most important parameter is the time-travel characteristic during opening stroke and the number of current zeros. If speed is increased, the number of available current zeros during effective portion of travel is reduced. If speed is reduced the number of available current zeros is more, but the pressure in SF_6 puffer cylinder may be inadequate.

During development testing, the time-travel characteristic is optimized.

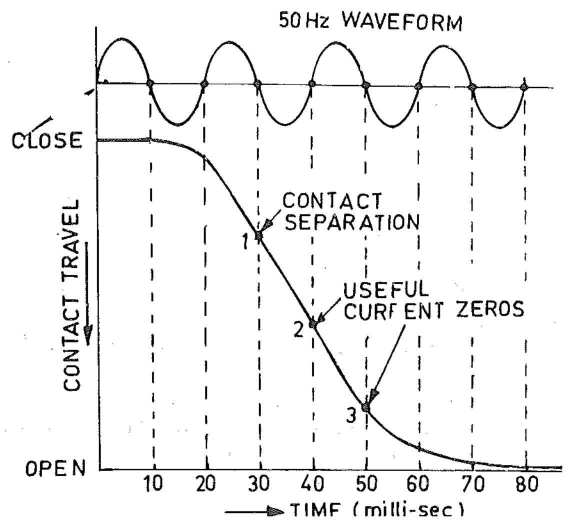


Fig. 11.15. Time-travel characteristic for opening stroke.

Summary

Short Circuit Tests provide a useful data for design and development of circuit-breakers and they are necessary to prove the making capacity, breaking capacity, breaking capacity, short time capacity and specified operating duty of the circuit breaker. The short circuit testing stations are filed type or laboratory type.

The number of useful current zeros, 1, 2, 3 depend upon the contact speed.

In laboratory type testing station there are specially designed equipments such as short circuit generators, short circuit transformers reactors master circuit breakers, making device etc. In addition there are equipment for measurements and control.

Direct tests are conducted according to Standard Specifications.

In unit testing one or more units are tested and from that the capacity of the complete breaking is ascertained.

In synthetic testing separate current source and voltage source and used for testing.

QUESTIONS

1. Why are short circuit necessary ? What information can be obtained from the short circuit tests ?
2. Describe with neat sketch the layout of a simple short circuit plant. Give details of equipment.
3. What is the difference between field testing and laboratory testing ? Explain the relative merits of each.
4. Describe the procedure of direct testing of a three phase circuit breaker for short circuit testing. Explain how is the making capacity, breaking capacity and short time capacity determined.
5. Explain the standard procedure of determining rate of rise of restriking voltage from a single frequency transient.
6. What is the difference between direct testing and indirect testing ? What are the various procedure of indirect testing ? Describe

   (*a*) Unit testing (*b*) Synthetic testing.
7. Calculate the natural frequency for a circuit having inductance 1.9 mH/km per phase capacitance 7.5 n F/km phase to earth, length of circuit 10 km.
8. With neat diagrams, explain the principle of synthetic testing.

   State the difference between 'Series Current Injection' and 'Parallel Current Injection'.

12

Insulation Requirement and High Voltage Testing of Circuit Breakers

Introduction—Conditions in Services—Design Aspects—Insulation failure—Some terms—Purpose of H.V. testing—Tests conducted—Application of voltage—definitions—Test voltage—Impulse tests—Power frequency voltage withstand test—Dry/wet—Test on auxiliary circuit—Standard test wave—Summary

12.1. INTRODUCTION

The current carrying parts of circuit-breakers are insulated from earth. Insulation is also provided between conducting parts of different phases. These insulations are subjected to normal voltages, internal and external overvoltages. The insulation in circuit-breakers serves three purposes :

— to provide insulation between phase and earth.
— to provide insulation in the contact-space during 'open' breaker.
— to provide insulation between phases.

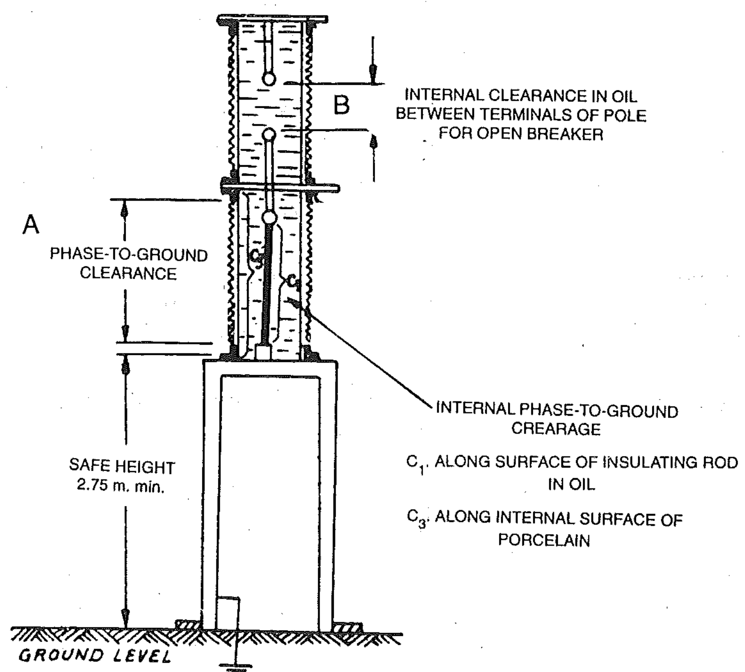


Fig. 12.1 Explaining insulation requirements of an outdoor circuit-breaker.

12.2. OVERVOLTAGES (Ref. Ch. 18. Ch. 46)

To insulators should withstand the over-voltages occurring due to internal and external causes.

The over-voltages are of three categories :

— Power frequency over-voltages, temporary over-voltages. *
— Impulse voltage surge due to lightning and switching.

The sustained power-frequency over-voltages occur due to regulation, Ferranti effect, etc. (Ch. 18)

The type of earthing (solid/resistance) influences the magnitude of over-voltages. For system above 145 kV the magnitude of internal over-voltages is significant. These are caused by switching, transients and travelling waves.

Impulse voltage surges occur due to lightning and switching. The switching impulse wave lasts for some hundreds of micro-seconds.

The performance of insulators is varified by power-frequency tests and impulse tests.

12.3. DESIGN ASPECTS (Ref. Sec. 2.18)

The following aspects should be considered

— Voltages to which the equipment is subjected during service conditions and during high voltage tests.
— The voltage gradient at conductor surfaces and along solid insulator surfaces at the voltages mentioned above.
— Technical data about electrical properties of the solid/liquid/gaseous dielectric materials employed in the equipment.

The stresses are calculated with the help of Electric Field Plots. Digital computation. The designs are based on intensive development tests (Ref. Ch. 10).

12.4. CAUSES OF FAILURE OF INSULATION

(*A*) **Tracking of Solid Insulators.** Tracking is formation of premanent conducting path along the surface of insulator. The following are the causes :

— Degradation of surface glaze by sparking.
— Presence of conduction film along the surface of insulator due to moisture, dirt, layer, etc.
— Mechanism of sparking along the surface arising due to breaking of leakage currents along the surface.

To prevent tracking the insulators should be dry, surface condition should be undamaged and clean. Insulators should be cleaned regularly.

(*B*) **Breakdown by discharge in solid Insulating Material.** The discharge occurs on the surface or within the insulator wherever the stresses exceed breakdown value. The surface discharge is caused by higher stresses, than permitted by the surface. The discharges within the insulator are caused by cavities, poor design/manufacture, presence of moisture.

The high voltage tests cause a harmful effect on the insulators. Though high voltage tests are intended to detect defects, the insulator suffers higher stresses during such tests and becomes weaker. Hence HV tests should be applied only when necessary, unnecessary, tests should be avoided.

(*C*) **Thermal Breakdown.** Heat is generated in the electrically stressed insulation, due to dielectric loss and conduction currents. Heat is imparted to insulation by the neighbouring current carrying parts. Heat is lost by the insulators by conduction, convection and radiation. Special cooling facility is provide wherever necessary. Resistivity of some dielectric materials decreases with

* Supply connection should be preferably to upper terminal and not to Lower terminal Isolators should be switched open after switching off the breaker.

increase in temperature whereas the loss angle increases. Thermal equilibrium implies a stable temperature at which the heat lost is equal to heat gained. If thermal stability is lost (say to inadequate cooling), the temperature rises indefinitely, leading to insulation failure.

Increasing the thickness of insulation indefinitely does not prevent insulation failure caused by thermal effects.

(*D*) **Failure of Electrical Insulation caused by Chemical Deterioration.** Some organic insulating materials show slow instability which increases with time and temperature. Paper loses its mechanical strength within a few days at temperature of the order of 150°C, even if it is protected from moisture and air. Oxygen and moisture cause rapid deterioration at such temperatures.

Moisture causes deterioration of transformer oil and other insulating materials whether solid/liquid/gaseous. Moisture has created special problems in SF_6 equipment. The moisture gets condensed on insulator surface and cause flashover.

At temperatures of 400—500°C, mica products slowly deteriorates, both electrically and mechanically.

(*E*) **Effect of Oxygen and Humidity.** Some organic and inorganic materials oxidise in presence of oxygen, ozone, particularly when exposed to light. Polythelene oxidises when exposed to bright sun-light. Rubber oxidises and cracks when exposed to light. Epoxy insulators are not suitable for outdoor use.

Some materials absorb moisture and lose electrical and mechanical strength under humid conditions due to hydrolysis. Polythelene, cellulose esters, other polysters are typical examples of such materials.

(*F*) **Incompatibility of Dielectric Materials.** Incompatibility means not suitable to be used together. Some dielectric materials are not suitable in particular assemblies because of their incompatibility with surrounding substance. For example, some synthetic materials deteriorate rapidly when placed adjacent to current carrying copper at temperature of about 80°C.

(*G*) **Electro-chemical Deterioration.** In some insulating materials, the impurities get dissociated under electric stresses, causing ionization of the material. Thereby the material deteriorates.

(*H*) **In Presence of Arc.** The insulating gas/oil used for arc extinction gets decomposed in presence of arc. Though the products of decomposition recombine after arc extinction, some remainder remains. Thereby the insulating properties of the dielectric arc affected.

(*I*) **Breakdown in Gaseous Medium.** When the dielectric stresses at sharp points increases above the limiting withstand value the internal flash-over can occur between the live point and earth or between live points. (Ref. Sec. 7.4 (*vii*)).

12.5. PURPOSE OF H.V. TESTING OF CIRCUIT-BREAKERS

A circuit-breaker connected in the system is subjected to high voltage transients due to switching and lighting. The insulation of circuit-breaker should not fail due to such voltage surges. The characteristics of the circuit-breaker insulation are specified by standards. These characteristics should be proved by conducting high voltages tests. According to the standard specifications, certain type tests and certain routine tests should be performed on circuit-breakers. The standards pertaining to H.V. testing cover the following aspects :

(1) To define the insulation characteristics of circuit-breakers.

(2) To standardize the insulation levels.

(3) To specify the tests intended to verify insulation level and conditions under which the test are made.

(4) To specify the markings on the rating plates of circuit-breakers indicating their insulation levels.

International Electrotechnical Commission (I.E.C.) and standards institutions like Indian Bureau of Standards, specify, standards covering the above aspects. The manufacturer normally conducts the type tests and routine tests in accordance with the above standards. The following description is based on I.E.C. Publication 56-4 on alternating current circuit-breakers and refers to circuit breakers for rated voltage above 1000 V.

12.6. TESTS ON A HIGH VOLTAGE CIRCUIT-BREAKERS

The insulation level (Refer Sec. 12.7) of a circuit-Breaker is verified by means of type test and routing tests.

Type tests are conducted on one or first few circuit-breakers of each type to prove the characteristics of that type. Routine tests are conducted on each circuit-breaker.

High voltage tests on circuit-breakers are the following :

Type tests. (*a*) Impulse voltage dry withstand test.

(*b*) One minute power frequency voltages dry withstand tests.

(*c*) One minute power frequency voltage wet withstand tests.

(For outdoor circuit-breaker only). Routine tests comprise one minute power frequency voltage dry withstand tests.

All the above mentioned tests are made on complete circuit-breaker.

Application of Test Voltage

The impulse test voltage and power frequency test voltage are applied as follows :

(*A*) **With breaker closed.** Between terminals of each pole in turn and the frame of the circuit-breaker ; the terminals of all the other poles being connected to the frame of the circuit-breaker and earthed.

Table 12.1. Power Frequency Voltage Withstand test and Impulse Voltage Withstand Test For Voltages upto 72.5 kV (Reference (Values)*

Circuit Breaker Rated Insulation Level		*One Minute Power Frequency Withstand Voltage*	
Rated voltage of Circuit-Breakers kV (r.m.s.)	*Standard impulse withstand voltage positive or negative polarity kV (peak)*	*For type tests kV (r.m.s.)*	*For routine test kV (r.m.s.)*
3.6	45	21	16
7.2	60	27	22
12	75	35	28
17.5	95	45	38
24	125	55	50
36	170	75	70
52	250	105	110
72.5	325	140	140

Table 12.2 (Above 72.5 kV Reference Values)*

Circuit Breaker Rated Insulation Level			*One Minute Power Frequency Voltage withstand*	
Standard Impulse Withstand Voltage			*For type and Routine Tests*	
Rated voltage kV (r.m.s)	*Full insulation kV (peak)*	*Reduced insulation kV (peak)*	*Full insulation kV (r.m.s.)*	*Reduced insulation kV. (r.m.s).*
100	450	380	185	150
123	550	450	230	185
145	650	550	275	230
170	750	650	325	275
245	1050	900	460	395
300	—	1050	—	460
420	—	1425	—	680

* These values are for familiarity. (Ref. Sec. 3.19.2)

(*B*) **With breaker open.** (*i*) Between the terminals of all the poles of the circuit-breaker connected together and frame of the circuit breaker.

(*ii*) Between one terminal of each pole and the other terminal of the same pole connected of the frame of the circuit-breaker. In multipole circuit-breaker the corresponding terminals of each pole are connected in parallel.

Test Voltages. Test voltages are specified by standards. Examples are given in Table 12.1 and 12.2.

12.7. SOME TERMS AND DEFINITIONS. (Ref. Sec. 3.19. 1/2. Ref. Fig. 12.1)

1. *Creepage Distance.* Shortest distance between two conducting parts along the surface of the insulating material.

2. *Clearance.* Shortest distance between two conducting parts along a stretched string.

3. *Clearance between Open Contacts.* Gap between open contacts.

4. *Clearance to earth.* Clearance between conductor and nearest earthed part.

5. *Clearance between poles.* Shortest distance between conducting parts of adjacent poles of the same breaker.

6. Amplitude Factor $= \dfrac{\text{Highest peak value of overvoltage}}{\text{Amplitude of power frequency recovery voltage}}$

7. *Insulation level of circuit-breaker.* It is the combination of rated voltage, the corresponding impulse withstand voltage and corresponding power frequency withstand voltage, which together characterize the insulation of the circuit breaker as regards its ability to withstand the electrical stresses. For the sake of convenience the rated insulation level of a circuit-breaker is designated by the rated voltage and impulse withstand voltage. BIL refers to Basic insulation level or Basic impulse level.

8. *Power frequency withstand voltage of circuit-breaker.* It is r.m.s. value of alternating voltage wave of power frequency (50 c/s) which the insulation of the circuit-breaker should withstand under specified conditions of test. (Ref. Sec. 3.19.2)

9. *Ground Clearance.* Distance between ground and the highest earthed point on equipment. (Ref. Fig. 12.1—Safe height).

10. *Impulse withstand voltage.* It is the amplitude of the standard voltage wave which the insulation of the circuit-breaker can withstand under specified test conditions.

11. *Indoor circuit-breaker.* It is the circuit-breaker which is designed for installation within a building or house such that it is projected from rains snow, abnormal dirt etc.

12. *Outdoor Circuit-Breaker.* It is designed such it can be installed under the open sky. It should withstand rains snow, dew, atmospheric dust deposits etc.

Ambient conditions for test :

Temperature 20°C.

Pressure 750 mm of mercury (at 0°C).

For other temperatures and pressures the specified test voltage, should be multiplied by a factor k given by

$$k = \frac{0.386b}{273 + t}$$

where b = pressure of air in mm of mercury

t = temperature in °C

12.8. IMPULSE VOLTAGE TESTS AND STANDARDS IMPULSE WAVES

This test is necessary for all indoor and outdoor breakers. The test is carried out as follows. Standard impulse wave of specified amplitude is applied five times in succession. If flash-over or puncture of insulators does not occur, the circuit-breaker is considered to have passed the test. If puncture occurs or if on two or more applied test wave flash-over occurs, the circuit-breaker is considered to have failed the test. During the test some waves should be applied with several of polarity.

The impulse voltage wave is generated in an Impulse Voltage Generator. During the test one terminal of the impulse generator is connected to the terminal of the circuit-breaker pole. The other terminal is connected to the earth and the frame of the circuit-breaker.

The peak value and wave shape of the test voltage is recorded by means of Cathode Ray Oscillograph with a calibrated voltages divider.

Voltage divider is used to reduce the voltage for measurement.

Impulse Voltage. An impulse voltage is characterized by

(*a*) Polarity

(*b*) Peak value.

(*c*) Virtual front T_1

(*d*) Virtual half time T_2

(*e*) Virtual time chopping T_e.

Standard lightning Impulse is a full impulse having a front time 1.2 m-sec and time to half value of 50 μ-sec. It is 1.2/50 impulse (Fig. 12.2).

Standard switching impulse wave is characterised by prolonged wave-front and wave tail. The typical switching impulse wave has front time of the order of 250 μs and half-time of 2500 μs. The permissible deviation in the crest value is of the order of 4 to 12%. The switching impulse wave has been specified for high voltage circuit-breaker rated 420 kV and above.

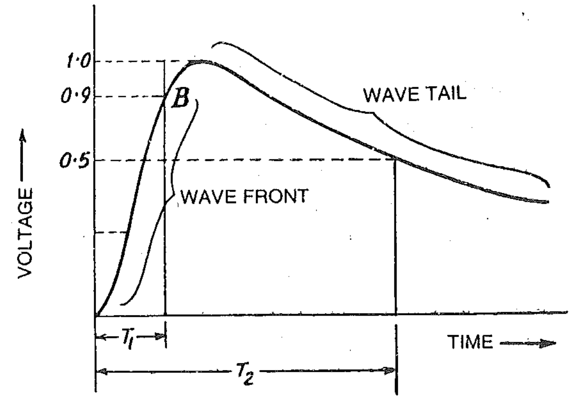


Fig. 12.2. Standard impulse wave.

12.9. IMPULSE GENERATOR

In impulse tests impulse voltage wave having a steep wave front and flat wave tails and high amplitude are usually applied to called 'Mark Circuit'. (Ref. Fig. 12.3). Capacitors C_1, C_2.......are charged by the rectifier to certain voltage. When the gas S is triggered by means of a spark the capacitors C_1, C_2........etc. discharge through series gap S_1, S_2 etc. and the impulse wave is applied to the apparatus under test. The total d.c. voltages is sum of voltages of capacitors.

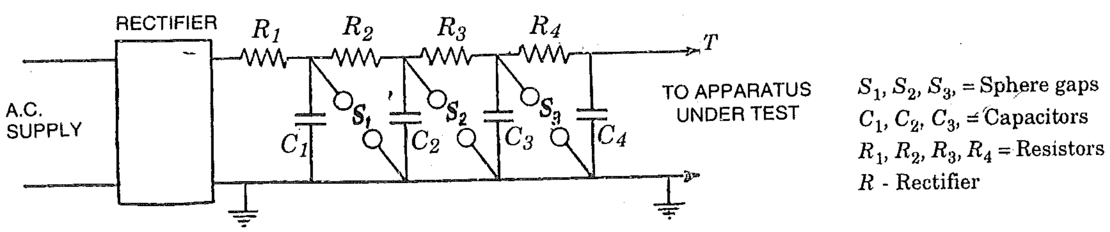


Fig. 12.3. Circuit of impulse generator.

12.10. TEST PLANT FOR POWER FREQUENCY TESTS

High voltage tests are conducted on electrical machines, switch gear, insulators, cables etc. These tests are conducted in high voltages tests laboratory. The equipment for conducting power frequency high voltage tests are the following :

(1) **Voltage source :** Single phase generator driven by a.c. motor. The terminal voltage can be varied widely changing the field current.

(2) **High voltage transformer :** These are single phase transformer units. For obtaining high voltage the units are connected in cascade.

(3) **Apparatus for voltage regulation :** During the test, the voltage is raised gradually. It is held at specified value for one minute.

(4) **Apparatus for voltage measurements :** Special methods are developed for high voltage-measurement. These include (*i*) sphere-gap, (*ii*) transformer ratio method, (*iii*) potential divider, (*iv*) methods of measuring peak voltage etc. Sphere gap is used for calibration of high voltage measurements.

(5) **Switchgear and protective relaying :** Safety device. Switchgear components include gate switch circuit-breaker etc.

In addition to the equipments (1) to (5) mentioned above, the following equipment is usually provided to conduct D.C. test, high frequency tests and impulse test.

(1) Instruments for measurements and record

(2) Devices to obtain high voltage D.C.

(3) Devices to obtain high frequency supply.

(4) Devices to obtain impulse wave.

(5) Equipment for testing dielectric oil, etc.

Fig. 12.4 gives a simplified diagram of H.V. testing circuit for power frequency test.

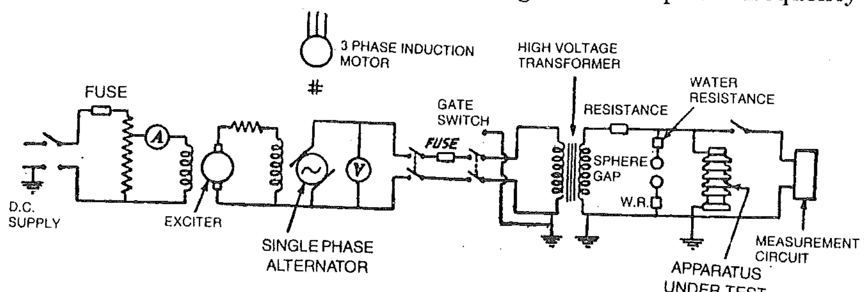


Fig. 12.4. Circuit for Power Frequency Voltage Test.

Description of Circuit. Fig. 12.4 illustrates, the arrangement in a test circuit. The test voltage is obtained from a single phase a.c. generator driven by an induction motor. The terminal voltage can be varied widely by changing the field current. The generator voltage is stepped up by high voltage transformer. The test voltage is supplied to the apparatus under test. The sphere gap is connected in parallel with the test specimen. The voltmeter on generator side, *i.e.* L.T. side can be calibrated by means of sphere-gap. In addition instruments for measurements may be connected on H.T. side by means of potential divider. Resistances are connected in the H.T. side to limit the current after breakdown. Circuit-breaker opens and protects the circuit in case of breakdown.

12.11. H.V. TESTING TRANSFORMER

Such transformers are single phase units. For obtaining test voltages upto 500 kV, usually a single unit is used. For higher voltages of 1000 kV and upwards two or more transformers are

generally used and are connected in *Cascade*. This method is convenient because a single unit for very high voltage is very large and costly. Cascade condition gives flexible test conditions. Cascade connection is illustrated in Fig. 12.5.

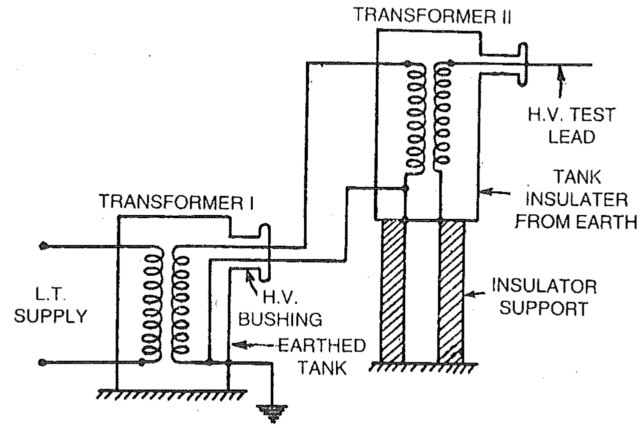


Fig. 12.5. Cascade connection of H.V. testing transformers.

Therefore, the insulation of H.V. Testing Transformer should be carefully proportioned. When the test specimen breaks down, the current is limited by insertion of water resistance in the circuit (Fig. 12.4). The kVA capacity of the testing transformers is relatively low (limited by 1 amp.) because current is relatively low.

Control of voltage is obtained by any one of the following methods :

(1) Variation of alternator field current.

(2) Tapped transformer.

(3) Resistance and inductance on supply side.

(4) Induction regulator.

The switchgear in the layout consists of main-switch circuit breaker, gate switch and is provided, with over-voltage relay, over current relay, interlocks, earthing facility and safety measures. The gate switch is placed ion the gate of screen enclosing the test field. It disconnects the supply to the transformer and earths the primary as soon as the gate is opened. Hence nobody can enter the test field when the HV transformer is energized.

The size and shape of conductor on test side-should be carefully designed so that no corona occurs. The diameters of conductors are at least 2.5 cm for 100 kV and 30 cm for 1000 kV to avoid corona under normal conditions and ample cleanness are provided.

12.12. SPHERE GAPS

Purpose. Sphere gaps are used for measurement of high voltages such as peak value of

(*i*) Power frequency alternating voltages.

(*ii*) Impulse voltage waves.

(*iii*) Direct voltages.

The procedure consists of establishing a relation between high voltage as measured by the sphere gap and indicating voltmeter, an oscillograph or device connected for voltage measurement. Under standard test conditions the voltage measured by sphere-gap can be derived from the spacing. It means from the known diameter of spheres, known test conditions and known spacing of gaps the peak value of disruptive discharge voltage can be derived from the standard table. From this value the other measuring instrument can be calibrated.

Description. Standard sphere-gap is a peak voltage measuring device constructed and arranged according to the rules specified by the standards, some of which are given below. Before conducting a test, the standards pertaining to High Voltage Testing Techniques and Sphere Gaps should be thoroughly studied. The sphere gap consists of two metal spheres of equal diameter (D) with their shanks, operating gear, insulating support, supporting frames, leads upto the point at which the voltage is to be measured. The standard values of diameter D recommended by I.E.C. Specification are the following twelves.

D = 2-5-6.25-10-12.5-15-25-50-75-100-150-200 cm (12 Standard Diameters)

One sphere is preferably connected directly to earth and the frame of the circuit-breaker. If resistance is connected in this circuit should be of a low value.

The other sphere is connected to high voltage conductor. The lead coming from high voltage transformer or impulse generator).

Measurement

Direct and Alternating Voltage. The voltage with a low magnitude is applied so that the transient switching surge voltage should not cause disruptive discharge. The voltage is increased gradually so that the voltage at which the disruptive discharge occurs, can be read accurately on low voltage indicator. Alternatively a constant voltage is applied across the gap and the spacing between spheres slowly reduced until disruptive discharge occurs.

The final measurement should be the mean of three successive readings agreeing within 3%.

Impulse voltages. Impulses are obtained from impulse generator. The interval between application of impulses should be at least 5 seconds. The charging voltage or spacing of the gap is adjusted till 50% probability of disruptive discharge is obtained. To obtain 50% probability, final reading is obtained by interpolation between the readings obtained with either (1) Two gaps or (2) Two voltage settings.

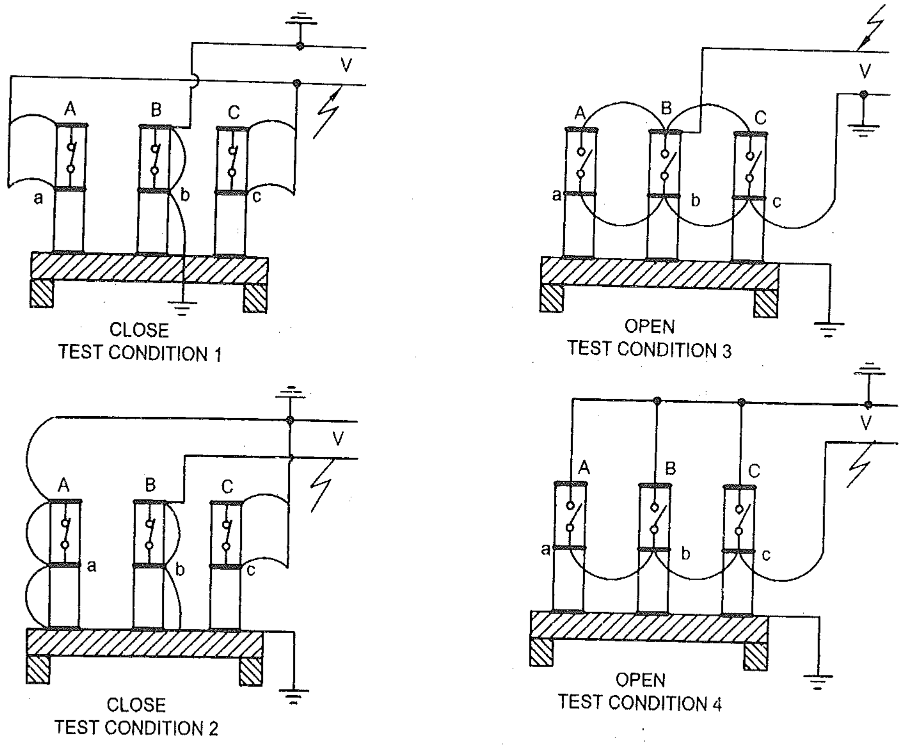


Fig. 12.6 Application of test voltage for power frequency tests and impulse test.

The readings should be such that in one case out of six applications of voltage 2 or less discharges occurs. In the second case out of 6 applied voltages 4 or more discharges occur.

Transformer Ratio Method. An indicating voltmeter is connected on L.T. side of high voltage testing transformer. The voltmeter is calibrated by means of sphere-gap connected on H.T. side. Once the voltmeter is calibrated, the voltage on L.T. side be measured by the same voltmeter and the voltage on H.T. side be obtained on multiplying with trans ratio.

Potential Divider Methods. In this method, capacitor potential divider (or resistance divider) is connected across the H.T. winding of high voltages testing transformer. The potential divider consists of several air capacitors in series. The voltage across one capacitor is a definite fraction of the total voltage. This smaller voltage is measured by means of electrostatic voltmeter.

Summary

High voltage circuit-breakers are subjected to type test and routine tests which include High Voltage tests :

(1) Impulse withstand test. (Standard Lightning Impulse)

(2) One minute power frequency voltage withstand test-dry.

(3) One minute power frequency voltage withstand test-wet.

(4) Impulse withstand test (Standard Switching Impulse-For 400 kV and above).

Test Condition No.	*Circuit-breaker*	*Voltage applied to*	*Earthed connection to*
1.	Close	Aa Cc	BbF
2.	Close	Bb	Aa CcF
3.	Open	ABC	abcf
4.	Open	abc	ABCF

QUESTIONS

1. State the difference between type tests and routine test. Why are high voltage tests necessary in case of high voltage circuit-breakers ?
2. What is the purpose of conducting high voltage tests on circuit-breaker through they are basically switching devices ?
3. Explain the methods of applying tests voltage in high voltage testing of circuit-breaker.
4. Define the 'insulation level' of a circuit-breaker.
5. Explain the procedure coducting power frequency voltages withstand test on a high voltage circuit-breaker.
6. Explain the procedure of impulse test on a high voltage circuit breaker.

13

Installation and Maintenance

Introduction—Maintenance of circuit Breaker—Contact—Arc Control Devices—Insulators —Operating Mechanism—Relays—SF_6 Gas—Oil—Safety—Installation—Erection—Drawout type switchgear —Control panels—Outdoor breaker

13.1. INTRODUCTION

The switchgear and protective relaying system should be always alert to operate against an unexpected fault. Switchgear which was in quiescent state has to operate immediately. For such an operation regular and detailed maintenance is necessary. The lack of maintenance may result in failure in operation.

The Switchgear manufacturer supplies "Instruction Manual of Installation, Operation and Maintenance.' These manuals should be carefully studied by trained maintenance staff. The code of practice booklets published by the standards institution, regulations of electrical installations are also useful. Detailed programme of maintenance of switchgear should be prepared with pre-determined intervals between inspections. The period may be one to three months for switchgear operation frequently and six months to twelve months of switchgear operating rarely. Further, it is unwise to leave the circuit-breaker close for a period longer than six months without opening, because the mechanism may become sluggish and contacts may need cleaning. Hence during the periodic maintenance, the circuit-breaker is purposely opened and closed by manual command.

The maintenance schedule is usually in the form of log sheets on which weeks, months of the year are tabulated. Each equipment in the sub-station or the plant is provided with a column. The maintenance period is indicated against each equipment. Further each major equipment is provided with a history card. The details about inspection, operation and remarks are written in these cards.

The spares, tools and instruments are important for maintenance duty. The spares are kept in stock with proper inventory control.

The maintenance work is done by trained staff according to the schedule. In case of difficult jobs the manufacturer is consulted. Operation and maintenance staff should be trained.

13.2. BREAK DOWN MAINTENANCE VERSUS PREVENTIVE MAINTENANCE

Maintenance is classified in two categories as follows :

— Breakdown or corrective maintenance

— Preventive maintenance

(1) *The breakdown on Corrective Maintenance* activities are undertaken after failure of an equipment. Such maintenance results in outage of circuit and supply. In general, it consists of locating the trouble, repair and recommissioning.

(2) *The Preventive Maintenance* is undertaken to ensure smooth and efficient working of a system, equipment. Preventive maintenance is undertaken as per schedule before breakdown of a system or machine takes place.

* Please refer : "Testing, Commissioning, Operation and Maintenance of Electrical Equipment" — Book by Khanna Publishers.

A performance record of each equipment is maintained and basing decisions on the service life of the equipment and the total number hours of service, it has put in. Repairs or replacements are made to ensure that no breakdown occurs at any time during the service.

Preventive maintenance is carried out in planned manner. Breakdown maintenance is carried out as and when necessary.

For Switchgear and protective equipment, preventive maintenance is recommended because failure of a switchgear cannot be permitted.

13.3. INSPECTION, SERVICING, OVERHAUL

Maintenance covers a wide range of activities aimed at keeping the equipment in perfect working condition for performing its function as per assigned duties. The choice of activities and schedule depends upon local requirements.

1. Inspection. The refers to the maintenance activity which comprises careful observation/scrutiny of the equipment without dismantling it. It usually includes visual and operational checks.

2. Servicing. This refers to cleaning, adjustment, lubrication and other maintenance functions without dismantling the equipment.

3. Examination. This refers to inspection with necessary dismantling, measurements and non-destructive tests to obtain data regarding the condition of components/sub-assemblies.

4. Overhaul. This refers to the work done with the objective of repairing/replacing worn-out parts and defective parts. The equipment, sub-assemblies are dismantled partly or completely. The condition of components is inspected. Dimensions of worn-out components are measured. The components worn-out beyond acceptable limit are replaced. The assembly is followed by functional checks and measurements to ensure satisfactory operation.

13.4. GUIDELINES FOR MAINTENANCE OF SWITCHGEAR

The requirement of inspection, servicing, examination and overhaul vary with

— Environmental aspects such as dust, chemical fumes, moisture/humidity, ambient temperature variations, etc.

— Operating duty; frequency of operation, rated current.

— Switching duty severity, *e.g.* repeated operations.

Manufacturer gives general guideline. It is not possible to obtain exact maintenance schedule meeting local requirement of each site. Hence maintenance schedule is determined after initial periodic inspection at each site. In case of switchgear and control and protection panels; distinction should be made between the maintenance of fixed devices like busbars, insulators enclosures and maintenance of switching devices like circuit breaker, isolator, earthing switch, contactor etc. having moving parts.

The fixed parts need regular inspection and servicing for removing dust, damp, corrosion etc.

Moving parts need regular inspection and periodic replacement of worn-out parts. The functional readiness of switching devices should also be ensured.

The maintenance of switching devices is related mainly with the wearing out of contacts, deterioration of quenching medium and mechanism components. The maintenance requirements of vacuum circuit breakers and SF_6 circuit-breakers are quite modest as compared with those of oil circuit-breakers, minimum oil-circuit-breakers. In vacuum circuit breakers, the interrupter is a permanently sealed unit and the contacts have long switching life. Puffer type SF_6 circuit-breakers have long switching life and the gas does not need replacement. Hence the present trend is to use maintenance free vacuum and SF_6 circuit-breakers.

Table 13.1 gives recommendation regarding the period of maintenance of contacts and quenching medium in terms of numbers of load operations and number of short circuit operations on rated short-circuit breaking current. The schedule should be established for each site by checking the contacts of one pole after every three months observing the rate of erosion.

During every breaking operation, contact looses and some material and the quenching medium gets decomposed. The decomposed products get deposited on the internal insulating parts of the circuit breakers. The deterioration of contacts and internal insulation is proportional i^2n, where i is breaking current in kA and n is the number of breaking operation. After cumulative $\Sigma i^2 n = K$, the contacts, internal insulation and the quenching medium needs inspection/servicing. The value of K depends upon the type of circuit breakers (Refer Table 13.1).

Table 13.1 Maintenance of Quenching Medium Contacts

Type of C.B.	*Maintenance of Quenching Medium*		*Replacement of contacts*		$K \Sigma i^2 n$
	Load Operation*	*Fault Operation*	*Load** Operation*	*Fault Operation*	
Air C.B.	—	—	3000	10 to 15	—
Bulk Oil C.B.	2000	6	2000	6	2000
MOCB	1000	3	1000	6	1000
Air Blast C.B.	—	—	15,000	25	15,000
SF_6 C.B.	5000	25	15,000	25	15,000
V.C.B.*	—	—	20,000	100	20,000

* Shelf life 20 years.

** Mechanical Endurance Test should be performed with specified number of operations on no load to confirm suitability of mechanism.

Table 13.2. Maintenance of Contacts

Type of C.B.	*Life of Contacts*	
	Number of load operations on rated load current	*Number of fault operations on rated short-circuit current*
VCB	10,000	50-100
SF_6	4,000	15-25
MOCB	1,000	3-6
Air break CB	1,000	1-6
Air Blast CB	4,000	15-25

13.5. FIELD QUALITY PLANS (FQP)

The activities in the field (site) include :

— Receipt and Storage of Equipment — Civil Works

— Installation (Erection) — Testing & Commissioning

— Operation and Maintenance; Trouble Shooting

— Overhauling

— Replacement after expiry of Life/Obsolecence

As per *ISO 9000 recommendations,* the customer's requirements for field services should be fulfilled and well-documented.

Field Quality plans contain : documents, instructions, data, drawings, formats for above, list of spares, list of tools/facilities, "Do's and Donots", Safety precautions, etc. should be prepared

by the manufacturer and sufficient copies should be given to each site. Customers operating staff should be trained in every activity. Following sections are guidelines for preparations of FQP.

13.6. MAINTENANCE OF CIRCUIT BREAKERS

Steps in Maintenance of Circuit Breakers

1. General Inspection. Observe the circuit-breaker visually. Note the cleanliness, terminals, earth connections, readings of counters, levels of quenching medium (in case of Oil Circuit-breakers) pressure of quenching medium in case of SF_6 circuit breakers etc.

2. Cleaning and Drying. Use trichloroethylene or other cleaning agent recommended by manufacturer. The fluid should be compatible with the surface to be cleaned.

Use air-pressure jet (3 kgf/cm^2) for cleaning.

Use clean cloth which does not leave fibres or particles on the surface.

Care should be taken to avoid falling of dust, iron particles, nutbolts washers etc. inside the breaker. Avoid water, moisture or dampness during the cleaning.

Congealed lubricants should be removed by means of solvents. The rolling and sliding surfaces should be cleaned, relubricated.

Before assembly of the circuit-breaker, the interrupter support porcelain components etc. should be cleaned in dry clean atmosphere.

After assembly, evacuate the breaker pole to remove moisture, dust particles etc. and then fill oil or SF_6 gas.

Internal dust and moisture causes gradual deposits on internal surface resulting in gradual increase of surface leakage currents and internal flashover due to tracking. Hence cleaning and drying is important.

Grooves for O-rings on flanges should be cleaned with trichloroethylene, air jet so as to remove hardened grease and dust. Such a dust or grease will make the uneven sitting of the new O-ring and cause gradual leakage of SF_6 gas/oil.

No dust, chalk-marks fibres, hard grease etc. is allowed on the O-ring grooves.

Terminals should be cleaned of dust, oxide coating if any by emery paper without iron particles.

3. Insulation Surface. Inspect visually, carefully for signs of cracks, tracking or any other defects.

Clean the internal surfaces and external insulating surfaces as mentioned in 2 above.

Insulation should be free from electrical or mechanical defects.

Perform insulation resistance measurement tests after cleaning and assembly. Insulation resistance measurement gives indication about the health of insulation.

In case of oil circuit-breakers and minimum oil circuit-breakers, the internal insulation should be cleaned thoroughly by means of trichloroethylene, clean cloth and air jet. The deposition of sludge and carbon particles, conducting dust particles shall be removed before reassembly.

In case of SF_6 circuit-breaker, the decomposition products (gray colour) get deposited on internal surfaces of insulators. These are non-conducting when dry. If the circuit-breaker is dismantled during moist atmosphere, these surfaces are not cleaned before assembly, the internal flashover is likely to occur despite the good properties of SF_6 gas.

In case of vacuum interrupters only external cleaning is possible.

In case of air blast circuit-breakers, no internal cleaning is generally necessary as fresh medium is used for arc-quenching. In case of porcelain-clad outdoor vacuum circuit-breaker, the pole units should be internally clean and dry to avoid internal flash-over by tracking.

Glass fibre pull rods should be cleaned thoroughly.

Particular attention should be paid to the nozzles, arc control pots. arc control plates. They should be cleaned. If burnt or disfigured, replace them.

After cleaning and drying measure insulation resistance by Megaohm-meter (Megger) between :

— Two terminals of each interrupter.
— between the terminal and earth.

4. Drying. Circuit breaker pole can be internally dried by circulating dry hot air or by evacuating to 2 mm of mercury.

In case of SF_6 circuit-breaker or porcelain clad vacuum circuit-breaker, the drying of pole units should be carried out before filling SF_6 gas or dry nitrogen.

SF_6 gas or dry nitrogen does not remove the water drops and dust deposited on the internal surface. Hence drying and evacuating is necessary.

A small portable vacuum pump with teflon hose is connected to the valve. The breaker is kept under vacuum for a few hours. Thereafter the SF_6 gas/dry nitrogen is filled.

The moisture is eliminated due to application of vacuum.

Drying is recommended before filling of fresh SF_6 gas/nitrogen/oil in the breaker.

5. Interrupter. Study the operation and maintenance manual of the circuit-breaker.

Note the important settings and measurements of moving contact, other movable parts with reference to fixed flanges and the allowed tolerance in the settings. Check simultaneous touch of 3 poles if slow closing and three lamp method.

Main activities in the interrupter maintenance include :

— Observation, cleaning, replacement of main/arcing contacts ; PTFE nozzles, arc-control pot plates etc.
— Cleaning the other parts as well.
— Replacing hardened O-rings, worn-out sliding parts.
— Removal of carbon/metallic decomposed products.
— Cleaning of venting systems to ensure free passage of oil/gases. The vents should be made free but not enlarged.
— Cleaning terminals and sliding contact surfaces.
— Assembly with proper settings of components.

6. Mechanism. Check operation 'open' ; 'close' ; 'closing followed by opening' locally. If operation O. C. CO are satisfactory the mechanism is satisfactory and does not need any major repair/maintenance.

Check operation counter. If the mechanism has operated more than 1000 times, it needs very close observation and may need overhaul. Check the condition of springs and dashpots. Two important tests to determine the health of the operating mechanism, linkages and moving contact settings include :

— Checking simultaneous opening and closing of 3 poles.
— Checking no-load times *vs.* travel characteristics of moving contact for O, CO, O-CO operations.

(*a*) **Method of obtaining Time-Travel Characteristic on no-load.** In case of MOCB or SF_6 CB poles, this characteristic is extremely important because the breaking capacity is related with the time/travel characteristics of moving contact. No-load characteristic gives sufficient indication about the health of mechanism linkages.

For satisfactory arc interruption the moving contact should open and travel with optimum characteristic.

* Insulators of circuit-breakers installed in heavily polluted areas and sea-shores need frequent external cleaning.

Slow initial movement indicates excessive friction between sliding parts.

Slow movement during middle of stroke indicates very high dynamic load during arc quenching.

Slow movement during final part of the stoke indicates excessive damping or low energy of operating mechanism during opening.

A straight rod is connected to the moving contact or movable part (contact or mechanism). This rod is in turn connected to the curvo-roller or rectilinear transducer (Travel Recorder).

Curvo-roller is a specially designed motor driven drum mounted on the top-hood of the MOCB. The pencil attached to the rod fixed on the moving contact touches the paper on the drum. The motor is driven electrically. The drum rotates at known speed. The graph sheet fixed on the drum has definite circumferential speed. During the opening stroke and closing strokes, the pencil gives the time/travel characteristic making on the graph sheet on the curvo-roller.

For high speed SF_6 circuit-breaker the curvo rollers are not suitable.

Rectilinear transducer is fitted suitably on the breaker frame. It has a cylindrical resistance with internal moving piston. The piston is attached to the rod with and swivel joint at the end.

The swivel joint and rod of the rectilinear transducer are connected to the moving rod attached to the contact movement system. In case of SF_6 or oil CB, a suitable rectilinear seal should be designed to permit movement without leakage of SF_6/oil.

The rectilinear transducer is connected like a potentiometer. The central terminal gives variation proportional to the travel of the contact.

The output is given to UV recorder. The trace of Time/Travel is obtained on U.V. Recorder. The trip signal/closing signal is also recorded simultaneously.

The Time/Travel characteristic should match with that obtained in the manufacturer works.

(*b*) **Method of checking the Contact Setting.** Follow manufacturer's instruction booklet. In case of MOCB and SF_6 ; measurement of distance from the top flange surface to the tip of closed contact may be possible.

In case of vacuum interrupter, a gauge with pointer may have been provided by the manufacturer to indicate contact erosion.

Measurement of Contact Resistance

The resistance between terminals of each interrupter and each pole is measured by means of micro-ohm meter.

The resistance across one pole is $(n \times r)$ where r is resistance per contact-pair/joint and n is number of contact-pairs/joints in series per pole.

A pair of contacts has a resistance of about 15 micro-ohms.

Contact resistance is inversely proportional to the contact pressure. Low contact pressure may be due to week springs or worn out contacts. High contact resistance causes excessive heating of contacts while carrying normal current and possible welding during through short-circuit.

(*c*) **Mechanical Assembly.** Check that all the nut bolts are in their position and check their tightness.

Check circlips, split pins.

Clear and lubricate sparingly.

Oil dashpots should be checked for current level and operation. Air Dashpots should be checked for current operation.

Clean inspect and replace worn-out parts during overhauls.

In case of spring operated mechanism check the ratchet wheels and prawls for broken or chipped teeth.

Valves of pneumatic mechanism or hydraulic mechanism should not be disturbed unless the diagnostic tests indicate the need for their checks.

(*d*) **Inter-pole linkages.** For ensuring simultaneous operation of 3 poles (within pole discrepancy of 5 milliseconds), the inter pole linkages should be checked for deterioration of springs other components. Linkage pins circlips, nut-bolts, etc. should be checked. Verify that fixings are tight and pivot pins are secure.

Maloperation of mechanism, interpole linkage, dash-pots etc. can be revealed by the time/travel record of 3 poles plotted on UV recorder as described earlier.

Congealed lubricants should be removed from sliding, rolling surfaces. The parts should be relubricated as per the instruction of the manufacturer.

Method of Checking Simultaneous Contact Touch

The moving contacts of each phase should meet the fixed contact practically simultaneously. At electrical method of checking the contacts is illustrated in Fig. 13.1. A low voltage supply, lamps are needed. Simultaneous glowing of lamps indicates simultaneous making of contacts.

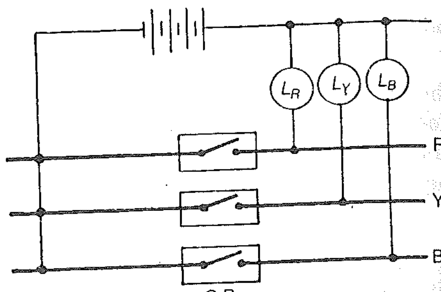


Fig. 13.1 Method of checking simultaneous contact meeting during slow closing.

7. Main Connections. Ensure that good contact is maintained and connections are right and secure.

8. Secondary Wiring and Fuses. Ensure tight and secure connections, cleanliness and freedom from dust and moisture. Heater in the cabinet should be checked and repaired, if necessary.

9. Earth Connection. The main and secondary earth connection should be tight and free from dust and rust.

10. Heater. The heater provided in the control cabinet should be in working condition.

11. Shutters. The shutters mechanism in metal-clad medium voltage Switchgear should be verified after pulling out of drawout unit and de-energizing the busbars.

12. Busbars and Busbar Chambers. The busbars and the busbar chambers should be checked for cleanliness of insulators, tightness of joints and freedom from dust, damp and foreign materials/insects etc.

There shall not be any loose joints or signs of overheating, melting, sparking.

13. Auxiliary Switches, Indicating Devices and Interlocks. Auxiliary switches shall be kept in clean an sound condition because the correct functioning of other items of equipment, including protective gear depends on auxiliary switch.

Inspect the contacts and clean or renew if necessary, where possible verify correct contact force and correct timing of contacts. Indicating devices such as mechanical ON and OFF indicators, semaphores etc. shall be inspected to ensure that they are in good order and operating correctly.

Interlocks and locking devices shall receive particular attention especially those associated with earthing and testing facilities. A defective or worn device may result in a dangerous condition. It shall be verified that any incorrect operation is satisfactorily inhibited lubricate as necessary.

Particular attention shall be paid to the required timing of the auxiliary contacts controlling the trip circuit.

14. Isolating Contacts. Clean inspect for signs of overheating, renew or recondition if necessary, lubricate as required.

15. Overload devices and Protective Relays. Routine maintenance should be carried out at correct intervals.

16. Instruments and Protective Transformer. Routine maintenance should be carried out according to instructions.

17. Control Relays or Contractors. Inspect mechanical parts for free movement with control and main solenoid or motor circuit isolated clean arc chutes. Inspect contacts and renew, if necessary.

Any flexible braids shall be inspected, especially for fraying at the terminations and renewed if necessary. Where exposed to external atmosphere, the braids shall be treated with a suitable protective compound which will not impair their flexibility.

18. Pressure Gauges and Pressure Switches. The readings of pressure gauges are checked against a standard gauge.

The operation of pressure switches should be checked against their setting.

19. Final Verification. Before returning to service after the overhaul, the circuit-breaker is subjected to operational checks by performing C, O, CO operation from local control cabinet and from the control room.

Simultaneous touching of the contacts of three-phases is verified.

Insulation resistance is measured between the terminals of open interrupter and between the lower terminal and earth.

Insulation resistance of auxiliary wiring is also measured.

13.7. TYPICAL MAINTENANCE RECORD CARD

History card is kept for each circuit breaker.

Circuit breaker S.N.

Make

Brake

Inspection date

Permit to work number

Component	*Observation*	*Action taken*	*Initials*
Mechanism			
Linkages			
Insulation			
Quenching			
Medium			
Main contacts			
Arcing contacts			
Terminals			
Final verification			

13.8. MAINTENANCE OF AIR BREAK CIRCUIT BREAKER, FUSEGEAR FOR LOW AND MEDIUM VOLTAGES

The schedule of maintenance depends upon the frequency of load operations and fault operations. For frequent load operations/fault operations, maintenance requirement is high. For indoor, dust-free installation with infrequent load operation, the following schedule is recommended :

— Inspect as often as possible with maximum internal of 12 months.

— Examine at 5 years interval.

— Overhaul when examination and diagnostic tests indicate need. Maximum interval of 15 years.

Table 13.3 Maintenance for Vacuum Circuit-Breaker

Clause	*Maintenance operation*	*Routine Maintenance*		
		Inspection	*Examination*	*Post fault maintenance*
1.	Operation check		×	
2.	General inspection		×	
3.	Cleaning		×	×
4.	Opening device (trip)		×	
5.	Insulation	×	×	
6.	Circuit-breaker enclosure (Interrupter)		×	
7.	Main connections		×	
8.	Secondary wiring and fuses		×	
9.	Mechanism		×	
10.	Auxiliary switches, indicating devices and interlocks		×	
11.	Shutters	×	×	
12.	Switching spouts	×	×	×
13.	Isolating contacts	×	×	
14.	Vacuum interrupter		×	×
15.	Isolating and earthing switchgear		×	
16.	Earth connection	×	×	
17.	Overload devices and protective relays	×	×	
18.	Instrument protective transformers		×	
19.	Control relays or contactors		×	
20.	Busbars and busbar chambers		×	
21.	Final verification	×	×	

13.9. MAINTENANCE OF VACUUM CIRCUIT-BREAKER

Vacuum interrupter is sealed for life and does not require any replacement of contacts for several thousands load operations and about 50 operations on rated short-circuit. Mechanism needs periodic lubrication as recommended by the manufacturer. The other parts need cleaning and general inspection.

13.10. MAINTENANCE OF SF_6 CIRCUIT-BREAKER

During periodic maintenance, the gas sample from SF_6 circuit-breaker is collected and tested for moisture and other impurities (IEC 376). The gas is circulated through filters containing activated alumina. The activated alumina absorbs the impurities like S_2F_2, SF_4 moisture etc. The gas can be used again after regeneration.

For installation and maintenance of SF_6 circuit-breaker a gas handling unit is necessary. This consists of a vacuum pump, valves, pipings, a compressor and a service tank.

The SF_6 gas in the breaker gets decomposed during quenching process. Most of the lower fluorides recombine, but some remain (S_2F_2, SF_4 etc.) in the decomposed form. They are partly absorbed by

activated alumina filters and dissicants. SF_6 gas subjected to arcing becomes corrosive, irritant and has bad odour. It should not be inhaled or left in atmosphere. It is collected into service tank of gas handling unit by means of the compressor.

The breaker poles are not dismantled before reclaiming the SF_6 gas in the service tank of the gas handling unit.

Spare cylinders of SF_6 gas in sufficient quantity should be arranged in advance before starting the maintenance work of SF_6 circuit-breakers.

If the sub-station has only a few SF_6 circuit-breakers, the simple smaller gas handling unit is adequate. For large sub-stations having several SF_6 filled equipment, a larger gas handling unit is necessary. A chemical laboratory for testing SF_6 gas is also recommended.

Pole Unit and Interrupter. At a suitable interval one interrupter per pole to be examined to establish the rate of burning and erosion of the contacts and the general condition in order to assess the necessity for further maintenance etc. This work must be carried out under dry weather conditions and precautions taken to avoid the ingress of any moisture dirt into the pole units.

Slight burning of copper or copper alloy contacts should not cause any trouble but heavier burning should be removed with a fine file (emery or carborundum paper should not be used). Copper alloy and other arc resisting metal contacts should be inspected for any signs of excessive burning. In general, considerable burning of contacts can be tolerated before replacement becomes necessary but it is recommended that here contacts require dressing, the minimum amount of material shall be removed and the manufacturers recommended profile maintained.

It is imperative that the force between contact shall not be materially reduced. Any burning away from the arcing area should be noted and investigated. Transfer contacts shall be inspected for any signs of a burning and cleaned as necessary.

The nozzle of the interrupter is usually made from PTFE. It shall be examined for excessive burning or erosion and this can be done by comparison with a new nozzle. In general the dimensions and profile of the nozzle are not as critical in SF_6 circuit-breaker and, therefore, a greater amount erosion can be tolerated before replacement becomes necessary (5%).

However, the manufacturers recommendations in this respect should be carefully followed.

The insulation adjacent to the arcing area should be cleaned as necessary. Burning of this insulation will indicate a misplaced arc and if found this must be investigated.

The entire interrupter is generally filled with thin dust of erosion of Teflon nozzle combined with fluorides of contact material. This dust is insulating when not exposed to SF_6 gas. Immediately after dismantling of the breaker, this dust absorbs moisture and becomes conducting. Hence it should be wiped-out completely by means of air-jet, cloth, trychloroethelene. This cleaning is essential resistance goes down and internal flashover occurs during the normal closed position between the live part and earth due to surface tracking along internal insulation.

The important steps in the maintenance of SF_6 circuit-breaker include internal cleaning and replacement of SF_6 gas.

The operating linkages should not be disturbed unless diagnostic tests or a visual examination indicate that this is necessary. The setting dimensions should be verified.

Filters and Dessicants. Filters (activated alumina) are installed in SF_6 circuit-breaker to filter out or adsorb some of the breakdown products. As a last operations prior to closing up the chambers of the circuit-breaker the filters and dessicants should be replaced. Under no circumstances should untreated filter or dessicant material removed from the circuit-breaker after service be heated.

Table 13.4 Maintenance for SF_6 Circuit-Breakers

Clause	*Maintenance operation*	*Routine Maintenance*		
		Inspection	*Examination and overhaul*	*Post fault maintenance*
1.	Operational checks	×	×	
2.	General Inspection	×	×	
3.	Cleaning		×	×
4.	Opening device (Trip)	×	×	
5.	Circuit-breaker enclosure		×	
6.	Gas system	×	×	
7.	Sulphur hexafluoride gas	×	×	×
8.	Insulation	×	×	×
9.	Local control kiosk	×	×	
10.	Pressure gauges		×	
11.	Pressure switches		×	
12.	Main connection		×	
13.	Secondary wiring and fuses		×	
14.	Earth connection,		×	
15.	SF_6 gas heater		×	
16.	Interpole linkages	×	×	
17.	Main mechanism		×	
18.	Auxiliary switches indicating devices and interlocks		×	
19.	Interrupters		×	×
20.	Local air receives and pressure vessels		×	
21.	Filters and desiccants		×	
22.	Overload devices and protective relays	×	×	
23.	Instrument and protective transformers		×	
24.	Control relay or contactors		×	
25.	Busbars and Busbar chambers		×	
26.	Final verification	×	×	×

13.11. INSULATION RESISTANCE MEASUREMENT

It is the responsibility of the user to ensure that the insulation of electrical switchgear has been tested and the result recorded before commissioning the equipment. During the life of electrical equipment insulation resistance testing will give a good indication of the condition of the equipment and if these tests are recorded can help in deciding maintenance requirement for the whole equipment.

13.12. INSULATION RESISTANCE MEASUREMENT AT SITE

Insulation resistance is measured by means of Megaohm meter (Megger). The megger comprise a megaohm meter with built-in d.c. generator. The minimum reading is zero and maximum is infinity. The scale is in megaohms. The two terminals of megger are connected across the insulation *i.e.* one to the conductor and other to earth body. The handle is rotated by hand or motor. The insulation resistance indicated by the pointer in megaohms.

For h.v. switchgear 1000 V or 5000 V (d.c.) megger is preferred. The insulation resistance of h.v. circuit-breaker is very high (above 10000 megaohms of infinity).

Insulation resistance of control circuit, trip circuit, relay circuit, secondary circuit, etc. is measured by means of 500 V megger. Value obtained should not be less than 1 megaohm.

For primary circuit, the insulation resistance is tested with the breaker closed ; between lower terminal and earthed frame for each interrupter.

With breaker open, insulation resistance is measured between terminals of each interrupter.

Test voltages of Insulation-resistance. The voltage which could be applied to primary insulation when making resistance test varies according to the voltage rating of the switchgear.

Table 13.5. Test Voltages for Meggering

3-phase system rating of primary insulating of switchgear	*Test voltage recommended for insulation resistance test (to earth and between phases) kV (d.c.)*
Upto 1 kV	1
Above 1 kV 3.6 kV	2
Above 3.6 kV to 12 kV	5
Above 12 kV	5

13.13. LIKELY TROUBLES AND ESSENTIAL PERIODIC CHECKS TO AVOID THEM

The point to be checked during the periodic maintenance include the following :

(*a*) The operating mechanism of the circuit-breaker should be in good working condition both mechanically and electrically.

(*b*) Insulation resistance phase to ground of each pole should be above 2000 mega ohms, (upto 1.1 kV); 10,000 mega-ohms for above 36 kV.

(*c*) Contact pressure is important. When the contact pressure is enough even a line contact can pass normal current without overheating. The resistance of pole unit should be less than 50 micro-ohms.

Trip circuit and battery supply. Maintenance of the trip circuit and battery supply is essential for the satisfactory operation of all protective relays. The battery should be inspected daily for correct voltage, specific-gravity etc. and it should be kept on trickle charge. The inter-cell connectors should be in good condition. There should be a pilot lamp or alarm indication to draw the attention of the operator, if the trip coil battery voltage falls below certain limits.

(*d*) Every relay should be tested once in six months, with suitable testing set and the records of such tests should be logged in a maintenance resistor. During tests a check should be made if any of the overload or time setting on the relay require change due to the increase or decrease in the load conditions since the date of last test.

Following defects are possible :

(*a*) Improper contact or misalignment of the contact prongs of the trip battery circuits, between the cubicle and the drawout truck.

(*b*) Point in an auxiliary wiring of supply from battery, or discharged battery.

(*c*) Circuit-breaker operating mechanism not being sluggish due to mechanical defects, or stiffness due to dust or rust, lack of lubrication, etc.

(*d*) Wrong CT or VT connections.

(*e*) Wrong relay settings for the load conditions.

Table 3.6. Common Troubles and Remedial Actions

	Trouble	*Possible causes*	*Possible Remedial Actions*
1.	Low insulation Resistance (below 2000 Mega-ohms) between — Phase terminal and earthed frame, with breaker closed — Phase terminals of a pole.	— Moisture — Dirty insulation surface internal and/or external — Poor oil — Carbon/copper particles sticking to internal surface	— Circulate dry hot air or oil through the breaker pole for 4 to 6 hours. — Dismantle, clean, reassemble Insulation resistance should be above, 2000 Megaohm, for 1.1 kV and above 10,000 megaohms above 36 kV
2.	Resistance between Terminals of Pole too high (above 100 micro-ohms) (15 micro-ohm per joint/contact)	— Reduced contact pressure — Loose connections — Contact surface damaged due to repeated operations — Insufficient contact wipe — Oxide film on contact surface	— Dismantle, repair and assemble again. If necessary, replace the contacts
3.	Unequal contact Wipe and Travel in 3-pole Measured from top surface of interrupter flange and the contact tip by a simple rod with — breaker open — breaker closed	— Contact erosion due to repeated load operations or short-circuit operations — Unequal length due to wrong adjustments of linkages.	— Inspect contact tips — Replace if badly eroded — Adjust contact if lengths are unequal in three pole
4.	One of the pole does not close	— Pull rod for contact damaged — One the links of that pole broken — Contact of that pole severely damaged.	— Dismantle the pole and repair the defect
5.	Breaker operation too Slow During opening (Timing from trip command to contact separation instant too large (60 ms instead of says 40 ms)	— Excessive friction in the pole unit. — Contact grip too high — Trip coil operation sluggish. — Low battery voltage, hence higher trip coil pick-up-time	— Identify the cause — Take Remedial action.
6.	Breaker does not operate on Electrical command	— Open control circuit — Spring defective — Trip circuit open — Trip latch/coil defective — Spring not changed — If breaker operates with manual operation of trip release, the mechanism is O.K.	— Check control circuit — Check closing spring visually — Identify the cause and take remedial action — Check supply to spring changing motor. — Check pressure switches, relays, control wiring.

13.14. INSTALLATION OF DRAWOUT METALCLAD SWITCHGEAR

(*a*) **Preliminary Preparation.** The preliminary preparations include study of drawings acceptance, report checking certificates and test reports of the equipment, completion of civil engineering work arranging the tools, lifting gears etc. organising the labour, prepare the schedule of installation, peparing sequence cards for erection of major items etc. Such cards indicate the sequence of operation items involved, procedure in brief etc.

Sequence Card for Erection of Switchgear Equipment

S.No.	*Operation*	*Tools, Lifting gear etc.*	*Drawing No.*	*Technique & productive*

The drawing include

1. Circuit diagrams of the plant.
2. Civil Engineering plans, foundation plans etc.
3. Dimension drawings of equipment.

(*a*) Location of switchgear. The switchgear may be

(*i*) indoor ;

(*ii*) outdoor.

For medium voltages from 3.3 to 24 kV indoor switchgear is popular. (Refer Ch. 15)

(*b*) Indoor switchgear should be located in a clean, dry room free from vermins, snakes, moisture, dust etc. Floor should be dry and levelled. The floor should withstand load of about 1000 kg/m^2 (200 lb/sq. ft). Enough space should be left in front and in the rear of the switchgear as recommended by the manufacturer. About 1.7 metres in front and 0.7 m in the rear of 11 kV drawout switchgear.

The following points are kept in mind :

1. Fire-proof doors, roof, ceiling etc.
2. Sealing of cable ducts.
3. Sub-division of switchgear.
4. Installation of fire-fighting apparatus.

(*c*) **Unpacking.** The equipment is packed in crates and is brought to site by railway and motor truck. Packages are lowered on the site by means of rope, hoist or crane carefully. Care is taken that they are always held in upright position throughout. On unpacking, the items are checked against the list.

Further the items are carefully inspected visually. If any damage is found, the matter should be informed to the manufacturer and insurance company immediately, and the damaged equipment should be given to insurance company.

(*d*) **Foundation.** The foundation is prepared according to the foundation plan. Holes are provided for grouting of foundation bolt. Trenches and passages are provided for cables and other piping. The floor should be correctly levelled and marked according to the drawing.

(*e*) **Erection.** The equipment is installed according to the procedure mentioned in the instruction manual. Some types of lifting device, special tools etc. may be necessary. The assembly is erected vertically. The vertically is checked by means of spirit level. If necessary, packing pieces are added in the base plate for obtaining proper level. After doing necessary adjustment and checking the level, the concrete mixture is poured into holes around foundation bolts and the nuts are tightened. It should be remembered that porcelain insulator columns are weak in tension. During erection, they should not be shifted under assembled state without stiffners. Stiffners are removed after assembly. Circuit-breaker should be dried out before filling gas/oil.

(*e*) **Relays.** It is advisable *not* to adjust the relay-mechanism. The faulty relay should be sent to the manufacturer since relay repair is as a specialized job.

Contacts of relay should be inspected for any sign of burning where necessary, glass paper should be used for cleaning. All the terminals of the relay should be checked for tightness. The wiring should be checked for security.

(*f*) **Bus-bars earthing connections.** The bus-bar contacts and making surfaces of connectors should be cleaned with emery paper or smooth file. The bus-bars assembled as soon as they are cleaned.

(*g*) **Connection of main cable.** Refer Sec. 15.21-Sub-section : Cable termination.

(*h*) **Earthing.** The earthing bar of the switchgear, the metallic non-current carrying part are connected to station earthing system. The risers are brought out from earthing system upto the equipment earthing points.

Safety. The maintenance work should be carried out with written permission of responsible people. A scheme should be adopted to issue permit card authorising the maintenance work to be done. Steps should be taken by concerned authorities to ensure safety. These steps include :

1. Isolation of the part from live parts during the period of maintenance. No switching on by mistake.
2. Danger notice such as the one given below should be placed.
3. The neighbouring point should be locked to avoid switching by a third person.
4. **Earthing.** The work equipment and conductors should be earthed by means of earthing connections, from both ends.
5. Proper tools, safety devices should be provided to the electricians.
6. The electricians should be well trained.
7. First-aid should be available.
8. Switching on should be allowed only after completion of work after cancellation of the permit by the authority.

Death can be caused even on 400 V installations, because negligence or accident.

13.15. SAFETY PROCEDURES

1. Follow the safety rules faithfully.
2. Take permission from authorised person for doing specific work.
3. Make sure of switch-off the supply from both ends. The switching-off and switching-on should be as per safety rules and with prior permission of the authorised person.

The repair/maintenance work of High Voltage Apparatus should not be undertaken unless the apparatus is made DEAD and Isolators are open and locked.

4. Place caution notice and danger notices near the work place and near the switching terminals.

WATCH ; DON'T SWITCH-ON MEN AT WORK

DANGER 440 V DON'T TOUCH

5. Keep barriers, ropes around the section under maintenance to clearly indicate maintenance zone and boundary of the neighbouring live zone.
6. Earth the various metallic parts of structures, bus sections, conducting parts etc. at two or more places before commencing the maintenance work.

7. Be familiar with circuit and auxiliary supply circuits. Switch-off both.

The recommended precautions to be taken before working on High Voltage apparatus (Above 650 V).

No person shall undertake any repairs, maintenance, cleaning, alteration of such works, on any part of High Voltage Apparatus unless such parts of the apparatus are : **Dead.**

Isolated and all practicable steps taken to lock off from live conductors :

Efficiently connected to earth at all points of disconnections of supply to such apparatus, or between such points, and the point (s) of work ; (Caution Notices fixed ;

Screened where necessary to prevent Danger and Danger Notice fixed ;

Released for work by the issue of a 'Permit to Work' or 'Sanction-for-Test'

And unless such person is fully conversant with the nature and also the extend of the work to be done.

It is the duty of the person issuing the Permit-to-Work or Sanction for Test to ensure that the foregoing provisions are complied with.

(*a*) Cleaning and painting of earthes metal enclosures, connections of circuits to or from live high voltage systems live line testing and live insulator washing may be carried out by only in accordance with the special instructions relating to these purpose issued by the Chief Engineer.

(*b*) Live Line Work on high voltage overhead line may be carried out in accordance with rule.

(*c*) Where the design of apparatus precludes the strict compliance with all details of these precautions, the work shall be carried out to the instructions of a Senior Authorised Person who must be present, and after agreement with the Control Engineer.

8. Check the **Safety Clearances** between nearest live points and other physical objects during maintenance. (*e.g.* ladders, platforms, lifting devices, metal-bars, etc.) Safety clearances must always be maintained. Otherwise the flashovers can result. Keep screens between live zones and maintenance zones.

9. Recommended precautions to be taken before working on Medium and Low Voltage systems.

Medium Voltage : 1 to 36 kV

Low Voltage : below 1000 V

Precautions to be taken before working on Medium and Low Voltage Systems. The consequences of shock or serious burns from short circuit associated with medium or low voltage systems may be serious or, in some circumstances fatal. Wherever practicable, therefore, work on **medium and low Voltage Apparatus,** conductors and equipment shall be done while they are dead and earthed.

When working on dead **medium and low Voltage Apparatus** suitable precautions should be taken by screening or other means avoid danger for inadvertent contact with live conductors with the working zone.

It is not always possible to make dead of earth **Medium and Low Voltage Apparatus.** All work on *Medium and Low Voltages Apparatus* must be carried out as if it were live unless it is provided dead earth from all the ends.

When working on *live Medium and Low Voltage Apparatus* suitable precautions should be taken by screening or other means to avoid danger from inadvertent contact with live conductors of earthed metal work.

Work on live *Medium and Low Voltage Apparatus* conductors or equipment should be undertaken only by a *Competent Person.*

Note. Attention is drawn to the fact that certain statutory requirements **Prohibit work on live medium and low voltage apparatus conductors or equipment.**

13.16. INSTALLATION OF OUTDOOR CIRCUIT-BREAKERS

Outdoor circuit-breakers are mounted on pre-fabricated galvanised steel structures.

The important steps in the installation include the following :

Receipt and storage

The packing cases are inspected and stored in indoor/covered stored in a planned location. Indoor equipment are stored indoor, outdoor equipment are stored outdoor.

Civil Works. These are carried out as a part of civil works. The foundation plan is decided on the basis of requirements of the clearness and the base of the equipment/structure. Pockets are provided for grouting the foundations bolts. Cables are laid on trays located in the cable trenches.

Earthing mat is made welded iron rod mesh and is burried in the yard of depth of upto 1 metre. The risers are brought up upto earthing point on the structure, equipment base.

The installations work is started after completions of foundations.

1. Check the readiness of foundations and their dimensions as per the drawings. Check the locations of holes for grouting with reference to foundation plan.
2. Check the level of foundation surface.
3. Place the base frame/structure of the circuit-breaker in position. Place foundation nuts spring washers and tighten. Make connection of earthing riser to the structure.
4. Assemble operating mechanism in its position.
5. Assemble support porcelains and interrupting heads.
6. Place the O-seals with care while assembly 5.
7. Join the links in the mechanism with the links in the pole units as explained in manufacturer's Instruction Book.
8. Give auxiliary supplies to mechanism.
   — for motor
   — for trip circuit and closing circuit.
9. Tighten all the bolts and other hardware. Remove packings.
10. If provision available, operate slow opening and slow closing.
11. Measure Insulation Resistance. Dry-out the pole units if necessary.
12. Fill quenching medium after drying out operation. Check leakage and ensure leakage free assembly.
13. Operate 'C and O' with manual initiation of releases.
14. Operate C.O. with electrical command. Measure Timings. Check simultaneous operations of 3 poles.
15. Try O-CO operations with electrical command.
16. Measure insulation Resistance and resistance between terminals of poles.
17. Make terminal connection, earthing connections.
18. Operate breaker from local control panel.
19. Operate the breaker from control-room by operators instructions and then by operating the relevent relays.

The breaker is ready for putting into service.

Precommissioning Checks/Tests

These are performed in accordance with the agreed field quality plan and include :

— Leakage tests
— Operation C, O, CO
— Time/contact travel characteristics

— Time tests
— Insulation resistance test on main and auxiliary circuits
— Measurement of low resistance between terminals of pole
— Checking of earthing connection
— Operation of breaker from local control cabinet.
— Operation of breaker from control room by manual command; by relay command.

The gas pressure should remain unchanged for at least a month (at given ambient temperature).

QUESTIONS

1. State the difference between :
   — Breakdown maintenance and preventive maintenance
   — Servicing and overhaul
2. State the step in installation of and outdoor Circuit Breaker.
3. Describe the steps in installation of an indoor metal clad switchgear.
4. State Commissioning checks on a 6.6 kV or 3.3 kV metal-clad switchgear.
5. Explain in detail the following for a circuit Breaker :
   — Procedure of Insulation Resistance Test at site
   — Procedure of High Voltage Test at site
   — Method of checking simultaneous contact touch
6. Prepare a check list for routine maintenance of an SF_6 Circuit Breaker.

14

HRC Fuses and Their Application

Introduction—Type—Definition—Construction—HRC Fuse link—Shapes of fuse element—Specifications of a fuse link—Characteristics of a fuse—Cut-off—Classification P—Q—R, Selection of a fuse link-Protection of motor—Discrimination—Tests on fuse.

14.1. INTRODUCTION

Fuse is a simplest current interrupting device for protection from excessive currents. As such, it is used for overload and/or short circuit protection in medium voltage (upto 33 kV)* and low voltage (upto 400 V) installations. Modern High Rupturing Capacity Cartridge Fuses (HRC) provide a reliable discrimination and accurate characteristics. In some respects HRC fuses are superior to circuit-breaker.

14.2. TYPES OF DEVICES WITH FUSE

1. Semi-enclosed or Rewirable Type. The fuse which can be seen in our houses are generally of this type. The fuse carrier can be pulled out and the blown out fuse element (wire which melts) can be substituted by a new one and carrier is replaced in the fuse base.

2. Totally enclosed or Cartridge Type. The fuse element (the conductor which melts) is enclosed in a totally enclosed container and is provided with metal contacts on both sides.

This type is available in two types :

(*i*) D type (*ii*) Bolted type

3. Current Limiting Fuse-link. A fuse-link which limits current to a considerable lower value than the prospective peak.

4. Drop-out-Fuse. A fuse-link in which the fuse-carrier drop out after the operation of the fuse thereby providing isolation between the terminals.

5. Expulsion Fuse. A fuse in which the arc occurring during the operation of the fuse is extinguish by expulsion produced by the arc.

6. HRC (High-Rupturing-Capacity, *i.e.* Breaking Capacity cartridge fuse). A cartridge fuse link having breaking capacity higher than certain specified value (*e.g.* above 16 kA for medium voltage cartridge fuse).

7. Striker Fuse. A device which incorporates a fuse and a mechanical device, the operation of fuse release the striker with certain pressure and displacement. Striker is used for signalling-tripping/indication.

8. Switch-fuse. A combined unit comprising, fuse and switch.

14.3. DEFINITIONS

— **Operation of fuse-link.** Process of pre-arcing and arcing resulting in 'blowing' of fuse-link.

— **Cut-off.** The melting of fuse-element before the current reaches the prospective peak. The value of current at which the cut-off occurs is called cut-off value.

* Recently, HRC fuses have been developed for applications upto 66 kV for distribution systems.

— **Pre-arcing Time.** Time between commencement of the current loop and the cut-off.

— **Arcing Time.** Time between cut-off and final current zero.

— **Total Operating Time.** Pre-arcing time plus acting time.

— **Fuse.** Fuse is a current interrupting device which opens the circuit (in which it is inserted) by fusing the element when the current in the circuit exceeds a certain value.

— **Fuse element.** The part of the fuse which is designed to melt when the fuse operates.

— **Fuse link.** The part of the fuse which needs replacement when the fuse blows out.

14.4. CONSTRUCTION

(A) Semi-enclosed or Rewirable Fuse. Everyone is familiar with this fuse which blows out when all the hostel lamps are glowing and somebody puts on a heater. The fuse carrier can be pulled out, the new wire can be placed and the service can be restored. Thus the cost involved is very much less. However, the fuse element (wire in this case) is exposed to atmosphere. Hence it is affected by ambient temperature. Such rewirable fuses have limited breaking capacity. For example, according to I.S. : 2086—1963 the rewirable fuse of 16 A normal current have a breaking current of 2 kA and those upto 200 A normal current have a breaking current of 4 kA.

Further, the characteristic of such fuse is not certain as it is affected by ambient condition and several other aspects mentioned below. Therefore, such fuse has limited application in industrial switchgear. Its use is limited to domestic and lighting loads. For all important and costly equipment totally enclosed cartridge fuses are used because they give a reliable protection.

Disadvantages of rewirable fuse as compared to cartridge fuse

(1) *Low breaking capacity.* Hence cannot be used in circuits of higher fault level.

(2) *Absence of accurate characteristic.* Hence protection is not reliable.

(3) It is subjected to deterioration because the wire is exposed to air, hence it is oxidised. This increases the resistance causing heating.

(4) Accurate grading not possible

(5) *No current limiting feature.*

(6) Slow speed.

(7) *Risk of external flame and fire.* However it is a cheap and easily replaceable fuse. One should be cautious in selecting this type of fuse.

(B) D-Type Cartridge Fuses (Fig. 14.1). The typical fuse comprises.

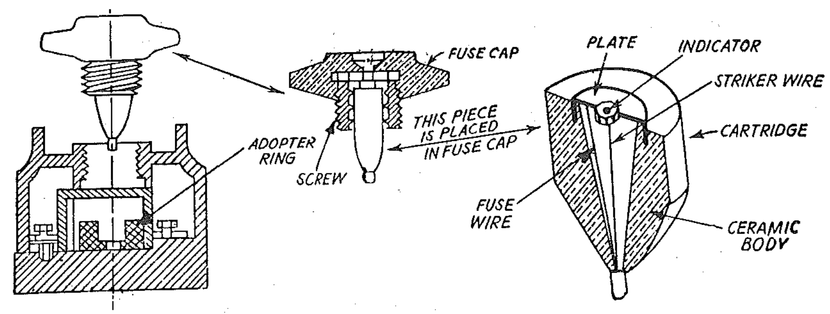


Fig. 14.1. D-type fuse.

1. Fuse base. 2. Adapter-ring. 3. Cartridge. 4. Fuse cap.

The cartridge shown in Fig. 14.1 (*a*) is pushed in the fuse cap. The cap is screwed on the fuse base. On complete screwing the cartridge tip touches the conductor and circuit between two terminal is completed through the fuse link.

(C) Link type

This type is available in two types.

(*i*) Knife blade type (Fig. 14.2).

(*ii*) Bolted type (Fig. 14.3).

(*d*) **Bolted type** (Fig. 14.3). Fuse link has two conducting plates on either ends. These are bolted on the plates of the fuse base. This type of fuse requires an additional switch so that the fuse can be taken out without getting a shock.

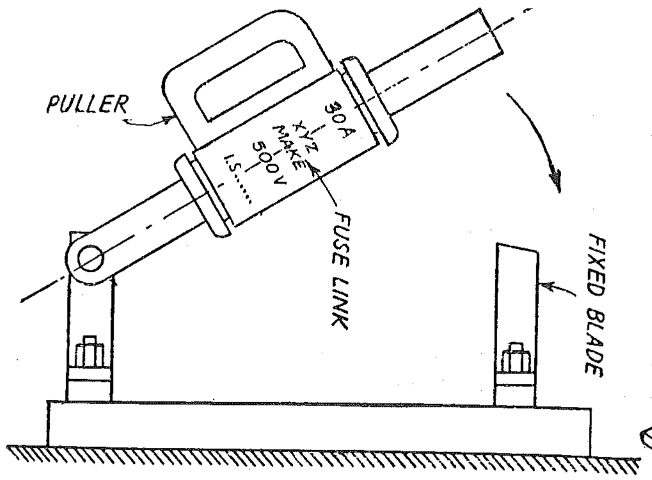


Fig. 14.2. Kinfe blade type.

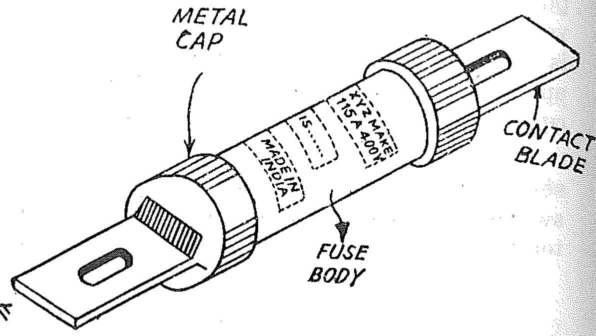


Fig. 14.3. Bolted type fuse link.

14.4.1. HRC Fuses for Semiconductor Devices and Thyristors

Solid State Devices (Diode, Thyristor etc.) are protected against surge currents by fast acting series connected HRC fuses. The HRC fuses for solid state devices have pre-arcing time less than 0.5 millisecond and arcing time less than 5 milliseconds (Ref. Fig. 14.8). The prospective short-circuit current would reach peak value in 10 milliseconds (half cycle). However with HRC fuse in circuit, the short-circuit current does *not* reach prospective peak and current is limited to a value corresponding to cut-off.

Generally, fuse is connected in series with the semi-conductor device or in series with a group of parallel connected semiconducting devices.

When a fuse blows, a part of circuit is removed from the current path.

Fig. 14.4 shows the locations of HRC fuses in single phase thyristor circuits.

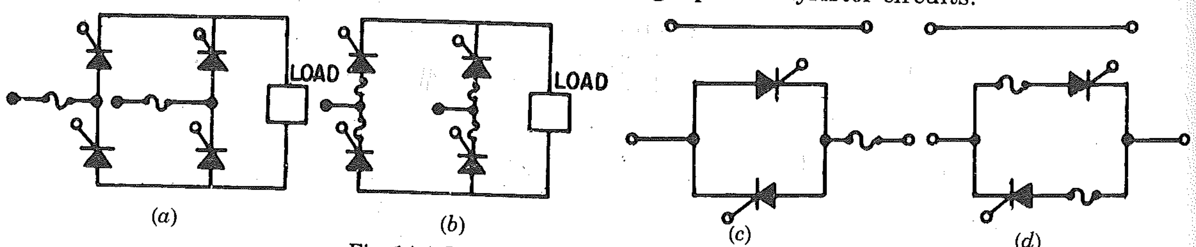


Fig. 14.4. Use of HRC fuse for thyristor protection.

Ratings of HRC Fuses for Thyristor Protection

Definitions of HRC Fuses (sec. 14.3) and Ratings (sec. 14.8) are suitably modified as follows.

1. **Rated Current.** Fuse rating is selected to suit the thyristor current in the circuit. These values are the maximum r.m.s. current permissible for the circuit and thyristor.

2. **Rated Voltage.** Fuse is rated normally in terms of r.m.s. voltage. Operating voltage must be equal or less than the rated voltage of the fuse. When fuse is used in DC circuit, the operating voltage must be lower than rated r.m.s. voltage. Manufacturers provide data on this derating.

3. **Fusing peak current.** (I_{fm}) The peak fusing current depends on maximum possible short circuit current to the circuit.

I_{fm} should be less than I_{TSM}

$$I_{fm} < 1.4\, I_{TSM}$$

I_{fm} should be less than $I''_{s\text{-}p}$ where $I''_{s\text{-}p}$ is peak of sub-transient fault current given by $I''_{s\text{-}p} = 1.6 \times \sqrt{2} \times I''_{s\text{-}rms}$

$I''_{s\text{-}rms}$ is subtransient fault current of the circuit.

4. **I^2t Value.** The I^2t value is a measure of the heat capacity of the thyristor. Generally I^2t value is given for a period of 10 m. sec. For times in excess of this, I^2t will be larger. For adequate protection against short circuit I^2t of fuse should be lower than I^2t of the thyristor. If fault current exceeds on cycle rating of the cell fuse has to perform current limiting function. Hence I^2t of the cell must be compared with total I^2t of the fuse, *i.e.* pre-arcing and arcing time. This varies with fault current and supply voltage, Published data allows such calculations to be made for combinations of fuse ratings, fault current and supply voltage.

5. **Arc Voltage.** This depends on L/R ratio of circuit.

Stresses on Solid State Devices for Selection of HRC Fuse. These include *power frequency (50 Hz) current stresses and Transient Current Stresses.*

Abnormal power frequency currents which exceed steady-stage current rating of a device occurs frequently. Under fault conditions, the equipment should be disconnected from supply to prevent to the solid-state device.

A thyristor has following current ratings :

I_{TAV} average steady state current.

I_{RMS} RMS value of steady current.

I_{TRM} repetitive peak current.

I_{TSM} non-repetitive peak surge current.

Transient current stresses are expressed in terms of Maximum di/dt and peak current. In various applications steady state ratings of the devices are specified. However, solid-state devices are prone to failure immediately or after a very short service, if the circuit is not adequately designed and protected.

To achieve reliability and long life, the entire circuit and auxiliaries should be adequately designed and protected, against peak voltage transients, maximum dv/dt, maximum di/dt and peak current. These abnormal transients are likely to occur during on/switching/off state as follows :

Maximum dv/dt peak voltage	during switching off and when off transient
Maximum di/dt	When turning on
Peak current	When fully on

A capacitor is connected in parallel with a thyristor to act as a "snubber' to limit dv/dt and prevent unintentional firing and also to absorb energy from voltage spikes. A resistor of 8 to 60 Ω is generally required in series with this capacitor prevent high di/dt when the thyristor is turned on.

High voltage transients can also be limited by non-linear voltage suppressors, matched to the maximum voltage rating of the thyristor and which have sufficient energy absorbing capacity to dampen the transient.

The di/dt at turn-on can be limited by the inductance inherent in the circuit or by an inductor added in the circuit. High frequency inverters and other applications requiring high di/dt can utilize fast turn on thyristors. The magnitude and rise time of the signal applied to the gate also influence the di/dt capacity of a device. Manufacturer's recommendations should be followed.

14.5. FUSE LINK OF HRC FUSE

The fuse link is a unit in which the fuse element is enclosed. The fuse link is replaced when it blows out. (Ref. Fig. 14.6).

The outer cover is usually of steatite, a ceramic material having good mechanical strength. Epoxy resins have been recently introduced and are replacing the ceramic material.

The fuse elements are fitted inside the body. The ends of the fuse elements are connected to the metal end caps. The metal caps are screwed to the ceramic body by means of special forged screws to withstand the pressure developed under short-circuit condition. End contacts are welded to the metal end caps. These contacts bolted on the stationary contacts on the panel.

An indicator pin is provided, which indicates when the fuse blows out.

The fuse body is filled with powdered pure quartz.

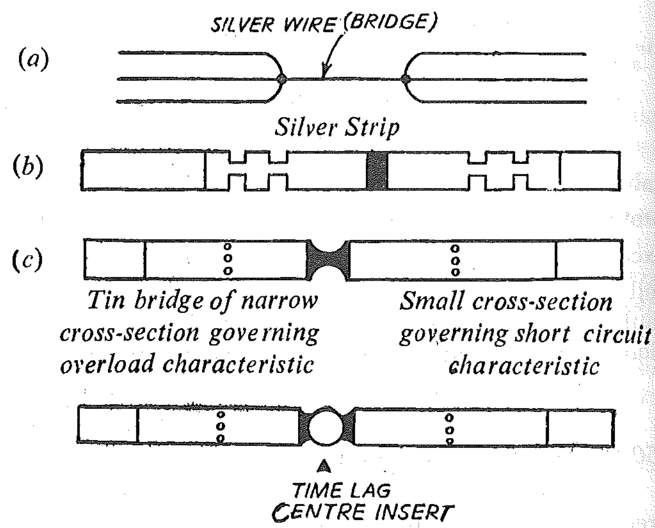


Fig. 14.5. Shapes of fuse elements.

The fuse element is of silver or copper with a special shape. Normally, the element has two or more sections joined by means of a tin joint. The element consists of several identical strips similar to those as shown in Fig. 14.5. The strips are interconnected such that the arc spreads instantly to all the strips.

The characteristic of the fuse is governed by material and shape of the fuse element.

14.6. ACTION OF HRC FUSE

Normally the fuse elements are in parts which are connected in the middle by tin bridge. The melting point of the tin bridge is precise and about 230°C.

The bridge does not melt at temperatures below the melting point. Since the melting point is higher than ambient temperature, the melting is not affected by the ambient temperature.

The current passing through fuse element produces heat which is proportional to $i^2 rt$. With a certain current, the temperature rises and the tin bridge melts producing a break in the circuit. Thereby an arc is produced. This arc immediately spreads over the neighbouring elements and they too melt. The metal vapour diffuses with the quartz powder and the product of chemical reaction produces a substance of high resistance which becomes an insulator. Thereby the space between the caps is filled with a material of high dielectric strength, as the current is interrupted.

14.7. SHAPE OF FUSE ELEMENT

The fuse elements are in the form of a wires or thin strips. The shape depends on the characteristic desired. Usually there are identical parts connected by a bridge of silver or tin.

14.8. SPECIFICATION OF A FUSE LINK

1. **Voltage Rating.** This is specified by the manufacturer. The rated voltage of the fuse should be equal to or more than :

(*a*) Voltage of the circuit in a single phase a.c. or two wire circuit.

(*b*) Line voltage in case of three phase a.c. circuit.

(*c*) Voltage between two outer wires in three wire d.c. circuits.

2. **Frequency.** A fuse link suitable for 50 c/s may not have same rating for other frequencies of d.c. circuits.

3. **Current Rating.** This rating is stated by the manufacturer. It is r.m.s. value of current which the fuse can carry continuously without deterioration, and with temperature rise within specified limits.

4. **Minimum Fusing Current.** The minimum current at which the fuse will melt. Asymptotic value of current from the characteristic of total operating time.

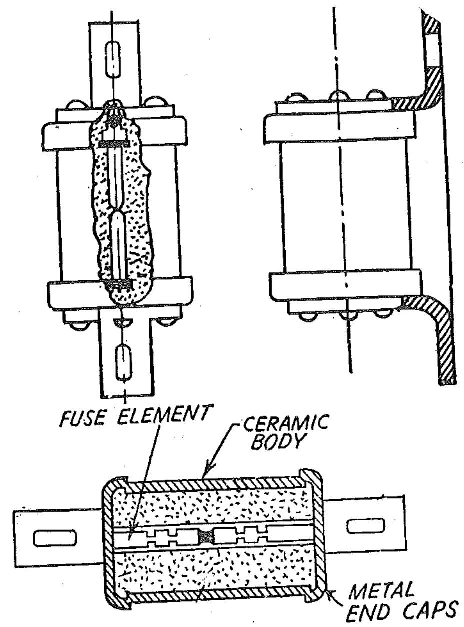


Fig. 14.6. HRC fuse link.

5. **Fusing Factor.** The ratio of minimum fusing current to the current rating, *i.e.*,

$$\text{Fusing Factor} = \frac{\text{Minimum Fusing Current}}{\text{Current rating}}.$$ Thus factor is more than 1.

6. **Prospective peak current of a circuit.** The current that would flow in the circuit if the fuse were replaced by a link of negligible impedance. Peak value of first current loop of short circuit waveform.

7. **Breaking capacity.** Highest prospective peak current under the prescribed conditions of voltage, power factor etc. which the fuse is capable of breaking. Fuse cuts-off before reaching the peak.

8. **Operation of fuse link.** Process of pre-arcing and arcing resulting in blowing of fuse link.

9. **Cut-off.** The melting of fuse-element before the current reaches the prospective peak. The value of current at which the cut-off occurs is cut-off value. Cut-off current is of instantaneous value.

10. **Pre-arcing time.** Time between commencement of the current loop and the cut-off. (ms)

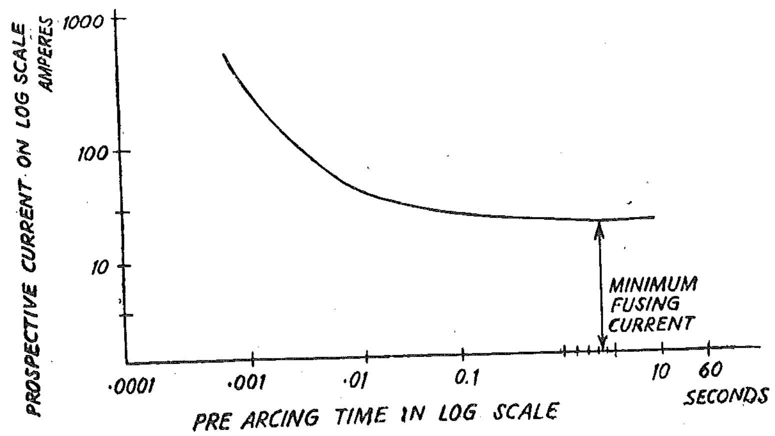


Fig. 14.7. Illustrates typical characteristic of a HRC fuse.

11. **Arcing time.** Time between cut-off and final current zero. (ms)

12. **Total operating time.** Pre-arcing time plus arcing time. (ms)

14.9. CHARACTERISTIC OF A FUSE

Normally the characteristics give pre-arcing time plotted against prospective currents upto the rupturing capacity rating of the fuse. Both the axis are plotted on logarithmic axis.

It is observed that as the prospective current increases, the pre-arcing time reduces. Further the characteristic becomes asymptotic and there is a minimum current below which the fuse does not operate. For currents near the minimum fusing current, the operating time is long. (Also refer Fig. 14.9).

14.10. CUT-OFF

The HRC fuses, slow acting of fasting, exhibit and interesting property known as *Cut-off.* The short circuit current is interrupted before it reaches the peak of first prospective current loop.

If the melting of fuse element prevents the current through the fuse link from reaching the otherwise attainable peak value the fuse to said to have cut-off. The instantaneous maximum value attained is called cut-off current.

Fig. 14.8 illustrates the *cut-off* action. On occurrence of short circuit, the current starts increasing. It would have reached a magnitude I_p if no fuse were there is protect. HRC fuse does not allow current to reach I_p. Instead, the element is cut-off and after a brief arcing time the current is interrupted. The cut-off value depends upon (1) normal current rating of the fuse ; (2) prospective current (3) the asymmetry of circuit waveform.

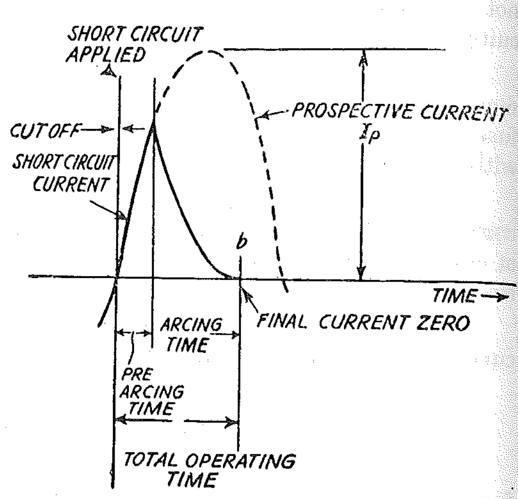


Fig. 14.8. Cut-off characteristic.

Cut-off property has a great advantage that the short circuit current does not reach the prospective peak. Hence the circuit is not subjected to electrodynamic stresses corresponding to peak prospective current. Hence the bus bar design is considerably simplified because now the maximum value of current for design purposes in cut-off value.

14.11. CLASSIFICATION AND CATEGORIES

According to B.S. : 88—1952 Fuse links are classified depending upon their fusing factor into 3 classes

Class P Fusing factor less than 1.25

Class Q Fusing factor less than 1.75

Class K Fusing factor more than 1.75

$$\text{Fusing Factor} = \frac{\text{Minimum Fusing Current}}{\text{Rated current}}$$

Quick acting and slow acting fuse. The fuse is quick acting or slow acting depending upon its characteristic. In some fuses there is a combination of these two features.

Note on categories of duty. Clause 8 of B.S. 88 : 1952 states that every fuse shall be assigned for convenience one or more of 5 categories of distinguished by the values of prospective current of test circuit stated in the table given on next page below, and denoted respectively by the number 1, 2, 3, 4, and 5, the number 1 to 4 being preceded always by the letters AC or DC respectively to whether the fuse is suitable for use in alternating-current or in direct-current and the number 5 being preceded always by the letters AC. The category of duty of which any fuse is assigned shall

be one having a distinguishing value of prospective current of test-circuit not greater than the breaking capacity rating of the fuse. The power factor of an A.C. test-circuit and the time constant of a D.C. test-circuit shall be the same for all tests for a given category of duty, and shall be of appropriate values as stated in the table 14.1.

Table 14.1.

Category of duty	*Prospective current of test-circuit (Amperes)*	*Power factor (Lagging) of test-circuit not greater than*	*Time-constant of test-circuit not less than*
AC_1 and DC_1	1,000	0.6	0.0030
AC_2 and DC_2	4,000	0.4	0.0040
AC_3 and DC_3	16,500	0.3	0.0100
AC_4 and DC_4	33,000	0.3	0.0100
AC_5	46,000	0.15	

Note. AC_4 is the highest category of duty normally required for A.C. service, only when it is known to be insufficient should category of duty AC_5 be specified.

14.12. SELECTION OF FUSE LINKS

The problem is not as simple as one may imagine. An improper blowing out of fuse itself may be comparatively insignificant but it may result in stoppage of a certain machine or failure of certain circuit. Such causes may lead to loss of production. *Hence reliable fuses should be used, which should be selected such that it will blow out under abnormal conditions only. It should not operate during temporary permissible overloads of switching surges. The following aspects should be considered in selecting the fuse :

(I) Nature of Load

(*i*) Normal current

(*ii*) Starting current, duration

(*iii*) Permissible overloads.

(*iv*) Whether steady load of fluctuating load

(II) Nature of Protection Required

(*i*) Overload of short-circuit protection.

(*ii*) Opening time slow or quick operation required.

(*iii*) Peak prospective current, desired cut-off value.

(III) Fault Current

(*i*) Fault current, peak prospective value.

(*ii*) Fusing factor desired.

(*iii*) Rupturing capacity.

(*iv*) Category of duty AC_1 and AC_5 or DC_1 to DC_4 [Refer Sec. 15.11 B].

(IV) Grading or Discrimination between other fuses and circuit breakers in the circuit.

These aspects will be discussed in the subsequently paragraphs briefly.

(*i*) **Steady load or Fluctuating load.** Fluctuating loads are those in which peaks of comparatively short durations occur. Steady loads fluctuated but a little from their normal value *e.g.* heaters.

* A vertical boring machines in a factory was out of order for two days. On tracing the trouble, it was found that a fuse in control circuit had blown. The loss was estimated to be 40 machine hours, about Rs. 24000.

In selecting a fuse for steady loads one has to decide whether to give *over-load protection of short circuit protection.* For over-load protection of steady loads class P fuses of fusing factor 1.25 are preferred. The fuses give protection against small but sustained over-currents. The fuse is selected from the available fuses on the basis of normal current of the circuit. The fuse of rated current equal to the normal current may be selected. If such fuse is not available the next greater rated current fuse is selected. The standard rated currents of fuses are as under :

2 — 4 — 6 — 10 — 16 — 25 — 32 — 50 — 63 — 80 — 100 — 125 — 160 — 200 — 250 — 400 — 500 — 630 — 800 — 1000 — 1250 amperes.

(*ii*) **Fluctuating loads.** The criterion for selection is that the fuse should not blow under transient overloads. For such feature the current/time characteristic of the fuse should be always above the transient current characteristic of the load, with enough margin. Hence it is necessary sometimes, to select a fuse rated current greater than normal current of the circuit. Further, fuses of class *Q* having fusing factor 1.75 may be suitable.

(*iii*) **Switching surges.** Switching of transformers, fluorescent lighting capacitor, motors etc. the current in-rush takes place. The fuse selected in the circuit should not blow out during the switching period. The chosen fuse should generally have a normal rating 25 to 50 per cent above the normal full load current of the protected apparatus and the fusing factor should be such that starting current is less than the fusing current.

Guidelines for Some Applications for steady-load Circuits

In circuits where the load does not fluctuate much from its normal value (*e.g.* in heating circuits) select the standard cartridge fuse-link intended for fuses having a current-rating equal to or next greater than the anticipated steady-load current. If other over-current protection is provided, or if discrimination is required, a cartridge fuse-link for a fuse of still greater current-rating may be selected.

For Fluctuating-load Circuits

When the load varies above normal in peaks of comparatively short duration, select fuse-links in accordance with the following general rules :

(*a*) *Transformers and Fluorescent-Lighting Circuits.* In general cartridge fuse-links intended for fuses of the current-rating next higher than the anticipated normal load current will stand the transient current-surge.

(*b*) *Condenser Circuits.* Select a cartridge fuse link intended for fuses for current-rating 25 per-cent greater than that of the circuit, to allow of the extra heating causing by the capacity effect.

(*c*) *Motor Circuits.* When the starting current of motor is known a suitable cartridge fuse-link can be selected by assuming that the starting current surge will persist for 20 seconds, and choosing one intended for fuses that will carry to the starting current for this time. Reference should be made to the time/current characteristics (Fig. 14.9).

When the starting current is not known, useful approximately assumptions are (*i*) that the starting current of a direct-stated motor is about 7 times of the full-load current and (*ii*) that the starting current of a motor with a 75 per cent auto-transformer starter-tapping is about 4 times the full-load current, and about 2-5 times with a 60 per cent auto-transformer starter-tapping or with a star-delta starter. For most slip-ring motors, normal running conditions, and not starting conditions, determine the fuse-link that should be used and it is ordinarily sufficient to select one capable of carrying the normal load-current.

Fuse manufacturer provides tables and graphs for general guidance in selection for motor starting, and is for use when only the supply voltage, the horse-power of the motor, and method of starting are known.

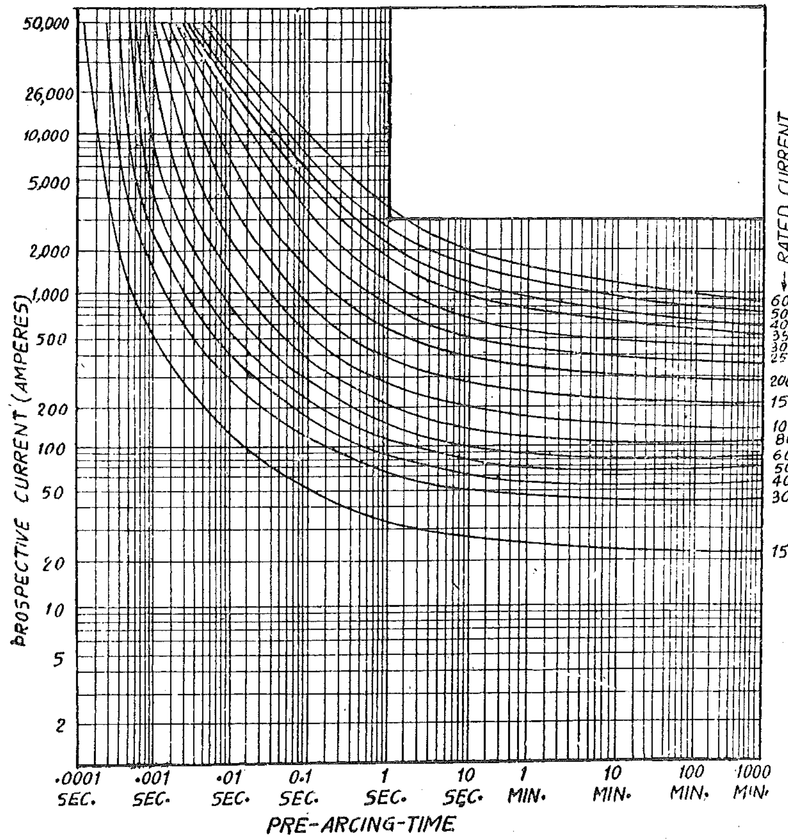


Fig 14.9. Time current characteristic of HRC fuse-link.

14.13. PROTECTION OF MOTOR*

The over-current relay provides over-current protection to the motor. Hence the fuses provide *short circuit protection* and high starting currents on locked-rotor. While choosing the fuse for the motor, the normal current of the motor is noted. The characteristic of current *vs.* time of motor for the starting period is plotted on the same graph on which the characteristic of some fuses are plotted.

The characteristic of fuse should lie above the characteristic of motor at all time. Further, there should be an appropriate margin to ensure that the fuse does not operate unduly during starting.

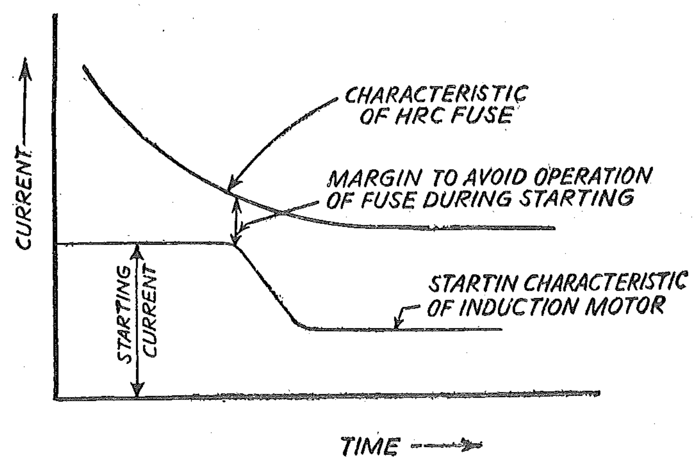


Fig. 14.10. Pre-arcing time/current characteristic of fuse matched with starting characteristics of motor.

* Also refer Ch. 31 : Protection of Motor, Sec. 15.6, 15.12.

Also, the breaking capacity of the interrupting device, *i.e.* contactor or circuit-breaking should be fully exploited.

For this purpose the other switching device should be coordinated with the fuse in such a way that for the value of fault currents upto the breaking capacity of the circuit-breaker (or contactor) the circuit-breakers operates and the fuse does not. For this purpose the characteristic of the circuit-breaker (or contactor) relay operating coil should be below the characteristic of the fuse as shown in the figure. These characteristics should intersect as a point (A) preferably above the breaking current capacity of the circuit breaker.

Here, the fuse gives back-up protection to the motor and is connected on the supply side.

When starting current of motor is not known as the following approximations may be made :

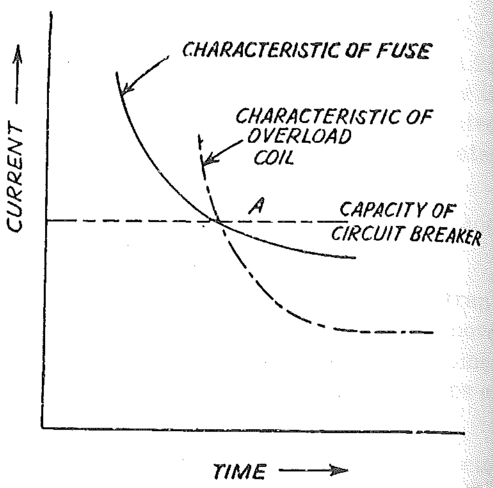


Fig. 14.11. Co-ordination between fuse and switching device, fuse on supply, circuit-breaker on load side.

	Type starting	Motor starting current *X* times full load current
(1)	Direct on line	7 to 8
(2)	Stator-rotor starter	1 to 2
(3)	Star-delta starter	2.5 to 3
(4)	Auto-transformer	2.5 to 4

14.14. DISCRIMINATION

When there are two or more protective equipments providing protection for the same circuit *e.g.* two or more fuses, a fuse and a circuit-breaker etc. there should be co-ordination between them. Discrimination concerns with correct operation of correct device. It means, the co-ordination between the fuse and the other equipment should be such that only the necessary device operates, the other remaining unaffected.

14.15. PROTECTION OF RADIAL LINES

Consider a simple case of two fuses *A* and *B* in series as shown in Fig. 14.12 power feed is from left to right.

A is called major fuse.

B is called minor fuse.

When fault occurs beyond *B*, only should operate and *A* should remain unaffected. This is called Proper Discrimination.

For proper discrimination in this case, the pre-arcing time of the major fuse *A* must be greater than the total operating time of minor fuse *B*.

Since the cut-off characteristic is difficult to be determined the manufacturer usually gives tables for selection of major and minor fuses base on the tests performed. Such tables are useful for selection of fuses.

As a guide rule, a ratio of 1.5 between the ratings of major and minor fuses is likely to give satisfactory discrimination upto short-circuit currents of 40 kA.

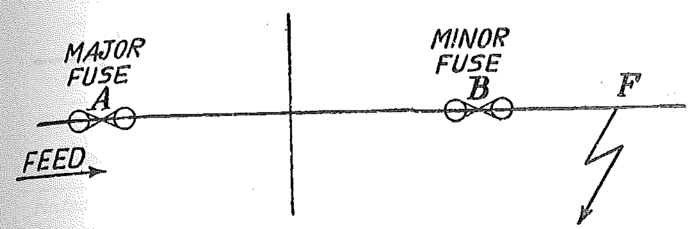


Fig. 14.12. (*a*) Co-ordination of fuses in radial circuit.

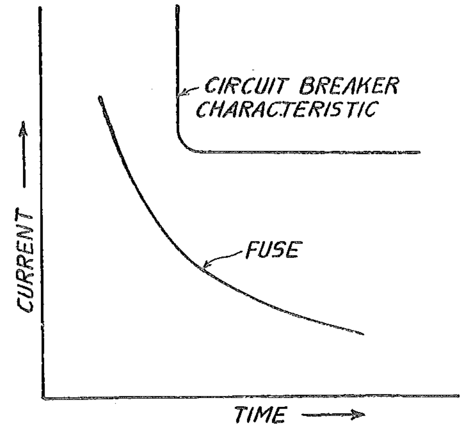


Fig. 14.12. (*b*) Fuse on load side and circuit-breaker on supply side co-ordination.

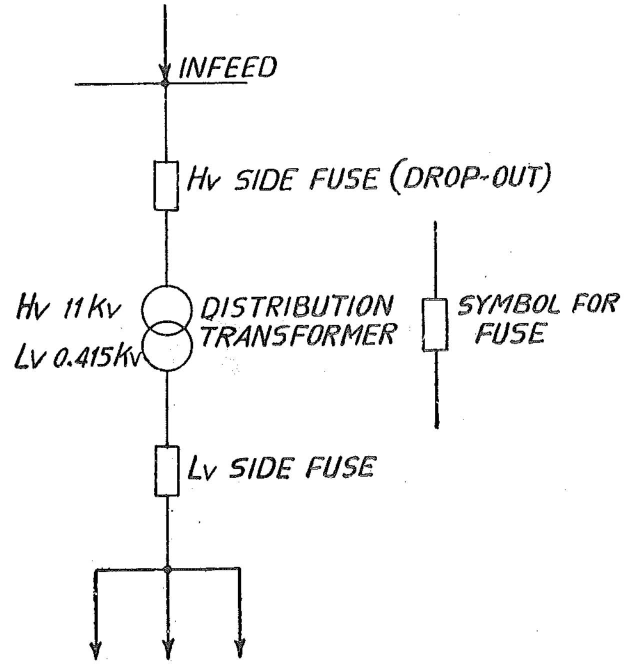


Fig. 14.12. (*c*) Co-ordination between fuses on HV and LV sides of distribution transformer.

Co-ordination of Fuse and C.B., Fuse on load side of the C.B.

In distribution boards, the circuit breakers is connected in the supply side [in-coming] : bus-bars and fuses are connected in load side. In such cases for faults on an out-going feeder, the fuse of that feeder should operate first. Circuit-breaker should be as a back-up. The characteristics of fuse and circuit-breaker should be matched such that the fuse takes less time for operation than circuit-breaker (Fig. 14.2 (*b*)]. Consider HV and LV fuses on corresponding side of a distribution transformer. Fuse on LV side should operate for faults on low voltage system beyond the LV fuse. Fuse on HV side should protect the transformer. It may be mentioned here that for economic considerations, no circuit-breaker and relays are generally provided for protection of distribution transformers below 500 kVA. The dropout fuses are used on HV side. (Refer Figs. 17.25 ; 17.26 ; 17.27).

14.16. PROTECTION OF MESHED FEEDERS WITH STEADY LOAD - BY HRC FUSES

In meshed-network fuse should have same rating may be provided for mesh connected circuit, though the short circuit current flowing to the fault may be different for each component circuit *e.g.* in Fig 14.13 when I total flows in Fuse I_1.

$$I_1 = I_2 + I_3 + I_4$$

If all fuses are of same rating.

I_1 will operate first, giving a satisfactory discrimination.

However in some cases the impedance of individual circuit may be quite different for example, Current 1-2 may be about 85 per cent of I-total. In such cases both fuses 1 and 2 may operate. In such cases the ratio $I_{COMPONENT}/I_{TOTAL}$ should be estimated and the fuses having accurate characteristics should be employed to discrimination.

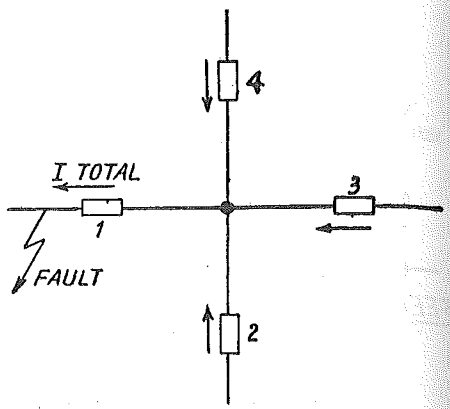


Fig. 14.13. Selection of fuse for meshed feeders.


Fig. 14.14. Switch-fuse combination incorporating HRC fuses.
Courtesy : Easun Engineering Co. Ltd. India.

14.17. EQUIPMENT INCORPORATING FUSES

Switch-Fuse. The combination of switch and fuse is very widely used for voltage and medium voltages. It is a compact combination, generally metal enclosed. The ratings of switch fuse units are in the following range :

60 A, 100 A, 200 A, 400 A, 600 A, and 800 A.

They have been developed for making capacities (prospective) upto 46 kA. They can safely break, depending upon ratings, currents of the order of 3 times rated load current. Fig. 14.14 gives a view of an open switch-fuse unit. Both 3 pole and 4 pole units are available. Switch-fuse units can be installed on metal-clad switchgear.

14.18. HIGH VOLTAGE CURRENT LIMITING FUSES

Typical Applications

— Transformer protection (distribution system)
— High voltage motor protection
— Backup protection for circuit-breakers
— Capacitors protection
— Protection of underground distribution systems.

Range and Dimensions*

Rated voltage (Mean Max) kV	*Length (mm)*	*Diameter (mm)*	*Rated current Amp*
3/3.6	192	51	6.3 to 100
		76	125 to 150
3/3.6	292	51	6.3 to 100
		76	125 to 355
6/7.2	292	51	6.3 to 63
		76	50 to 164
10/12	1292	51	6.3 to 40
		76	31.5 to 100
20/24	442	51	6.3 to 40
		76	25 to 71

14.19. EXPULSION TYPE HIGH-VOLTAGE FUSE

Expulsion fuse comprises of hollow open ended tube made of synthetic resin-bonded paper. The fuse element is placed in the tube and the ends of the element are connected to suitable fittings at each end. The length of tube is generally longer than conventional enclosed fuses. The arc caused by breaking of fuse element causes decomposition of inner coating of the tube and the gases thus formed assist arc extinction. Such fuses are developed for 11 kV, 250 MVA and are used very commonly for termination of distribution transformers over-head lines, cable terminating with overhead line.

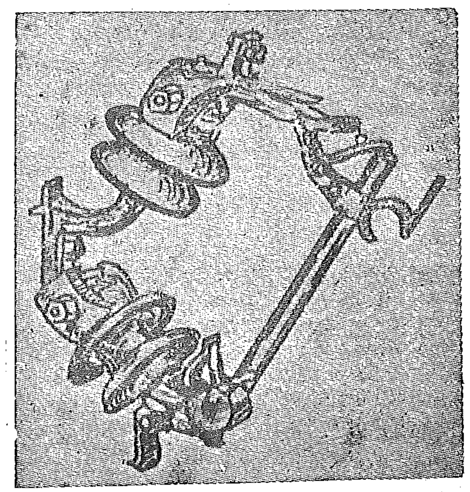


Fig. 14.15. Expulsion fuse-one pole in closed position.

14.20. DROP-OUT FUSE

The melting of the fuse causes dropping of fuse element under gravity about its lower support. Thereby additional isolation is obtained. Such fuses are used for protection of out-door transformers. When the linesman observes operation of the fuse, he can lift the complete tube from the hinge by means of a special insulator rod and brings down the tube for replacing the element. After replacing the element the tube is replaced in the hinge and the device is closed in a way similar to closing of Isolators. Drop-out-fuse-isolator combination is generally pole mounted.

* VDE 0670; IEC 282-1 ; DIN 43-625.

Striker Fuse

Striker is a mechanical device having enough force and displacement which can be used for closing signal/tripping/indicator circuits. A force of a few kg can be obtained.

14.21. TEST ON FUSE

Tests are necessary to provide the least characteristic and ratings of the fuse. All tests on fuses are type tests and at least three samples of each current rating are tested.

The tests conducted are the following :

(*i*) Rated current test, temperature rise.

(*ii*) Current time characteristics.

(*iii*) Determination of minimum fusing current. Determination of maximum non-fusing current.

(*iv*) Test of duty, *i.e.* satisfactory opening at rated voltages for current upto rupturing capacity.

(*v*) Cut-off characteristics.

(*vi*) Resistance measurements.

(*vii*) Various performance tests.

The manufacturer gives the ratings to the fuses on the basis of the Type Tests.

QUESTIONS

1. Compare 'HRC Fuse' and 'Circuit-Breaker' as interrupting devices.
2. What is the meaning of HRC fuse ? How does it operate ?
3. What is 'cut off ? How is it beneficial in protection of bus-bars ?
4. Explain the aspects to be considered in selecting a fuse.
5. What are the considerations in selecting fuse for
   (*a*) Motor protection (*b*) Transformer protection (*c*) Heaters (*d*) Lighting local.
6. Explain the following terms for HRC fuse :
   (*a*) Cut-off (*b*) Pre-arcing time (*c*) Arcing time.
7. Discuss the method of selecting the rating of HRC fuse for motor starter.
8. Define 'Normal Current' and 'Fusing Factor' for HRC fuse.
9. Write short notes on any two :
   — Drop-out fuse
   — Striker fuse
   — Characteristics of HRC fuse
   — Co-ordination of fuse with back-up breaker.
   — Co-ordination of circuit-breakers with back-up fuse.
   — Protection of low voltage induction motors.

15-A

Metal-enclosed Switchgear, Controlgear and Contactor

Introduction—High voltages indoor Metalclad Switchgear—Low Voltage Indoor Metalclad Switchgear—Low voltage circuit-breakers—Low voltage controlgear and Contactor—Control-panels—Control Room—Flame-proof Switchgear.

15.1. INTRODUCTION

In Conventional Outdoor Installations (rated 36 kV and above) the various substation equipment like circuit-breakers CTs, PTs, Isolator etc. are installed under open sky. Necessary clearances are provided between phases, phase and ground. The equipment for such outdoor switchgear are manufactured separately and are erected at site as per the switchyard layout.

For low voltages (below 1000 V) and medium high voltages (below 36 kV) the clearances required between phases, between phases and ground are relatively small. Hence all the components (busbars, circuit-breakers, fuses, CTs, PTs, Isolators, meters, instruments, Relays etc.) can be provided in/on *factory assembled metal enclosed units.* Such switchgear is called *Unit Type Metal Enclosed / Metal-clad switchgear.*

Circuit breakers rated below 1000 V and Switchgear rated below 1000 V are generally indoor type and are used at final load points. Unlike HV circuit-breakers, LV circuit-breakers may have to operate repeatedly at relatively low powers factor currents. Hence the design and specifications of low voltage switchgear and circuit-breakers is markedly different from HV Switchgear. *Controlgear* is used for switching and controlling power consuming device such as motors, furnaces, vehicles, *equipment, processes* etc. Contactors are used at switching devices for normal and overload currents. Short-circuit currents are interrupted by HRC fuses or circuit-breakers.

Control Panels are installed in control room. From control panel, the operator can know, what is happening in the plant. The operator can control, start, regulate or switch-off the main-circuits from control panels. The control panels are designed and assembled to customer's specifications.

15.2. TYPES OF SWITCHGEAR

Indoor switchgear is used for medium, low and high voltages. It is in a variety of forms these switchgear units and applications in industrial plants, production floors, workshops, power stations, sub-stations, electrical distribution networks. The indoor switchgear is used in industrial plants such as chemical, petrochemical cement, dairy, textile plants, floor mill etc. They are also used in power plants and in distribution sub-stations.

(1) Stationary cubicle type, in which the components occupy fixed positions.

(2) Draw-out type or truck type switchgear in which the circuit breaker is installed on a carriage which can be pulled out to provide isolation. (Ref. Fig. 15.2).

(3) Compound filled or SF_6 filled switchgear. In which certain enclosures are filled with dielectric liquid or the whole switchgear enclosure is filled with SF_6 gas. (Refer Chapter 7)

(4) Fuse switch units and ring mains.

(5) Flame-proof or Explosion-proof switchgear which is designed and built specially for hazardous locations.

(6) *Cellular type.* (Which is now obsolete). The units are separated by brick-walls and R.C.C. slabs.

(7) *Corridor switchboard.* A switchboard on which the devices are mounted on two opposite sides separated by accessible corridor.

(8) *Mimic diagram board.* A switchgear on which the mimic diagram of main circuit is reproduced.

(9) *Metal-clad switchgear.* In this switchgear, the components are arranged in separate compartments with metal-enclosures intended to be earthed. The components include : Switching device, busbars, CT, VT etc. this barriers between compartments are metallic and earthed. The shutters may be insulating or metallic. Metal-enclosed switchgear called cubicle switchgear has no internal compartments.

(10) *Indoor switchgear.* Switchgear intended for indoor use.

(11) *Switch board.* An assembly comprising switchgear, electrical connections etc. and supporting frame.

(12) *Out-door Kiosk.* An enclosed outdoor self-contained unit connections are via bushings or cables. Metal enclosure contains CB, CT, VT, Busbars, Meters etc.

(13) *Compartmented Switchgear.* A metalclad switchgear having barriers of insulating Refer Ch. 15-B.

PART A—HIGH VOLTAGE INDOOR METAL ENCLOSED SWITCHGEAR

15.3. GENERAL FEATURES OF INDOOR METAL-ENCLOSED SWITCHGEAR

The indoor switchgear is generally factory assembled and unit type. Each unit has horizontal bus-bars of standard length. The required number of units are assembled in a line. The bus-bars are connected. The components are enclosed in sheet metal enclosure or cast iron enclosures. Hence these switch-gear are called Metal clad or Metal-enclosed switchgear.

The term switchgear covers a wide range of equipment for switching, interruption, measurement, control, indication etc. In indoor switchgear there are several components. These are assembled and provided with an enclosure. The components for switching and interruption include (1) Switches, (2) Switch-fuse combinations (3) Air-break/Bulk-oil/Minimum oil/Vacuum/SF_6 circuit-breakers (4) H.R.C. Fuses, (5) Isolators, (6) Earthing switches.

The components for measurements include current and potential transformers, measuring instruments.

The items in protective system include relays, instrument transformers etc. The components are chosen to suit customer's requirement.

Bus bars are essential components of switchgear. Bus-bars are defined as conductors to which several incoming and outgoing lines are connected. Bus-bars are of copper or aluminium. They are supported on epoxy-insulators block or resin bonded paper or resin bonded laminated-wood. The design, type depends on rated normal current and short-circuit capacity. The bus-bars are enclosed in bus-bar chamber. For single bus-bar arrangement, three conductors are provided for phases and one for neutral and earthing. The bus-sections of neighbouring units are connected by copper aluminium links.

The incoming and outgoing power cables are provided with cable-terminations. Power cables are brought in through cable trenches and terminated in the switchgear units. The rated voltage corresponds to busbar voltage. *

Current-transformer used in metal-enclosed switchgear are generally ring-type. They are fitted on insulated primary. The insulation is provided by cast epoxy-resin fittings.

Earthing facility is important. Each enclosure is earthed.

When circuit-breakers are incorporated in the switchgear, several inter-locks are necessary.

* High voltage : About 1000 V e.g. 3.6 kV, 12 kV, 36 kV, as per IEC.
Medium voltage : 1 to 36 kV as per CIRED.

15.4. DRAW-OUT TYPE METAL-ENCLOSED SWITCHGEAR

In this type of switchgear, the circuit-breaker and some other components are mounted on a withdrawable carriage. After opening the circuit-breaker the circuit-breaker is drawn-out mechanically by manual gear, resulting in isolation. The carriage is pulled out. In some earlier designs jacking arrangement was provided to raise the breaker-unit. Drawout switch-gear has mainly following components : (Refer Fig. 15.1 *a*).

1 = Busbars
2 = Circuit-breakers (SF_6)
3 = Current transformer
4 = Voltage transformer
5 = Cable termination
6 = Low-voltage compartment
7 = Cladding
8 = Shutters
9 = Isolators, etc.

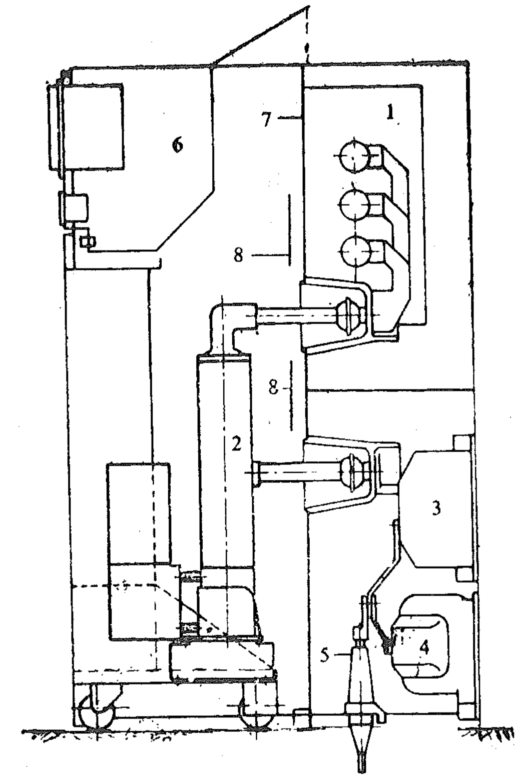


Fig. 15.1. (*a*) Metal-enclosed, 12 kV, Indoor Draw-out type Switchgear.

Normally the following interlockings are provided :

(1) The circuit-breaker must be in the open position before it can be lowered in its position/drawn out.

(2) The circuit-breaker cannot be closed before raising it to plug-in position/pushed in.

(3) Circuit-breaker can be closed only after raising to its final plug-in position.

(4) Interlockings between isolators, earthing switches and circuit-breaker.

Details of erection and arrangement in this type of switchgear are given in Sec. 13.4 Fig. 15.1 illustrates the arrangement. The circuit-breaker is installed on a movable truck. The circuit-breaker is tripped by a relay or by manual signal.

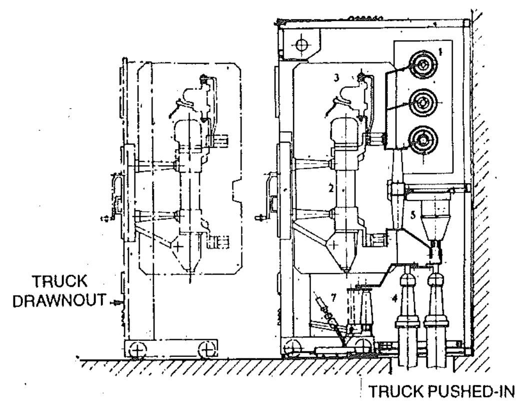
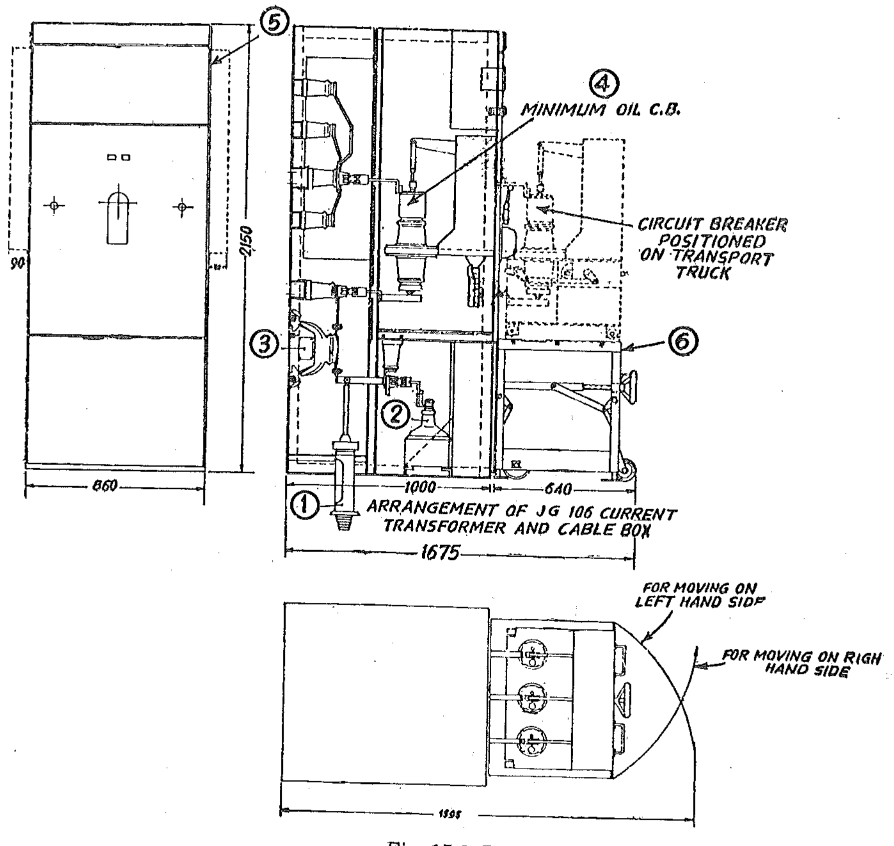


Fig. 15.1. (*b*) Indoor Metal enclosed Switchgear with

1. Busbars
2. Circuit-Breaker (SF_6)
3. Primary Relay
4. Cable-end seals
5. Current Transformer
6. Voltage Transformer
7. Earth.



1. Cable end
2. Voltage transformer
3. Current transformer
4. Minimum-oil circuit-breaker
5. Metal enclosure
6. Truck in withdrawn positions

Fig. 15.2. Draw-out type switchgear.

Table 15.3

Rated Voltage	*MVA Range*	*Rated Current Range*
12 kV*	250 MVA	
	350 MVA	400 A, 800 A, 1200 A, 1600 A
	500 MVA	2000 A, 3000 A, 3500 A
	750 MVA	
7.2 kV*	250 MVA	400 A, 600 A, 800 A, 1200 A
	350 MVA	1600 A, 2400 A, 3200 A.
	500 MVA	
3.6 kV*	150 MVA	400 A, 800 A, 1600 A, 2000 A
	250 MVA	1200 A
440 V**	15.6 MVA	400 A, 600 A, 800 A,,
	26 MVA	1200 A, 2400 A

* Circuit-breaker may be minimum oil, air break, vacuum of SF_6 type.
** Circuit-breaker or contactor generally air break type.
Contactor are used for control gear for repeated load switching.

15.5. SWITCHGEAR WITH VACUUM INTERRUPTERS

Vacuum interrupters have become popular in metal-clad switchgear. Several leading manufacturer in the world have introduced 7.2 kV, 12 kV and 36 kV vacuum switchgear during 1980's.

Mechanism is either 'solenoid closing/spring opening type' or 'spring-closing/spring opening type, Refer Fig. 15.3 illustrating operation of a triple-pole 12 kV metal-clad vacuum switchgear operated by a solenoid closing/spring tripping mechanism. *When solenoid (I) is energised, the breaker closes as follows :*

The magnetic field of the solenoid (17) lifts the plunger (2) through a distance of about 14 mm. the linkages, 5, 6, 7, 9, 12, 13 turn such that Insulating Rod (13) is driven vertically upwards so as to close the breaker. Simultaneously during the closing operations, the springs 14 and 8 get charged and contacts are held in closed position by spring pressure.

While opening, the contact spring '8' and return spring give the required force to open the contacts through about 8 to 12 mm travel. (Ref. Sec. 2.9.4 Solenoid mechanism.)

Vacuum switchgear used for motor switching incorporates *RC* surge suppressors having R =100 ohms and $C = 0.1\ \mu F$. (Ref. Fig 18.5). The RC surge suppressors absorb switching surges and are connected between phase and ground.

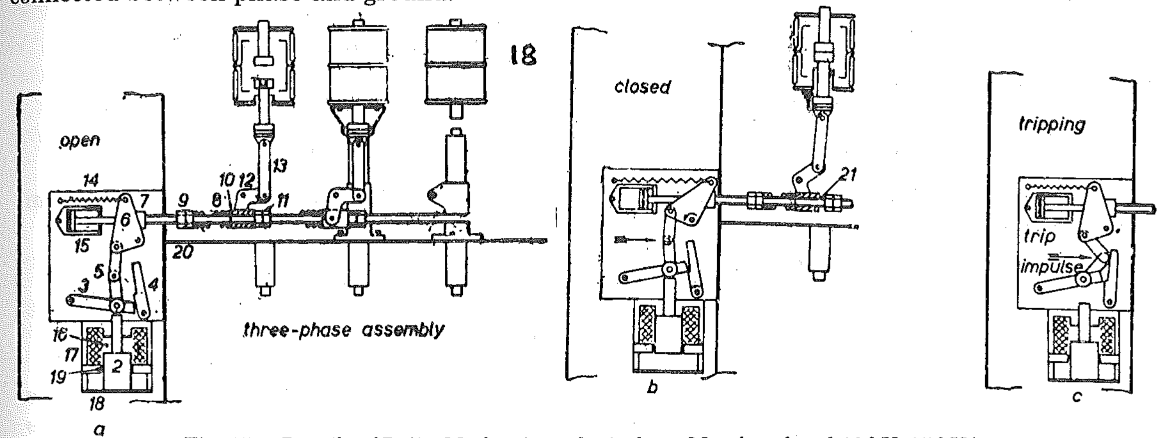


Fig. 15.3. Details of Drive Mechanism of a 3-phase Metal enclosed 12 kV, 25 kVA Vacuum Switchgear with Solenoid-closing Mechanism.
(*Courtesy* : Brush Switchgear Ltd. England)
(*a*) *3-phase* Assembly (*b*) Closed position (*c*) Tripping position

1. Solenoid	2. Plunger	3. Lever	4. Latch	5. Linkage
6. Lever	7. Drive rod	8. Contact Pressure Spring		9. Lock nuts
10. Sleeve	11. Lock nuts	12. Lever	13. Insulating rod	14. Return springs
15. Air buffer (Dash pot)		16. Air-gap	17. Magnetic circuit	18. Vacuum Interrupter.

PART B-LOW-Voltage Metalclad Switchgear and Low Voltage Circuit-breaker

15.6. UNIT TYPE METAL CLAD LOW VOLTAGE SWITCHGEAR AND MOTOR CONTROL CENTERS [REFER FIG. 15.4]

The design is of totally enclosed in superior quality gray iron castings. The rugged construction makes this type of switchgear ideal for industrial use on production floor, workshops, supply systems, electric plants, industrial plants etc.

The Switchgear and motor control centres are built of unit type bus-chambers of standard lengths having standard flange opening as the top and bottom, various units of bus-bar chambers securely bolted to each other forming and totally enclosed bus-bar chamber, with necessary number of flange openings for incoming and outgoing feeders. The bus-bar chamber is provided with detachable covers on both the ends.

Incoming and outgoing feeders are mounted on the top and bottom of bus-bar chambers, the feeder units are directly coupled to the bus-bar chamber through the flange openings.

The complete switch-boards assembly is mounted on a rigid channel is on framework suitable for wall mounting, or detachable pedestals for suitable floor mounting.

These switch-boards are front access type. All components are accessible from the front of the board for easy maintenance and replacement. The switch-board can, therefore, directly placed against the wall, resulting in minimum floor area coverage.

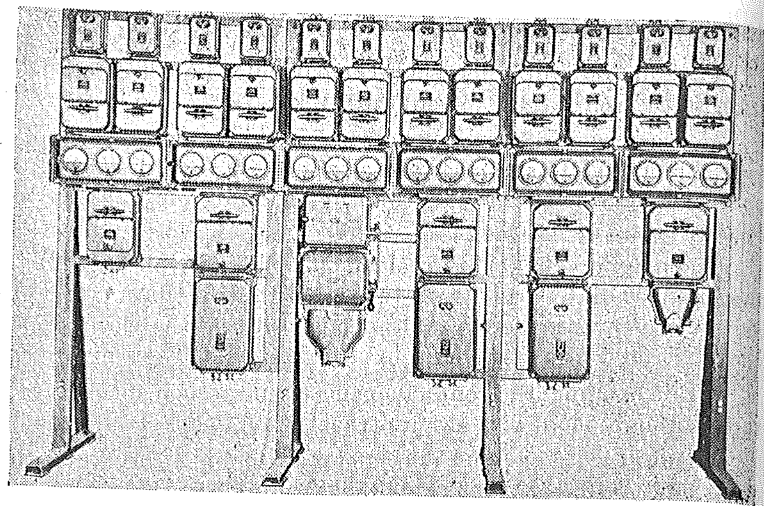


Fig. 15.4. Low voltage-Motor control centre : Metal-clad, indoor, low voltage switchgear. (*Courtesy* : Larsen and Toubro Ltd., India)

There are basically four types of designs :

(*a*) Switch-board with outgoing switch fuse units for main distribution boards.

(*b*) Fuse distribution boards with outgoing fuse units to serve sub-distribution boards.

(*c*) Motor-control centres consisting of outgoing motor starters backed by HRC fuses or switch fuses units.

(*d*) Switch-boards with incoming and outgoing circuit-breakers.

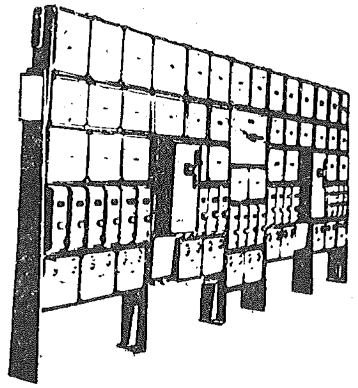


Fig. 15.5 Low voltage Metal-clad switchgear.

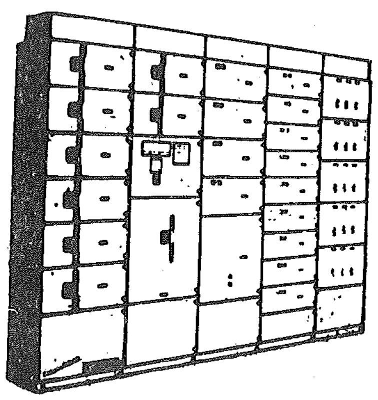


Fig. 15.6 (*a*) Low voltage sheet-metal enclosed load control centre.

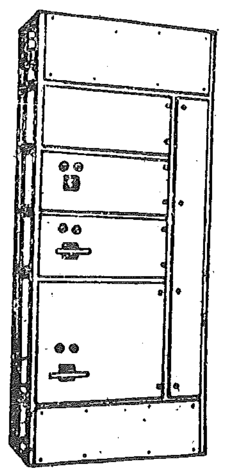


Fig. 15.6. (*b*) Low-voltage sheet-metal enclosed motor-control-centre. (Refer Fig. 15.7 for Details)

15.7. LOW VOLTAGE CIRCUIT BREAKERS

The circuit-breakers intended for circuits below rated voltage 1000 volts a.c. or 1200 volts d.c. are covered under the group low voltage switchgear. The construction, ratings, designs, specification for low voltage-breakers are generally different from those of high-voltage circuit-breakers (Ref, IEC - 15.7). However the theory discussed in Secs. 3.2 to 3.5 applies to voltage circuit-breakers also.

15.7.1. Classification.

The low voltage circuit-breakers are classified as follows :

(1) According to the method of control for closing operation, viz.,

- Dependent manual closing,
- Independent manual closing,
- Dependent power closing,
- Stored energy closing.

(2) According to the medium for interruption :

- Air-break circuit breaker (Ref., chapters 2 and 7)
- Oil immersed.

(3) According to the degree of protection provided by the enclosure (Ref. IEC - 144, Sec. 15.21).

15.7.2. Rated Quantities

The rated characteristics of low voltage circuit-breaker are slightly different from those for high-voltage circuit breakers.

Rated Voltages

- Rated operational voltage (U_o) is a value of voltage to which the making and breaking capacities and short-circuit performance categories refer.
- Rated insulation voltage (U_i) of a circuit-breaker refers to the voltage to which the test voltages, clearances and creepage distances refer. Rated insulation voltage is

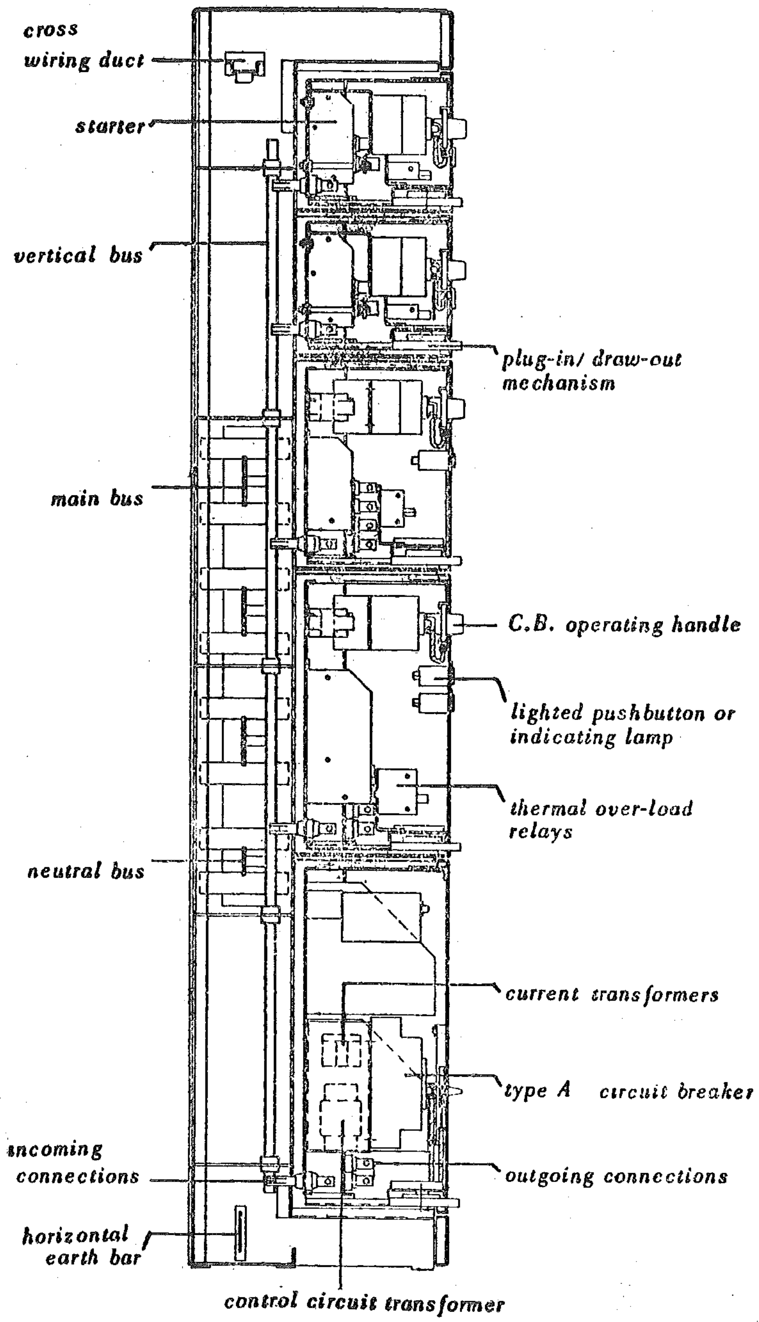


Fig. 15.7. (Cross-section of the load control centre in Fig. 15.6 (*b*).

generally the maximum operational voltage.

— For polyphase circuits, the rated voltage refers to voltage between phases.

Rated Currents

— **Rated thermal current (I_{th})** is the maximum current r.m.s. value of d.c. current or steady value a.c. current, which the circuit-breakers can carry in eight-hours duty.

— **Rated uninterrupted current (I_u)** is the value of which the circuit-breaker can carry in an uninterrupted duty.

Rated Duty

— Eight hour duty (Ref. Sec. 15.13)

— Uninterrupted duty

— **Rated short-circuit making capacity.** The rated short-circuit making capacity of a circuit-breaker at rated voltage, rated frequency and rated power-factor (or time-constant) is the value of prospective peak current that the circuit-breaker is capable of making and is expressed as prospective peak current. In a.c. circuit-breakers the rated making capacity should not be less than the rated breaking capacity multiplied by factor n. The factor n is of the order of 1.41 to 2.2 (Ref. Table) and depends upon the rated short-circuit breaking capacity. (Ref. Secs. 3.19.5 and 3.19.6).

— **Rated short-circuit breaking capacity.** Breaking current in a pole of a circuit-breaker refers to the current at the initiation of arc during the breaking operation. Rated breaking capacity (I_{cn}) refers to the r.m.s. value of a.c. component of current which the a.c. circuit-breaker can break under the specified conditions of voltage and power factor.

Relation between rated short-circuit making capacity, short-circuit breaking capacity and power factor

Rated short-circuit breaking capacity	*Standard p.f.*	*Minimum S.C. making capacity*
$Icn \leq$ (amperes)		($n \times Icn$)
1500	0.95	$1.41 \times I_n$
1200 to 3000	0.9	$1.42 \times I_n$
3000 to 4500	0.8	$1.47 \times I_n$
4500 to 6000	0.7	$1.53 \times I_n$
6000 to 10000	0.5	$1.7 \times I_n$
10000 to 12000	0.3	$2.0 \times I_n$
20000 to 5000	0.25	$2.1 \times I_n$
20000 to 50000	0.2	$2.2 \times I_n$

Relation between power-factor and factors n is based on the ratio R/L of the circuit. (Ref. Eq. 3.17)

$$\cos\phi = \frac{R}{\sqrt{R^2 + \omega^2 L^2}}$$

By increasing R, $\cos\phi$ approaches unity. Refer Eq. 3.17, which gives the variation of d.c. component as

$$id_c = Ae^{(-R/L)t}$$

By increasing R, the value of i_{dc} decreases more rapidly. Hence the value of n reduces with improvement in power factor.

Rated short-time withstand current refers to r.m.s. value of current (for a.c. circuit-breakers) which the circuit-breakers can carry for a specified short-time (generally 1 sec), (Ref. Sec. 3.19.7).

Short-circuit Performance Categories

Category	*Operating sequence for short-circuit tests*
P-1	*O—t—CO*
P-2	*O—t—CO—t—CO*

O — represents a breaking operation.
CO — represents a making operation followed by breaking.
t — represents specified time-interval.

Type of releases for low voltage circuit-breakers. Release is a device, mechanically connected to a circuit-breaker, which release the holding means and permits openings or closing or circuit-breaker.

— **Overload release.** The over-current release is intended for protection against overloads.

— **Thermal overload release** responds to overloads by means of thermal action of the current flowing in the release.

— **Shunt release.** A release energized by the voltage source, *i.e.*, parallel to the load.

— **Under voltage release** is a shunt release which permits opening of a circuit-breaker when the voltage across the terminals of the release faults below a predetermined value.

15.7.3. Test on Low-voltage Circuit-breakers

— Type tests.

— Routine tests. (Ref. Secs. 10.2, 10.3)

Type tests

— verification of temperature rise limits. (Ref. Sec. 10.2.2)

— dielectric tests. (Ref. Ch. 12)

— short-circuit making and breaking tests. (Ref. Ch. 11)

— rated short-time withstand current. (Ref. Sec. 11.6)

— mechanical endurance test.

— electrical endurance test.

— verification of overload performance.

Routine tests

— mechanical operation tests.

— calibration of releases.

— dielectric tests. (Ref. I.E.C. 157)

15.8. 'EXPLOSION-PROOF' OR 'FLAME-PROOF' SWITCHGEAR

The term "Explosion-proof" is used in USA and 'Flame-proof' is used in UK and India, 'Pressure-proof type' in Germany. These three terms are synonymous.

Flame-proof enclosures of switchgear are specially designed and built for installation in hazardous locations. The hazardous locations include those which have

— Highly inflammable gases/vapour or liquids.

— Combustible dust.

— Combustible fibres floating in air.

— Highly inflammable liquids like petrol, naptha, benzene, ether, acetone, etc. These explosive mixtures of air and inflammable gas can explode in presence of electric arc or electric spark.

The primary consideration in the design or flame- proof enclosures is to prevent such explosion. The flame-proof switchgear should be built such that

The construction should be strong, enough to withstand the high pressure from within, caused by explosion of gas which enters the enclosure.

— The design should be such that the flame or spark within the enclosure should not be carried out of the enclosure.
— The enclosure should be gas-tight.
— The flame-proof switchgear should be installed, as far as possible away from hazardous location, in the rooms where explosive gas is absent. The switchgear should be 'flame-proof', or 'explosion-proof' and should satisfy the codes and standards specified for such switchgear.

When gas or mixture of air and gas explodes inside the enclosure, the flame of the burning mixture should be confined entirely within the enclosure and should not be communicate to outside atmosphere, so that the ignition of inflammable gas is prevented.

It is, therefor, necessary to make the enclosure strong enough to withstand high pressures generated within the enclosure due to internal explosions. The enclosures are built ruggedly. The sizes are also relatively ample.

SF_6 Gas insulated Switchgear (GIS) is metal enclosures filled with SF_6 gas. SF_6 gas is not flammable and is ideally suitable for 'Flame proof Switchgear'.

SF_6 switchgear is hermetically sealed. The internal gas pressure is 3 kgf/cm^2. Static seals and dynamic seals are provided with flanges, rotary shafts to ensure gas tight construction.

PART C
LOW-VOLTAGE CONTROL GEAR AND CONTACTORS

15.9. LOW VOLTAGE CONTROL GEAR

Control gear is a general term covering switching devices and their combination with associated control, measuring, protective equipment intended for control of power-consuming equipment.

Control gear comprises the following :

— some form of switching device capable of make and break the current in one or more electric circuits, such as contractors, circuit-breakers, switches, thyristors.
— measuring equipment comprising CTs, PTs, measuring instruments, measuring circuits, etc.
— regulating equipment such as voltage regulator, current regulator, speed regulator, temperature regulator.
— protective equipment such as fuses, relays.
— structural components such as enclosures, support structures, bus-bars, interconnections.

Control gear is primarily used for control of power consuming equipment such as motor, furnace, rolling mill, paper making machinery.

15.10. CONTACTORS

Contactor is a mechanical switching device capable of making, carrying and breaking electric current under normal circuit conditions including operating overload conditions.

The contactors are basically for operation under normal conditions and overload conditions. This condition distinguishes the 'contactors' from 'circuit-breaker'. Circuit-breakers must necessarily be capable of making, carrying and breaking short-circuit currents as per the assigned.

However contactors may be capable of making and breaking short-circuit currents, if they are designed for short-circuit duties also.

Contactors is usually intended to operate more frequently. During the mechanical endurance test contactors are operated 0.001 to 10 million times on no load to verify their resistance to mechanical wear.

Contactors have a main circuit and a control circuit. The contactors are designed according to the method of energising the control circuit, namely.

— electromagnetic — pneumatic — electro-pneumatic

15.11. SOME TERMS AND DEFINITIONS

1. **Electromagnetic Contactor.** A contactor in which the opening and closing of main contactors is achieved by means of a electro-magnet.

2. **Electro-pneumatic Contactor.** A contactor in which the force for closing and opening the main contacts is provided by an electrically operated pneumatic device. The electrically operated valve opens the passage of compressed air, thereby the air from auxiliary compressed air system enters the cylinder of the contactor and the contacts are operated.

3. **Main Circuit.** The conducting parts of a contactor designed to close or open. The current flows from the supply to the load through the main circuit of the contactor.

4. **Main Contact.** The contacts in the main circuit intended to carry the load current when the contactor is in closed position.

5. **Control Circuit.** The circuit which is energised or deenergised electrically for opening/closing operation of the contactor.

6. **Auxiliary Circuit.** The circuit other than the main and control circuit.

7. **(a) Contact (make contact).** A control contact which is closed when main contact is closed.

(b) Contact (break contact). A control contact which is open when the main contacts are closed.

15.12. CONTACTOR STARTERS FOR MOTORS [Ref. Sec. 31.4.1.]

Contactor starters are commonly used for starting squirrel cage induction motors. The starter has the following components enclosed in a sheet metal enclosure ;

1. One or more contactors.
2. Control circuit consisting of solenoid, auxiliary contacts etc.
3. Overload relays.
4. Start, stop, reverse push buttons.

Generally there are two distinct circuits namely, main circuit through which the current flows to the motor ; and an auxiliary or control circuit. The contactors are the switching units which can perform even 10 million operations under normal conditions. It consists of three main contacts (for 3-phase motor starter) and one or two auxiliary contacts. There is a control coil. When the coil is energized, the contactor closes by attracted armature action. When the coil is de-energized the contactor opens. Remote control of the starter can be obtained by making suitable connection in the starter. [Ref. Fig. 31.2 (*b*)]

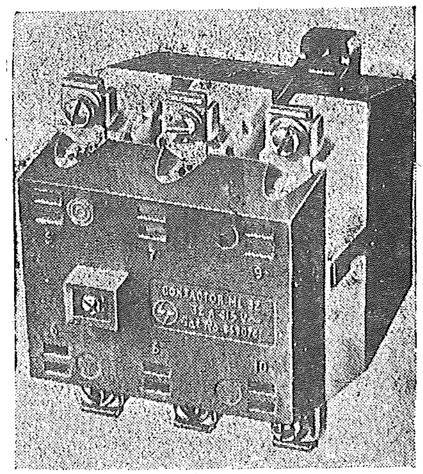


Fig. 15.8. Contactor.
(*Courtesy* : Larsen and Toubro Ltd., India)

In reversing contactor starter, there are two contactors, one for forward rotation and other for reverse. Only one is closed at a time. Phase reversal is obtained by the to contactors. Fuses provide back-up and short-circuit protection. Thermal relays provide over-load protection. (Ref. Sec. 31.4.2)

The following types of starters are common :

(1) Direct on line contactor starter. (2) Reversing contactor starter.

(3) Star-delta contactor starter.

15.13. RATED CHARACTERISTICS OF CONTACTORS

(1) **Type** — Electro magnetic — Electro-pneumatic — Pneumatic

(2) **Interrupting medium**

— air — oil — SF_6 gas — vacuum

(3) **Rated Values**

(*i*) **Rated Voltages**

— *Rated operational voltage* (U_0) *for three phase contactors. It is the rated voltage between phases.*

— *Rated insulation voltage* (U_i). It is the voltage to which the dielectric tests, creepage distance are referred.

(*ii*) **Rated Current**

— *Rated thermal current* (I_{th}) is the maximum current the contactor can carry on eight-hour duty without the temperature rise exceeding the permissible limits.

— *Rated operational current* (I_o) of a contactor is stated by the manufacture by taking into account the rated frequency, operational voltage, rated duty and utilization category.

In case of contactors for motors, instead of/in addition to the rated operational current, maximum rated through put may be assigned.

(*iii*) **Rated Duty and Service Conditions**

(*a*) **Eight hours duty.** Contactors carry steady normal current for more than eight hours until the maximum temperature rise is attained. The rated thermal current (I_{th}) of the contactor is determined on the basis of eight hours duty.

(*b*) **Uninterrupted duty.** Contactor remains closed without interruption for a prolonged time (more than eight hours, weeks, months, years).

The dust, dirt, oxide coatings on contacts lead to progressive heating.

(*c*) **Intermittent duty.** Duty in which the contactors remains closed for periods having a definite relation with no load period, both no load and load periods are too short to allow thermal equilibrium. In intermittent duty, the contactor is made on and off in such duration that the thermal equilibrium is not reached.

For example :

In an intermittent duty, current of 200 A flows for four minutes in every fifteen minutes. This intermittent duty may be stated as : 'Intermittent Duty : 200 A, 4 min 1/15 min' or as 'Intermittent Duty : 200 A, 4 operating cycles per hour,

$$\frac{4}{15} \times 100 = 26.67\%$$

The standard values of on-load factor are :

15%, 25%, 40%, 60%.

The standard classes of intermittent duty as per IEC 158.1/1970 are as follows :

Class 0.03—upto 3 operating cycles per hour
Class 0.1—upto 12 " " " "
Class 0.3—upto 20 " " " "
Class 1—upto 120 " " " "
Class 3—upto 300 " " " "
Class 10—upto 1200 " " " "

Operating cycle comprises one closing operation followed by one opening operation.

For large number of cycle the following expression is recommended :

$$\int_0^T i_2\, dt\, D\, I_{th_2} \times T$$

where i = current

T = total operating cycle time

I_{th} = rated thermal current.

(*d*) **Temporary Duty.** Duty in which the main contacts remain temporary closed for such a period that thermal equilibrium is not reached.

Example. 10 minutes, 30 minutes, 60 minutes and 90 minutes.

(*e*) **Making Capacity.** Rated making capacity of a contactor is the value of the current under steady condition which the contactor can make without welding or excessive erosion of contacts and without excessive display of flame.

The making capacity of a contactor is specified with reference to the following :

— voltage between poles before contact making.

— characteristic of the test circuit.

— utilization of category.

The rated making capacity of an a.c. contactor is expressed in terms of r.m.s. value of symmetrical component of current.

(*f*) **Breaking Capacity.** The rated breaking capacity of a contactor is the value of current which the contactor can break without excessive erosion of contacts or display of flame. For a.c. contactors, the rated breaking capacity is expressed by r.m.s. value of symmetrical component of current.

The condition of reference for breaking capacity are the following :

— characteristics of test circuit. — recovery voltage — utilization category.

Utilization Categories of Contactors

Category	*Applications*
AC-1	Non-inductive or slightly inductive loads, resistance furnaces
A.C. AC-2	Slip-ring induction motors : Starting, plugging*
AC-3	Squirrel-cage induction motors : Starting, switching, off
AC-4	Squirrel-cage motor : Starting, plugging, inching**
D.C. DC-1	Non-inductive and slightly inductive loads
DC-2	Shunt-motors : Starting, switching off
DC-3	Shunt-motors : Starting, plugging, inching
DC-4	Shunt-motors : Starting, switching off
DC-5	Shunt-motors : Starting, plugging, inching.

For details regarding conditions of making and breaking currents and power factors for various categories, please refer IEF 158.1 'Contractors'.

(*g*) **Utilization Category of Contactor.** Utilization of contactor is characterised by values of current and voltages expressed as multiple of rated operation current and rated operation voltage and power factor or time-constant and other test conditions.

* *Plugging :* stopping the motor rapidly by reversing the primary connection.

** *Inching (Jogging) :* energizing the motor once or repeat periods to obtain small movements for mechanisms.

15.14. TESTS ON CONTACTORS

The tests on contactors (Ref. IEC 158.1) are classified as

— Type tests — Routine test — Special tests

Type tests include the following :

— Temperature rise tests
— Dielectric tests
— Making capacity tests
— Breaking capacity tests
— Operating limit tests
— Mechanical endurance tests
— Short-circuit tests (if applicable)

Routine tests include :

— Operating tests — Dielectric tests.

Special test included electrical endurance tests.

PART D

15.15. CONTROL BOARDS OR CONTROL PANELS

In generating stations, receiving stations and sub-stations, the control and relaying equipment is installed in control-rooms. The arrangement of control and relay equipment needs careful attention to suit the layout and operational requirements of the installation. The requirements vary widely with the type and size of the station.

(*a*) **Large Installations.** When control of a large number of circuits is desired, as in the case of generating stations, the arrangement should be such that, the indicating apparatus should be clearly visible from the central place. To achieve this purpose, the equipment should be compact. The terminals should have good accessibility. The general trend is to provide separate panels for :

(*i*) Control and indication equipment and

(*ii*) Relay and indication equipment, voltage regular equipment.

The diagram of main connections are given on the front face of the panel, there diagrams indicate the positions of the circuit breakers and isolators. The control operator gets the idea as to which breaker open or closed. The controls of generator and main transformer circuits are generally brought on a separate control-desk, located centrally, in front of main control-board. Separate control desks are provided for prime-movers and boilers.

(*b*) **Medium Size Installation.** In medium size installations, panel width can be increased to accommodate relay and other equipment. In case of complex protective schemes, a separate relay panel is necessary.

Construction

The constructional features vary with the manufacturer and applications. However, a general pattern can be described. The control and relay boards are built of self-contained sheet steel cubicles. These cubicles are assembled on common channel-iron base plates according to the needs.

The cubicles are fabricated as follows : The angle-irons or channel-irons are cut according to drawings. The pieces are welded to form the frame. Sheets are cut on shearing machine to required sizes. They are placed on the frame at appropriate position and are welded.

The sheet of thickness 3 to 5 mm are used. The wiring is suitable for 250 V and are generally of grade 7/0.029 cable. The standard colour code (B.S. 158) is generally used. *Terminal Blocks* are used for connecting the wires.

Synchronising Arrangements

The panel for synchronising, can be conveniently arranged on the upper portion of the cubicle. The indicating instrument show "Incoming Volts", Bus-bar Volts" and "Slow or Fast".

Cubicle arrangements

The cubicles are arranged in a line, side by side. Sometimes, the relay cubicles are arranged back-to-back with their respective control cubicles, with a corridor in-between. The corridor is roofed and troughs are provided for wiring which run between the control and relay panels. The operator's control desk, personal-computer and Video-Display Screen, Event Recorder are usually located at the centre of the control room. Mimic-diagram board is at the front.

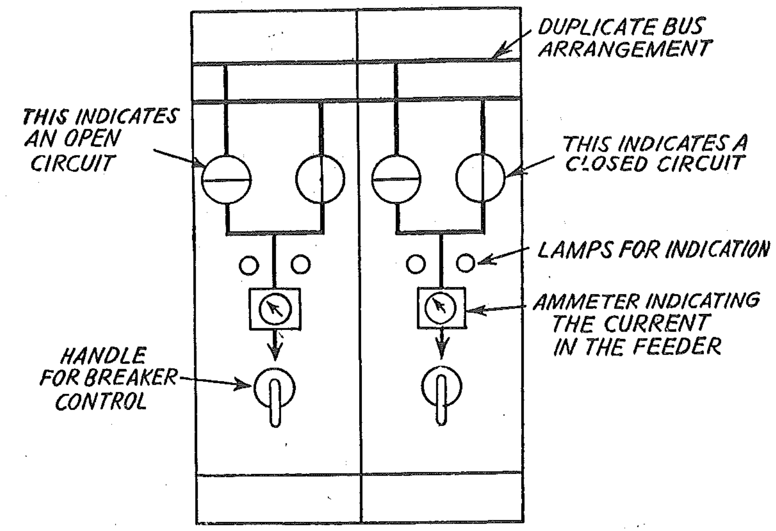


Fig. 15.9. Two units of a panel with Mimic-diagram. The diagram shows the circuit arrangement.

Panel Types*

These are illustrated in Figs. 15.4 and 15.9. There are a variety of patterns. The dimensions of cubicles are standardised.

(*a*) **Panel with Mimic Diagram**

(*b*) **Relay Panel.** As mentioned earlier, the relays are on a separate panel. Fig. 15.9 illustrates a typical panel. The type and number of relays depends on requirements.

(*c*) **Instrument Panel.** Indicating ammeters, voltmeters, energy meters, their selector switches, recording instruments, if any, fitted on instrument panel. Other types include

(*d*) Synchronizing panel.

(*e*) Automatic voltage regulator panel.

(*f*) Process control panels.

(*g*) *Event recorder.* Every operation in the main circuit/control circuit is recorded on print-out.

(*h*) *Fault Recorder.* The oscillographic record of variables is printed on graph sheet.

(*i*) *SCADA.* Supervisory control and Data Aquisition.

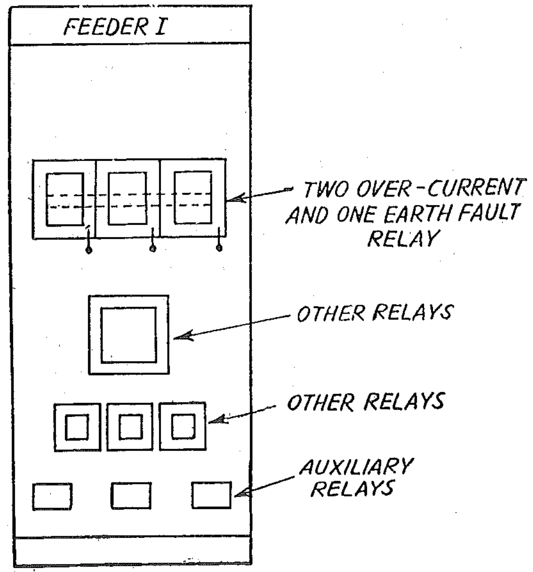


Fig. 15.10. Relay Panel, only one unit shown.

15.16. CONTROL ROOM-LAYOUTS

The layouts of control-room depend on the size and type of installation. Fig. 15.10 illustrates a typical layout. The types of panels installed in the room are indicated in the figure.

* Carrier communication panel is connected to the power line through coupling capacitor. Communication can be carried out between the stations by carrier channels. D.C. supply for protective relating is obtained from battery system.

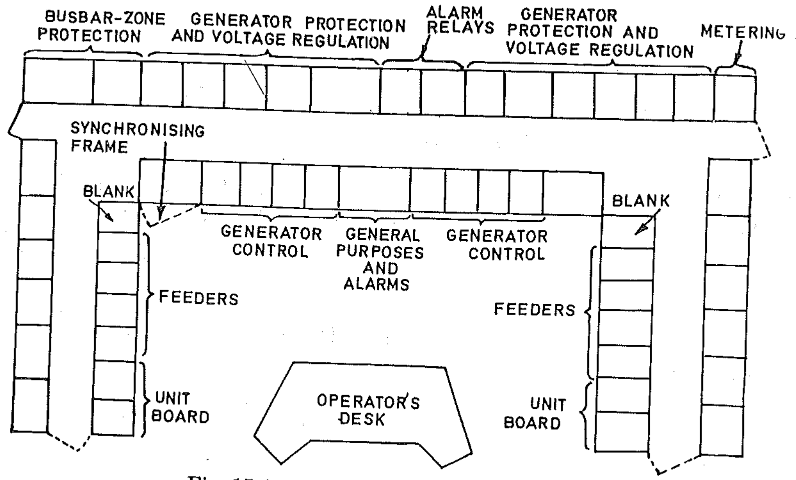


Fig. 15.11. Layout of a control-room.

QUESTIONS

1. Describe the construction of an indoor metal clad switchgear.
2. What are the various types of designs in medium voltage in door switchgear.
3. Which are the essential components in metal-clad switchgear ?
4. Describe the construction of a draw-out type or truck type switchgear ?
5. Describe the contactor starter with reference to its components and the function. (Ref. Fig. 31.2).
6. Describe the construction of SF_6 metal-clad switchgear. State its advantages.
7. Why the metallic non-current carrying metal parts of switchgear should necessarily be earthed ? Which safety precautions should be considered in the design of metal-clad switchgear ?
8. Draw an electrical single line diagram of a metal-clad switchgear.
9. State the design features of Flame-proof switchgear.
10. What are the merits of vacuum switchgear ?
11. Define the following terms with reference to contactors :
    — Breaking capacity — Category of duty — Rated thermal current.
12. Discuss in detail the major differences in the specifying the ratings of low voltage circuit-breaker and high voltages circuit-breaker. (a.c. only).

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* Ref. Sec. 7-13 for SF_6 Insulated Metal-clad Switchgear used for voltages from 12 kV to 760 kV.
Ref. ch. 15-B for medium voltage switchgear with VCB and SF_6 CB.
Ref. ch. 15-C for Low Voltage Controlgear and Switchgear.

15-B

Medium Voltage Metal Enclosed Switchgear with SF6 CB and VCB

Part I : Introduction — Classification — Range — Application — Special requirements.
Part II : Constructional aspects — Variants — Cable terminations — Degree of protection — Design aspects cable termination systems.
Part III : Switching Phenomena — Motor Switching — Capacitor Switching — Repeated Switching — Associated problems SF_6 *B* and VCB.
Ch. 15-C : Low voltage controlgear and Switchgear.

PART I : APPLICATION AND RANGE

15.17. TYPE AND RANGE

The various types of Indoor Metalclad/Metal-enclosed switchgear described in Ch. 15A Part A have undergone significant improvements during 1980s.

Indoor Metalclad/Metal-enclosed Medium Voltage AC Switchgear are used in industrial and distribution substations, power plants etc. for voltage between 1 kV and 36 kV. Such switchgear are purchased by a very wide range of users. The earlier versions called cellular type and fixed type are no more preferred in India. Metalclad and Metal enclosed factory assembled drawout type switchgear are now very common.

The earlier designs had bulk-oil circuit-breakers and later minimum oil circuit-breakers. The SF_6 circuit-breakers and vacuum circuit-breakers have become very popular due to their non-explosive and maintenance free performance and better capabilities for repeated reliable switching under various switching conditions. With these circuit-breakers the switching phenomena like motor switching, capacitor switching, arc furnance switching, traction duty etc. has become easy.

The constructional of medium voltage switchgear can have several variants. The design is generally tailor-made to meet customers particular requirements.

15.18. IEC AND CIRED CLASSIFICATION

IEC defines voltage classes as follows :
Low Voltage. Upto and include 1000 V.
High Voltage. Above 1000 V.
IEC *does not* distinguish between Medium, High, EHV and UHV switchgear.
CIRED (The international conference of distribution systems) defines the following :
Low Voltage. Upto and include 1000 V.
Medium Voltage. Above 1000 V and upto and including 36 kV.
High Voltage. Above 36 kV.
The above are rms phase to phase voltages.

Chapter 3, Table 3.3 gives the various assigned ratings and the range of High Voltage AC circuit-breakers based on IEC 56 and IS 2516.

IEC 298. Revised Edition 1979 defines for the first time the various types of indoor metalclad switchgear as follows :

Metal-enclosed Switchgear is a general term for switchgear assemblies having earthed external metal enclosures upto but excluding the external connections. Metal-enclosed switchgear is divided into following three categories.

1. Metalclad Switchgear in which the main components are arranged in separate compartments with metal barriers. The shutters covering the fixed contacts (when carriage is drawn out) may be of insulating materials.

2. Compartmented Switchgear. It is a metalclad switchgear, but the barrier are of insulating material. Compared switchgear gives higher internal clearance between live parts and nearest earth parts because of insulating barriers.

3. Cubicle Switchgear has no internal compartments. It is more commonly known as metal-enclosed switchgear.

Table 15.1-B gives the range of above types.

In Metalclad Switchgear : separate metal compartment is provided for at least each of the following :

— Each main switching device

— Components connected to one side of switching device *e.g.* the feeder circuit.

— Components connected to the other side of switching device, *e.g.*, busbars.

The partitions between compartments are metallic and are earthed.

The **Cubicle switchgear** (Metal enclosed switchgear).

The number of compartments are less than those mentioned above. The degree of protection of partitions is less than that required for external enclosures. There are no partition and compartments.

Table 15.1-B Range of Metalclad Switchgear and Main Ratings

Rated Voltage kV, rms	*Preferred type*	*Busbar arrangement*	*Rated current A rms continuous*	*Rated S.C. current 1 sec kA rms*	*Rated Insulation Level*	
					1 in, 50 Hz kV rms	*Impulse kV peak*
7.2	ME	Single	630-3150	12.5-50	20	60
	C	Double				
12	ME	Single	630-3150	12.5-50	28	75
	C	Double				
17.5	ME	Single	630-3150	12.5-40	38	95
	C	Double				
24	ME	Single	630-3150	12.5-40	50	125
	C	Double				
36	ME	Single	630-3150	12.5-31.5	75	170
	C	Double				

ME = Metal-enclosed ; C = Compartment ; MC = Metalclad.

PART II. Constructional Aspects

15.19. CONFIGURATION AND VARIANTS

The functional requirements of a metal-enclosed switchgear include :

1. Control. Switching on/off during normal conditions for operation, automatically during abnormal conditions ; sequential switching etc.

2. Relays, Metering, instruments ; A, V, MW, MWh, cos ϕ, *f*.

3. **Earthing.** Facility to apply an earth connection readily to the circuit connection (and also to busbars).

4. **Testing.** Provision for making test connection to circuits (and also to busbars).

5. **Maintenance.** Provision of inspection, checking, servicing overhaul.

6. **Safety** to operators against explosion, fire, shocks, accidents. Interlocks to prevent wrong closing or opening.

7. **Degree of Protection.** This is designated by IP followed by two numerals. *e.g.* IP 3X, IP 5X.

A typical metal-enclosed switchgear has following components (Ref. Sec. 15.3) :

— Busbars, busbars connections

— Switching devices : Circuit-breakers, load break switches, isolators, earthing switches.

— CTs, VT

— Cable termination for incoming and outgoing power cables.

— Instrument and relay panel, metering panels.

— Electrical and mechanical interlocks.

The required components are arranged to form the factory assembled units and the total switchgear. In metalclad switchgear the components are housed in compartments. In metal-enclosed switchgear, there are no partitions and compartments.

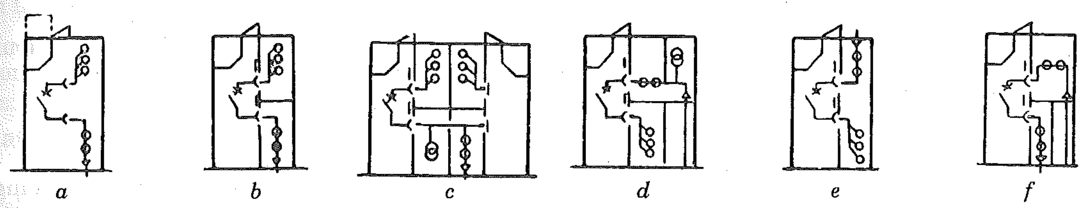


Fig. 15.12. Variants in Metal enclosed Switchgear Panels.

a = Standard metal-enclosed panel *b* = Standard compartment panel
c = Duplex panel (Double bus-bar) *d* = Busbar and cable entry reversed
e = Top cable entry *f* = Panel with cable entry and cable exit.

In fixed type switchgear (no more preferred). The circuit-breaker unit is fixed and required isolators and earthing switches are provided with it.

In withdrawable switchgear (described below) the circuit-breaker unit is on withdrawable truck. After opening, the circuit-breaker truck can be withdrawn by pulling out the truck for isolation and inspection. While putting in service the circuit-breaker carriage is pushed in and the breaker is closed.

The variants in the configuration of cubicles of a drawout switchgear have been illustrated in Fig. 15.12. The layout of the total switchgear and the configuration of the individual cubicles is selected in accordance with the customers requirements.

Fig. 15.12 (a) illustrates one unit of a Metal-enclosed switchgear defined as cubicle switchgear in IEC.

This particular unit has following design features :

— Tubular single busbars mounted directly against the wall side of the cubicle.

— Front access for cabling therefore, the cubicle can be mounted directly against the wall.

Fig. 15.12. (b) shows a metal-enclosed type design with fully separated compartments for busbars, circuit-breakers, cable termination and with independently operated shutters.

Fig. 15.12 (c) illustrates Duplex Back-to-Back arrangement with complete duplication of busbars, and circuit breaker **compartments**. By equipping both the cubicles with the circuit-breakers, automatic bus transfer scheme and/or uninterrupted power supply scheme (UPS) is possible (Ref. Sec. 43.19). A front-to-front layout with appropriate arrangement of the cable connections provide 100% duplication with maximum security of supply. Principle of duplicate busbar system is described in Sec. 17.4.

Fig. 15.12 (d) and (e) show cable entries from below and from above at a suitable predetermined height above the floor level to suit the routing of cables with respect to civil works.

Fig. 15.12 (f) shows a single cubicle with cable connection from floor level and higher level. Such arrangement may be suitable for voltage control equipment, small generators, etc. where two feeders should be independently switched/isolated.

15.20. DRAWINGS AND DIAGRAMS

The design and construction of a metal enclosed switchgear is based on the following.

1. **Single Line Diagrams.** The diagram illustrates the main circuit and the main components viz. CB, isolator, busbars, incomers, outgoing lines CTs, VTs etc. (Fig. 17.26).

2. **Electrical Layout Diagrams.** This illustrates the arrangement of busbars and components in the switchgear and the cubicles.

3. **Civil Layout Diagram.** This illustrate physical arrangement of cubicles and switchgear with reference to the walls, floor, ceiling, cables trenches etc.

4. **Control Diagrams.** These illustrate control circuits, protection circuits, interlocking circuits, measurements, metering etc.

5. **General Arrangement and Overall Dimensional Drawings.** These give the various dimensions, foundation plan and general arrangement of the cubicles.

Metering Facilities

These include :

— Measurement of current, voltage, power, MVA, MVAr, on busbar side, cable side, incoming and outgoing circuits.

— Instruments are provided in the panel and are connected to CTs, VTs.

— Instruments for tariff purposes *e.g.* kWh meter.

— Relays for protection supervision etc.

Busbar VTs may be on withdrawable cubicle or as fixed cubicle.

The instruments and relays are flush mounted on the front side of the switchgear.

Enclosure Designs, Degree of Protection, Arc-Proof Test

The degree of protection against accidental contact with live parts and against the ingress of dust etc. is defined in detail in IEC Recommendations.

Standard degrees of protection by enclosures applicable to switchgear as regards :

1. Protection of persons against contact with live or moving parts inside the enclosure and protection against ingress of solid foreign bodies : dust

2. Standards specify the following :

Designations for these protective degrees are defined by IEC.

The degree of protection by enclosure is confirmed by tests. These tests are type tests for enclosure. They are carried out on standard products or prototype. Where this is not feasible the test should be carried out in accordance with an agreement between manufacturer and user.

15.21. DESIGNATION FOR THE DEGREE OF PROTECTION

The designation used for the degree of protection consists of the letters IP followed by two characteristic numerals :

It is recommended that the characteristic letter and numerals be marked on the name plate, or on the enclosure.

The standard cubicle design provides the degree of protection known as IP3X, being that normally specified for indoor switchgear. For cubicles used in particularly polluted environments this can be increased to IP5X. The switchgear is also available in a 'vermin-proof' design, additional precautions being taken to prevent the entry of insects, etc. In this case particular attention must be paid to ensure that all cable access openings are closed off when erections is completed.

Designations applicable to switchgear

First Numeral	*Description*
3	Protected against solid particles 2.5 mm dia
4	Protected against solid particles 1 mm dia
5	Dust protected
6	Dust tight
First Numeral	*Description*
O or X	Not protected against water since installed indoor.

IEC Recommendation No. 298 now includes standards for the performance of 'arc-proof' testing. The test requirements are for an internal fault arc of full short-circuit value to be continued for one second without danger to an operator standing in front of the cubicle. For some contracts, proof of this capability is agreed by the manufacturer and corresponding tests are performed, the cubicle being slightly modified by the addition of a separate door as for the vermin-proof cubicle designs. When 'arc-proof' switchgear is used the substation building has to be designed accordingly in order to achieve the correct degree of protection. The hot gas must be routed to a place where it can do no harm to operators.

The operating practices of some countries require special enclosure designs. The two most common requirements are for the circuit-breaker truck to remain within the enclosure when in the test/isolated position.

Maintenance Earthing

During operation and maintenance the first function performed on a switchgear is earthing of busbars and equipment. Operating practice as regards earthing is highly diverse so that alternative must be provided ; the following are the most frequently employed and are available in standard cubicles.

— Hand applied earths. Earthing cables manually applied by means of an insulated operating rod.

— Circuit-breaker earthed.

Truck mounted circuit-breaker with an appropriate set of connections short-circuited and earthed. The truck is provided with the necessary voltage testing and interlocking facilities. As a further variant, fittings are available which permit a normal feeder circuit-breaker to be used for earthing purposes.

— Earthing switch, either of the non-fault or fault-making type.

The isolator is permanently mounted in the cubicle and key-interlocked with the circuit-breaker. Live-line indication motorized operation of the isolator and electrical interlocking are possible when a voltage transformer is installed on the cable side.

Ancillary Devices and supplies

These include load break switches, fuses, voltage limiting devices such as surge suppressors, surge arrestors, neutral grounding resistors etc. These are housed in separate compartments of the metal enclosed switchgear. Auxiliary transformers required for substation lighting may also be incorporated in the cubicle. The Auxiliary DC supply 9110 VDC/220VDC) is obtained from Rectifier set and battery. Batteries are kept float-charged. Auxiliary AC supply is obtained from Auxiliary Transformer.

(Ref. Sec. 17.3 for details about load break switches and sec. 17.13 for Factory substations).

15.22. CABLE TERMINATIONS SYSTEMS

The incoming and outgoing cables require proper terminations system. Fig. 15.12 (*a*) to (*f*) illustrates the locations of cable terminations in the metal enclosed switchgear.

In earlier decades oil-impregnated paper insulated cables were used and these were terminated in metal boxes filled with liquid cable compound such as bitumen compound.

During 1970's epoxy cable sealing systems have been introduced.

The classification of cable boxes/cable joints/cable terminations can be made by various methods as follows :

1. **Classification based on voltage class.** Upto 1 kV, upto 6.6 kV, upto 11 kV, upto 33 kV.

2. **Classification based on application.** Jointing between straight lengths, trifercation, termination, type of cable.

Jointing is used for obtaining long length of cable line than available length of single cable. The number of joints/km length of cable line should not be more than six. The cable joints must be hermatically sealed, corrosion-resistant and should be mechanically and electrically strong.

3. **Classification based on material.** Cast iron jointing box, lead jointing box, epoxy junction box and type of cable.

4. **Classification based on design shape.** Straight, T-shaped, Y-shaped and X-shaped.

Epoxy Cable Sealing

Epoxy cable jointing systems are widely used for cable joints.

They have a number of advantages over cast-iron and lead cable boxes. They are compact and lighter in weight take shorter time and less labour for installation. Epoxy resins readily adheres to metals, provide reliable hermetic sealing, is not attacked by corrosion, and are sufficiently resistant to moisture.

Epoxy kits are manufactured at factories and delivered on site in the form of hollow epoxy or plastic shells. The shells are mounted on the cable joint and filled with epoxy resin plasticizer filler and hardener.

Plasticizers and fillers gives thermal stability, elasticity and mechanical strength of epoxy resin and reduce thermal expansion coefficient of the compound to a value approaching that of copper aluminium and lead, which are most frequently brought in contract with the compact with the compound when cables are joined together. The hardener accelerates polymerization of epoxy resin. Thereby reducing the hardening time of the compound.

Epoxy jointing systems are most often used for the low voltage, medium and high voltage connections of 1, 3.3, 6.6 and 11 kV cables.

The epoxy cable jointing system is composed up epoxy body, sheet steel screen, two cones with metal collars fitted with them. One of the cones is attached to the tabular portion of the cable in the factory. The other cone is fitted at site.

After making conductor jointing the epoxy compound is poured from a low height in the form of a continuous jet, 12 mm wide while doing this, tap the cable jointing system with a wooden hammer to help the escape of gas bubbles of the surface.

Check the compound for its hardness 15 hours after filling the cable jointing system by touching it with your hand ; at a temperature of 20°C the compound must harden in 12 hours after filling. A higher or lower ambient temperatures the hardening time is respectively, shorter or longer.

Epoxy compound is delivered on site already packed and with the filled introduced. The hardener is introduced at the time of installation of the cable jointing systems and terminations. The compound must be thoroughly mixed with the hardener and left to settle 10 to 15 minutes for the escape of air. The ready compound is effective for a period of :

0.5 to 1 hour at an ambient temperature of 0° to 10°C.

1.5 hour at an ambient temperature of 11° to 20°C.

2 hour an ambient temperature of 21°C to 35°C.

In mixing or filling the epoxy compound, care should be taken to prevent its contact with human skin and to protect human eyes because the compound (while not polymerized) contains toxic chemical agents that may cause local irritation and inflammation.

Locking and Interlocks

Metal-enclosed switchgear require several safety features including screens, locks and interlocks.

Padlocks are filled to ensure that unauthorised persons cannot operate the switchgear.

Key type interlocks ensure that one operation releases the key to perform the next sequential operation.

Electrical interlocks are essential in all metal-enclosed switchgear. With electrical interlocks, it is impossible to disconnect a switching device from the busbars. When it is in closed condition secondly, interlocks ensure that the switching device is in final correct position before it can be closed.

Some important features include :

— Unless circuit-breaker is open and in final correct position and isolators closed, it should be impossible to close the circuit-breaker.

— It should be impossible to close the circuit-breaker until earthing switch is opened.

— If a circuit-breaker carriage is used for earthing its tripping should be inoperative.

Load break Switches, Fuse-switch Units

By suitable choice of circuit-breakers, load break switches and fuse switch combination ; the metal clad switchgear can be made economical. (Ref. Figs. 17.26, 17.27).

Circuit-breakers are used for fault interruption and back up. Load-break switches for normal opening and closing operation. Further details in Sec. 17.13.

PART III. Switching Phenomena Associated with Medium Voltage Switchgear with SF_6 CB and VCB

15.23. GENERAL ASSESSMENT CRITERIA

Total Cost

This term denotes the cost arising from purchase, operation and servicing with respect to a specific required switching function. It is important to take the sum of all these costs into consideration. SF_6 and Vacuum circuit-breakers have very modest maintenance requirement. Hence they are economical during their long service life (about 20 years).

Mechanical Performance

Mechanical trouble accounts for the majority switchgear failures. Servicing requirements of a mechanical nature can be very costly.

Earlier switchgear with bulk-oil and minimum-oil circuit-breakers were designed for endurance of 1000 mechanical operations only. After that, overhaul was necessary. Modern VCB and SF_6 CB mechanisms for medium voltages are tested for the endurance of 5000 to 20,000 mechanical operation. The sliding parts are of PTFE requiring no oil lubrication. The maintenance requirements of mechanisms are modest.

Electrical Switching Phenomena

This concerns :

— The reliable breaking of currents ranging from full or partial short-circuit currents, through load currents down to magnetizing currents, motor switching, capacitor switching etc.

— Electrical side-effects likely to endanger other network elements *e.g.* switching over voltages produced when switching motors or transformers, restrike phenomena, voltage escalation phenomena etc. and precautions.

— Competent handling of various switching functions arising from special service conditions. Import switching functions associated with Medium Voltage switchgear include the following :

— Integrated Current Switching Capacity ($\Sigma I^2 n$)

Switching function	*Associated Phenomena*
1. Motor Switching, switching of low magnetising currents.	— Current chopping during opening.
	— Voltage escalation during closing of motors.
	— Overvoltages and failures of motor insulation.
2. Low arc current.	— Longer arcing time for self-generated pressure type CB like MOCB, OCB.
3. Capacitor switching cable switching.	— Restrike phenomenon, voltage surge, Breaker flashover, insulation failure.
	— High frequency inrush currents, pressure-rise.
4. Switching of Inductive loads.	— Current chopping.
5. Repeated switching.	— Breaker suitability with reference to maintenance schedule.

This term denotes the sum of all current values ranging from rated current to short-circuit which may be admissible switched before any attention need be paid to the switching chamber.

— Long-Term Rated Current Carrying Capacity.

It may be assumed that all switchgear is capable of handling the current it is rated for during entire service life.

MOCB, SF_6CB and VCB have different switching characteristics and need particular study before applications.

15.24. INTERRUPTION OF INDUCTIVE CURRENTS AND SMALL INDUCTIVE CURRENTS. (Ref. Sec. 3.12)

Following values of small/large inductive currents occur in practice

Transformers on no-load	: Upto 20 A
Neutral-grounding reactors	: Upto 2000 A
Neutral grounding transformers with reactor	: Upto 400 A
Load currents of motor	: Upto 1000 A
Starting current of motor	: Upto 5000 A
No-load current of motor	: Upto 20 A
Induction furnaces	: Upto 2500 A

Circuit-breakers which are capable of breaking short-circuit currents of several kA, find these inductive currents very small to interrupt.

The current may get chopped at current I_c before natural current zero giving rise to voltage (V_P)

$$V_P = I_c \sqrt{L/C}$$

$$f_n = \frac{1}{(2\pi \sqrt{LC})}$$

where V_P = Peak of switching overvoltage, Volts

f_n = Frequency of transient Hz

L = Inductance in load circuit, Henry

C = Shunt capacitance of load circuit, Farads

I_c = Chopped current, A, instantaneous Value

In circuit-breakers in which the dielectric strength across the contact gap gets rapidly re-established after current chopping (*e.g.* VCB, ABCB), there is no re-ignition of arc after current chopping and this can lead to inadmissible high switching overvoltage.

In case of OCB, MOCB the possibility of current chopping is less as the pressure generated in arc-quenching chamber is low for smaller currents. (Refer Sec. 6.3).

In case of ABCB and double pressure SF_6 blast circuit-breaker, the possibility of current chopping is more. (Ref. Sec. 6.3, External Extinguisher source).

In case of single pressure puffer type SF_6 CB. The gas is blown over the arc axially and the arc diameter is reduced to zero at current zero. Hence possibility of current chopping is less. (Ref. Sec. 7.5).

In case of VCB current chopping is likely for certain range of current. However in modern VCB, the chopping current is limited below 5 A by use of special chromium copper sintered contact tips with a small amount of material (1%) which vaporise easily. The vaporisation of this material helps in post arc conductivity and very low chopping levels.

15.25. SWITCHING-ON OF A MOTOR, VOLTAGE SURGE DUE TO MULTIPLE REIGNITION

So far, we discussed overvoltages occurring during opening of circuit-breakers. In motor closing, switching over-voltages can occur during closing of a circuit-breaker due to multiple re-ignition phenomena possible with VCB.

Consider closing of a VCB for starting a medium voltage motor.

In the first pole to close (or prestrike when contacts come closer), a surge wave is injected into the motor by the supply circuit (cable network, capacities) the surge is of at least peak to phase voltage if the source is rigid, *i.e.* having large capacitor or cables on supply side.

The voltage appearing on motor terminals U_m will be

$$U_m = U_s \left(\frac{2Z_i}{Z_c + Z_i} \right)$$

where U_m = Voltage appearing at motor terminal

U_x = Incident surge amplitude

Z_c = Surge impedance of supply cable

Z_i = Impedance of motor

Typical values of Z_c are 0.5 to 8, ohms and Z_i are 20 to 50 ohms. With these values

$$U_m = 2U_s$$

Due to damping and other effects actual value of U_m is between 1.5 to 1.8 U_s.

The three poles do not close simultaneously due to prestrike, difference in contact touch. The pole discrepance is of a few milliseconds (1 to 5). As the first pole close or prestrikes, the surge from the first pole to close will cause oscillations in the motor winding and the open terminals of other two windings, will show oscillatory overvoltage. Assuming first prestrike occurs a maximum voltage of the wave the peak voltages across second and third pole may approach a value of 2.0, 2.3 (= 0.5 + 1.5 to 1.8) times peak phase to neutral voltage. If any of those poles then close or prestrike, a surge wave of the same magnitude will be injected into motor circuit. Also the wave may be enhanced by reflection at motor terminals by factor 1.5 to 1.8 resulting in theoretical maximum swing of 3.0 to 4.1 per unit.

The above analysis for closing on a standstill motor. If the motor is running at full speed while the energising, and out of phase condition may occur, resulting higher than above values.

The large motor above 75 kW are supplied at medium voltages. The supply is given through power cables of some length between the switching device and the motor. Lumped capacitor are provided near the motor or switching for providing compensation for reactive power.

Following switching conditions are involved :

Closing — On no load
— On running motor which was switched off.
— re-switching of motor during starting.

Switching off : — One load
— During starting.
— On no load.

Severe conditions causing switching overvoltage include :
— Opening stalled motor
— Opening motor while starting.
— Closing the running motor.

Contact speed and contact material of vacuum circuit-breaker and vacuum contactors have influence on the prestrike behaviour.

The amplitude and rate of rise of overvoltage at closing is influenced by the surge characteristics of the motor, the surge characteristics of the connecting cable and supply network.

Type of circuit-breaker seems to have no influence on the normal prestrikes.

When the length of cable between the switch and the motor increases, the time to peak of switching overvoltages increases, rate of rise decreases.

High surge impedance of supply reduces the rate of rise and amplitude of surge-voltage.

Lumped capacitors (used for power factor correction) or a large number of cables connected to supply bus enhance the amplitude and rate of rise of surge-voltage.

While closing vacuum contactors or vacuum circuit-breakers, high frequency repetitive transients may occur due to multiple high frequency reignitions while closing. The pre-ignition (described above) causes high frequency transients with saw-tooth wave forms. Vacuum gap quenches the high frequency current zeros but rising voltage causes pre-strike again. This occurs repeatedly at high frequency 10 to 100 kHz for a few milliseconds (1 to 5). However such a phenomenon usually does not results in voltage escalation since the breakdown of vacuum gap causes limitation of amplitude of overvoltage. When interruption of starting-currents of motor and stalling currents is avoided by appropriate control actions ; the closing transients represent the next most severe switching condition will produce switching transient every time giving a statistical rise of excessive overvoltage and successive degradation of motor insulation eventually leading to motor insulation break-down.

15.26. MOTOR SWITCHING WITH PUFFER TYPE SF_6 CIRCUIT-BREAKERS

The puffer type SF_6 circuit-breaker have a very low current chopping level. This is due to the physical properties of the SF_6 gas, and low pressure axial blast in puffer principle. Because of the easy ionizability of sulphur, the plasma in SF_6 circuit-breaker remains conductive down to relatively low temperature, which counteracts instabilizing of the arc and there with interruption of the current before the natural current zero. The arc is blasted gently, which however due to the excellent arc extinguishing properties of SF_6 is adequate to assure interruption of the current. Because of this axial gentle blasting, the current chopping level of the puffer type SF_6 circuit-breaker is very low. Hence overvoltage occurring during motor switching due to current chopping are whithin permissible limits. The dielectric recovery of the contact gap of SF_6 circuit-breaker is very rapid. This is due to the electronegative behaviour of SF_6 and its dissociation products. In addition, the contacts of the SF_6 puffer type circuit-breaker must travel a certain distance before circuit-breaker is able to interrupt (buildup of the required blasting pressure). For this reason the reignition probability of SF_6 self-extinguishing circuit-breaker is low. Reignition if any takes place through contact gap filled with ionised gas and does not allow the over voltage to reach high value. Current is interrupted at next zero.

The capability of interrupting high-frequency transient currents (di/dt at current zero upto a several (100 $A/\mu s$) is a unique characteristic of vacuum circuit-breakers. The associated phenomena such as virtual current chopping or multiple reignitions with voltage escalation occur with vacuum circuit-breakers. Such phenomena do not occur with puffer type SF_6 circuit-breaker because of the gentle blasting of the arc in the current range cannot interrupt high frequency currents. A reignition if any occurs, only once on the 50 cycle wave due to insufficient contact travel. Sequences of reignitions with sawtooth-like voltage characteristics as they occur from vacuum switching principles, do not occur with the SF_6 circuit-breaker. This property is useful for puffer type SF_6 in motor-switching applications. Hence puffer type SF_6 circuit-breaker are used without additional RC surge suppressors.

15.27. CAPACITOR SWITCHING

In medium voltage range capacitor switching applications include :

— Cables on no load, upto 100 A.

— Capacitor bank switching upto 2000 A.

The switching is of two types.

— Opening of single capacitor bank and associated restrike phenomenon (Sec. 3.14.1.).

— Closing of one capacitor-bank against another (Parallel bank-switching) and associated phenomenon of high frequency, high amplitude inrush currents during pre-ignition.

Opening of Capacitive Currents (Refer Sec. 3.14.1).

Where the current is interrupted the capacitor remains charged at + V_{ph}. After half a cycle the voltage of contacts. On supply side reaches – V_{ph}. Thus the contact gap is subjected to 2 V_{ph}. half cycle after current zero.

If contact gap does not withstand this voltage, the breaker restrikes causing release of energy from capacitor to supply side and another voltage rise after next current zero giving 4 V_{ph}. The result is that the stress on the insulation and the contact gap due to this voltage is much higher than before the first restrike. With increasing over voltage, the danger of further restrikes is very high.

So-called "Soft" circuit-breakers *e.g.* minimum oil and bulk-oil circuit-breakers which have no forced oil circulation, circuit-breakers with magnetic blowout and airbreak contactor have a tendency to restrike. They are not suitable for capacitor switching due to possibility of restrike.

SF_6 circuit-breakers have higher rate of dielectric recovery of contact gap and are, therefore restrike free for large capacitive currents. Vacuum breakers have best dielectric recovery and are ideally restrikes free.

Switching a Capacitor Bank into the Busbars

The making current I_m of a capacitor bank being switched into the power system can be calculated from the rated current I_c of the capacitor bank, the natural frequency f_c of the transient current between the power system and the capacitor bank and the frequency of the power system. The making current of an uncharged capacitor being switched on at the voltage maximum is given by

$$I_m = I_c \frac{f_c}{f} \qquad \text{...(1)}$$

The natural frequency f_c can be calculated from the inductance L of the power system and the capacitance C of the capacitor.

$$f_c = 1/2\pi\sqrt{LC} \quad ...(2)$$

The maximum rate of rise of current S_{max} is given by

$$S_{max} = I_m \, 2\pi f_c \quad ...(3)$$

Making currents up to approximately 15 kA and rates-of-rise or current upto approximately 20 $A/\mu s$ occur in practice.

Connecting Capacitors in parallel

The capacitor to be switched on is not charged and is switched on at the voltage maximum. This is assumed to be the most unfavourable case.

The equations (1), (2) and (3) are also valid in this case. However, the inductance of the power system L in equation (2) is to be replaced by the inductance L_2. L_2 is inductance of inductor connected between C_1 and C_2 for limiting in rush currents.

In practice, the inductane L_2 between the capacitors is very low as compared to the inductance L of the system and can be neglected. The transient currents are determined mainly by the inductance L_2 between the capacitance C_1 and C_2.

The natural frequency f_c is given by :

$$f_c = 1/2\pi\sqrt{L_2 C} \quad ...(2a)$$

The total capacitance C is given by

$$C = \frac{C_1 C_2}{C_1 + C_2} \quad ...(4)$$

and L_2 is inductance between C_1, C_2. As $f_c > f$, the making currents and rate-of-rise of current which occur when capacitors are connected in parallel are much higher than those which occur when capacitors are connected to the power system. Making currents upto 40 kA (or higher) and rates of rise of current upto 1000 $A/\mu s$ are possible in practice.

The making currents which occur when paralleling capacitors cause very high pressures and inadmissibly high-rate-of-rise of pressure in oil circuit-breakers. For this reason the inductance L_2 between the capacitance C_1 and C_2 must be provided.

In VCB, SF_6 CB there is no excess of pressure in the interrupter.

15-C

Low-Voltage Controlgear and Switchgear

15.28. APPLICATIONS AND BASIC REQUIREMENTS

The low voltage controlgear, contactor, low voltage switchgear etc. have been briefly described in Sec. 15.6 to 15.15. The classifications by IEC and CIRED define Low Voltage as voltage upto and including 1000 V. (Sec. 15.20). The definitions of metal-enclosed switchgear mentioned in Sec. 15.29 apply to the Low Voltage Switchgear covered in this chapter.

Low voltage switchgear and controlgear has a very wide range of applications. The switchgear is subjected to severe electrical and mechanical stresses associated with particular application. The low voltage switchgear has to perform the specified duty over a long span of operating life, with minimum maintenance requirements. The space available is generally less and the switchgear should be compact. The *design should be good-looking, compact, Safe and easy to install, operate and maintain.* The degree of protection and surface treatment are equally important.

The major differences between low voltage switchgear and High Voltage Switchgear include the following :

— Specifications and ratings are different.

— Characteristics of low voltage circuits with respect to stresses on switching device during opening and closing are different than those of HV circuits.

— Number of Switching operations demanded from low voltage switching devices (between periodic maintenance intervals) are very high (several tens of thousands to a million) as against a few thousand for a medium voltage switching device. The contact life of LV switching device is important.

— Medium voltage switching device has higher creapage distance, higher internal clearances than that of LV switchgear.

— LV switching device has generally a short contact travel. (a few mm) as against a long contact travel of MV switching device (a few cm). Due to small contact travel, the contact travel characteristics of an LV switching device is markedly different from that of MV switching device.

— Contact bounce assumes great significance in LV switching device.

— LV switches designed from very long mechanical life and contact life. The contacts are pressure type with minimum contact wiping and contact wear.

— In HV switchgear only four types of switching devices are used. These are circuit-breakers, Isolators, Earthing Switches and Load-break Switches (Sec. 17.3). In LV Switchgear several types of switching devices are used (Sec. 15.31).

15.29. COMPONENTS AND MODULAR STRUCTURAL CONFIGURATION

The LV Switchgear or controlgear has modular construction. The module of required rating are assembled to form the complete switchgear. Modular construction (called unit type construction in Sec. 15.6) enables the manufacturer to simplify the inventory and to produce required tailormade switchgear economically and in batch quantities. User gets his requirement at lower cost, with necessary variation and in shorter delivery periods.

In the modular construction of LV switchgear standard modules of specified dimensions and ratings are assembled together as per required circuit diagram. Modular system is used for cast-iron clad switchgear (Fig. 15.4), low voltage metal-enclosed load control centre (Fig. 15.6 *a*, *b*; Fig. 15.7).

The essential components in low voltage switchgear include components similar to high voltage metalclad switchgear described in Sec. 15.3, *i.e.*,

— Switching devices. Circuit-breaker or contactor or some other device along with its operating mechanism.
— Fuse Boxes or Fuse-switch combinations
— Busbars
— Incoming cables and cable terminations
— Outgoing cables and cable terminations
— Structure for supporting the modules, enclosure.
— Earthing facility, earthing switches, earthing busbar.
— Interlocking facility
— CTs, VTs, over load relays as required
— Measuring instrument chamber
— Control cabling; etc.

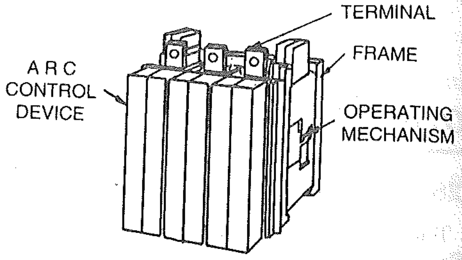


Fig. 15.13. Appearance of modern air-break contactor.

15.30. SWITCHING DEVICES

Several types of switching devices are used in LV switchgear. The switching devices are called circuit-breakers, Contactors, auxiliary switches, limit switches, motor starters, etc.

Table 15-C-1 gives the list and features of various switching devices.

Table 15-C-1. Switching Devices in LV Switchgear

Type of Switch	*Classification based on*	*Switching devices*
Circuit breakers (indoor, metal enclosed, with current limiting features) Ref. Chapter 5 -Miniature -Moulded-case	Breaking capacity for short-circuit current breaking. Circuit-breaker has assigned short-circuit breaking capacity and making capacity.	— Air break circuit breakers used exclusively in low voltage switchgear both for AC and DC duties (Ref. Chapter 5) — Miniature circuit-breaker molded case circuit-breakers (Sec. 5.11) — Oil-circuit breakers, SF_6 circuit breakers, Vacuum circuit-breakers are used for MV switchgear and HV switchgear. They are not used in LV switchgear
Switch-fuse combinations (Ref. Sec. 14.17)	Use of HRC fuse along with manual Switch	Fig. 14.14
Contactors (Ref. Sec. 15.10)	Switching load current and overload currents.	— Air-break are used in LV switchgear. — Suitable for large number of switching operations on load/overload
Load-break Switches.	Switching on load current and overload current.	— Rated opening and closing capacity upto 1.5 In. Lever switch with arcing chamber.

Type of Switch	*Classification based on*	*Switching devices*
Motor starters	Switching on and off the motor circuit; capability to make and breaker the starting currents.	Contactor starters, Oil immersed starters, star-delta starters, Direct-on line starters.
Isolating switches	Switching the circuit under no active load.	For safety, for isolation.
Manually operated switches.	Switches operated by hand or by foot.	
Remote controlled switches	Power operated	Compressed air, motor mechanism or solenoid operated switches.
Limit switches	For switching when particular limit of physical quantity is reached.	Mechanical switch is arranged to operate by physically moving part on the machine. Limit switch contacts can be connected in motor starter circuit.
Stop switch	No restoring force	Lever switch, pressure switch, cam switch
Lock switch	With mechanical lock and trip-free release	Motor protection circuit-breaker.
Key or push button	With restoring force	With contactors
Selector switches	For selection of circuit between two or more alternative current paths	Change over switches Multiple switches.
Auxiliary switch	For switching on/off auxiliary circuits several pairs of contacts which include NO-Normally open NC-Normally closed NO-NC Short-time contacting NO	Auxiliary circuits are for switching, operating, locking signalling etc.

15.31. MECHANICAL RATED LIFE OF A SWITCHING DEVICE

Rated Contact Life. These terms are complementary. The LV switching device is designed and rated to perform a large number of mechanical operations per hour and several thousand mechanical operations during its operating life.

Rated Mechanical Life of a switching device is expressed in terms of the number of switching operations can be performed without loading the current path. Nominal value of rated mechanical life is assigned at 90% of the limiting value.

Rated Contact Life is assigned with reference to the capability contacts to perform number of switching operations on full load.

Majority of switching devices are capable of performing more than assigned number of switching operations during the life. Table 15-C-3 gives data about typical values of rated mechanical life for various types of LV switching devices.

Table 15-C-2. Reference Values of Rated Mechanical Life of LV Switchgear Devices

Type of switching device	*Class as per VDE 0660*	*Rated Switching frequency per hour on no load*	*Rated Mechanical life in Number of switching operations on no load*
Isolators, large switches, lever switches, high speed switches, large circuit breakers etc. large motor starters.	AI	10	1000 (10^3)
Medium and small circuit breakers, Medium and small motor switches for railway vehicle, high speed switches	BI	20	10,000 (10^4)
Large contactors, pressure switches manual motor switches.	CI	50	100,000 (10^5)
Smaller contactors, Control switches for intermittent operations switching devices for small haulage equipment.	DI	500	10,00,000 (10^6)
Contactors for intermittent operation in auxiliary drives, in rolling mills, for special machine etc.	EI	3000	100,00,000 (10^7)

15.32. DESIGN ASPECTS FOR LONG MECHANICAL LIFE

Long mechanical life is an essential requirement of a LV switching device for the economic use—Long mechanical life cannot be expected from switching devices having higher contact load (Table 15-C-3, A1). However, devices such as contactors having lower contact load are designed for very lage switching frequencies and mechanical operating life (D_1, E_1).

For achieving long mechanical life, the design of contactors has been perfected over the years through continuous design and development efforts. Following principles are used :

— **Small, low weight components.**

Components are made of optimum size with reduced weights and removal of unnecessary extra material. This ensures reduced dynamic stresses. Earlier designs had oversize components.

— **Form Locking of components.**

Use of form-locking design, *i.e.* the structural forms of neighbouring components are such that the assembly is easily made by mutual supporting and guiding position with minimum screws, springs, clips, pins etc. The components should remain in desired position during 'open' and 'Close' switch position by their mutual shape.

Pressure contacts. Long mechanical life and long contact life requires reduced mechanical contact wear. **Pressure contacts** are preferred in which contact wear due to wiping action is avoided.

Maintenance-free bearings

Bearings get worn out quickly during mechanical operations due to heat developed with mechanical loading and wear of sliding components during operations. Bearings are 'weak spots' in the switching device. Bearings are not accessible for maintenance during service life. They cannot be easily replaced.

Wear of bearing components depends on (1) temperature during continuous mechanical operation due to mechanical loading (2) Coefficient of friction of sliding surfaces and effect of lubrication (3) Characteristics of materials (4) Commulative travel of sliding surface (km) and material lost by abrasion (rubbing actions) mg/km.

Abrasion between steel shaft and brass housing is reported to be 150 times that between corresponding steel shaft and plastic housing.

In LV switches, for small sliding components sliding surfaces are preferred with

— plastic sliding against steel

— Plastic sliding against plastic

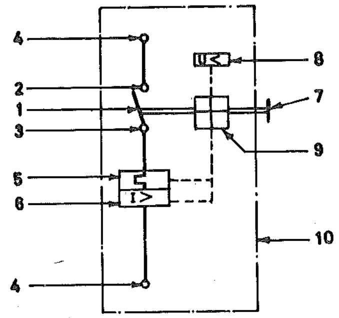
Porous plastics are preferred as they act like sintered metals. Permanently lubricated bearing surfaces are preferred. Special coatings such as PTFE (Teflon) are used on plastic and metal contact surfaces to reduce coefficient of friction.

15.33. MAIN ELECTRICAL CIRCUIT AND COMPONENTS IN A SWITCHING DEVICE

Fig. 15.13 (*a*) represents a single phase schematic diagram showing essential components associated with the Low Voltage Switchgear (contactor or circuit-breaker).

The main components shown in Fig. 15.13 (*a*) include the following :

— Switching device
— Moving contact terminal
— Tripping unit
— Latching system for switch 1
— Undervoltage trip
— Fixed contact terminal
— Terminals for connection to busbars
— Overcurrent trip (usually electromagnetic)
— Operating handle or drive
— Enclosure



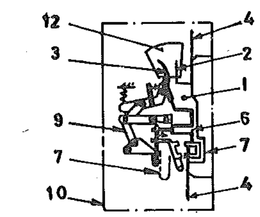
1. Main switching device
2. Fixed contact
3. Moving contact
4. Connection (terminal)
5. Tripping unit (electromagnetic)
6. Tripping unit (thermal)
7. Handle or operating mechanism
8. Undervoltage trip
9. Latching system
10. Enclosure

Fig. 15.13. (*a*) Schematic diagram of LV Switching Device. (Single phase representation)

Fig. 15.13 (*b*) shows the configuration of a simple air-break circuit-breaker incorporating the above components and also the following :

— Fixed contact
— Arc extinction device
— Moving contact
— Support frame.

The principle of air-break circuit breaker and arc extension by elongation of arc has been described in Chapter 5.1.



1. Main switching device
2. Fixed contact
3. Moving contact
4. Connection (terminal)
5. Tripping unit (electromagnetic)
6. Tripping unit (thermal)
7. Handle or operating mechanism
8. Under voltage trip
9. Latching system
10. Enclosure
11. Support frame
12. Arc Quenching device.

Fig. 15.13. (*b*) Configuration of LV Air-break Switch.

15.34. MAIN CIRCUIT COMPONENTS ASSOCIATED WITH CONTACTOR STARTERS OF LV

Direct-on-line started Induction Motors. The components include :

— HRC fuse — Contactor — Thermal relay

Fig. 31.2 (*a*), (*b*) and 31.4 in Chapter 31 protection of Induction Motor gives the details.

15.35. PROTECTION ASPECTS

The protection of LV loads is provided by

— Thermal relays and overload tripping devices
— Under-voltage tripping devices
— HRC Fuses for short-circuit protection
— Circuit breakers with current limiting feature for short circuit protection, stalling protection.

Chapter 31 gives details about motor-protection.

15.36. CONTACT TRAVEL CHARACTERISTICS OF LV SWITCHING DEVICE DURING OPERATING AND CLOSING OPERATIONS, SWITCHING TIME DEFINITIONS.

The switching device performs opening and closing operations. The contact travel characteristic is plotted with Time on X axis (in milli-seconds) and contact travel on Y axis in mm.

The important time-steps in the contact travel characteristics for LV switching devices as defined in VDE 0660 are as follows :

Definitions of remote controlled LV Switching Devices in main current path.

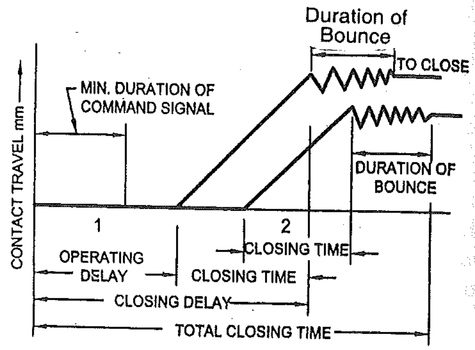


Fig. 15.14. (*a*) Time travel characteristic during closing of LV switch contacts. (Definitions as per VDE 0660)

(A) For the Closing Action (making operation) the following definitions are applicable (Fig. 15.14 (a)).

1. **Delay before movement.** It is the time from the commencement of the communel pulse to the commencement of the movement of the contacts.
2. **Closing time.** It is the time from the commencement of the command until the contacts of the first pole to close first make contact.
3. **Delay before closure.** It is the time from the commencement of the command pulse until the contacts of the first pole to close first make contact. It is equal to the sum of the delay before movement and the closing time.
4. **Duration of bounce.** It is the time from the first make until the final contact in a switching operation (Fig. 15.14 (*b*)).
5. **Total closing time.** It is the time from the commencement of the command pulse until all contact members have finally closed.

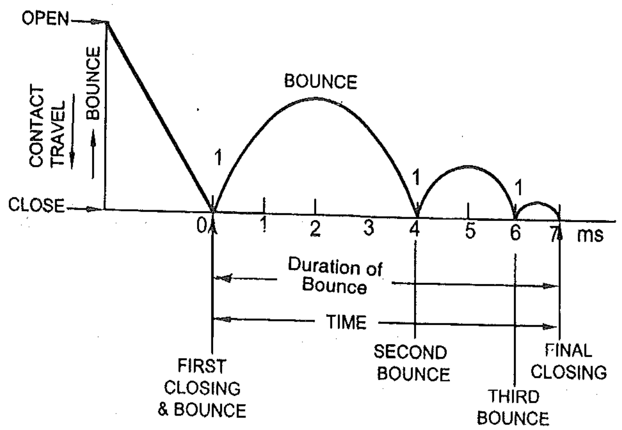


Fig. 15.14. (*b*) Time-travel characteristic of contact bounce during closing of LV switch/contactor.

(B) For the Opening Action (Breaking operation). The following definitions are applicable (Fig. 15.15).

1. **Tripping time.** It is the time from the occurrence of the condition which cause tripping until the holding system is removed or the restoring force of the switch is released. The times of additional relay devices, whether dependent on or independent of the current, are included in the tripping time.
2. **Inherent operating time.** It is the time from when its holding device is released until the commencement of opening of the contacts of the last current path to open.
3. **Opening delay.** It is the time from the occurrance of the condition which causes tripping until the commencement of opening of the contacts of the last current path to open. It is the sum of the tripping time and the inherent operating time.
4. **Arc Development time.** It is the time from the commencement of opening until the maximum of the restricted short-circuit current.
5. **Arc Duration.** It is the time from the commencement of the contacts in the first pole to open until the end of the current flow in all poles.

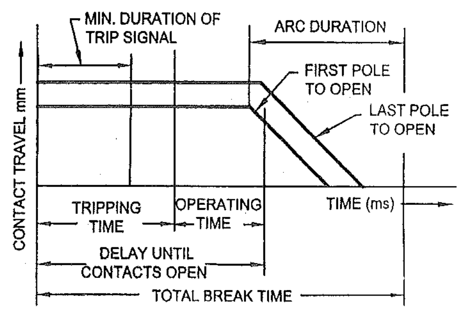


Fig. 15.15. Time-travel characteristic during opening of LV switch contacts. (Definitions as per VDE 0660)

6. **Total breaking time.** It is the time from the occurrance of the condition which causes tripping until the end of the current flow in all poles.

(C) The Minimum Duration of the command pulse

It is the shortest time for a closing or opening pulse which is necessary for the complete or opening of the switch. The minimum duration of the command pulse may include any intentional time delays.

(D) The transfer time of a change over switch which operates with "break before make".

It is the time from the opening of the one contact position until contact is first made at the other.

(E) The overlap time of a change over switch, which works with "Make before break".

It is the time from the find closure (closure after completion of bouncing) of the one contact position until the opening of the other.

15.37. CONNECTION AND CROSS SECTIONAL AREA OF CABLES

The external circuit is connected to the switching device by means of leads (cables/conductors). The part which provides the connection is called the "Connection". The connections carry the circuit current. The type of connection and size of connection used depends upon nominal value current.

Types of Connections

The current carrying paths include the connections. The get heated due to I^2Rt losses. Connection resistance should be low. They should not become loose due to mechanical vibrations. Types of connections include

Screw connections are used with curved spring washers, flat plate and nut etc. Spring washers ensure constant high pressure connection and securing the position of screw.

Flat connections are used for higher current ratings.

Plug connections are without screw. The male part is inserted into female part. The grip is provided by the spring action of the female part.

Soldered connections are used for smaller wires upto 2.5 mm^2 cross section. Table 15-C-3 gives data about applications.

Table 15-C-3. Application of types of Connections

Type of connections	*Application wire size*
Screw with spring washer	1×2.5 mm^2
Screw with Frame Terminal	2×5 mm^2
Flat connection	Flats of high current
Plug connection	
Soldered connection	Upto 2.5 mm^2

15.38. CONTACT CONFIGURATION AND DESIGN ASPECTS

The requirement of Contacts depends upon

- — required frequency of operation, *i.e.* number of switching operations per hour and rated contact life.
- — required normal current rating
- — required rated electrical performance characteristics
- — rated utilization category

The contacts are in pairs, with are fixed contact and other moving contact.

Main contacts are designed for achieving low contact resistance, long contact life.

Contact pressure is important. Contacts for LV switches are generally designed without contact grip.

Fig. 15.16. (*a* to *f*) illustrates various configuration of contacts for LV air break switches, and LV air/break contactors.

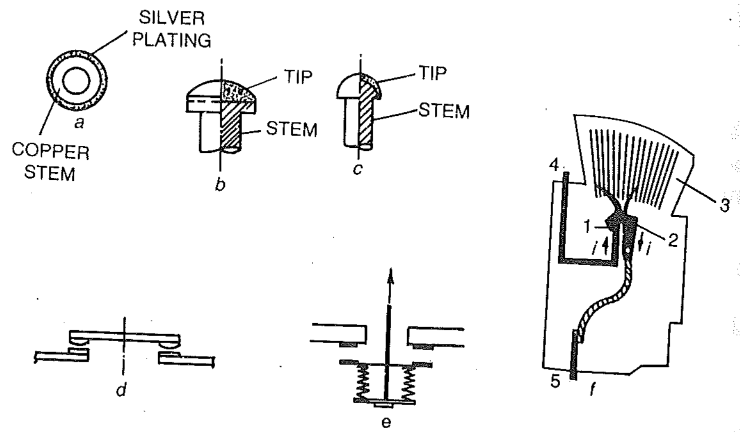


Fig. 15.16. (*a* to *f*) Contact configurations in LV switches.

Requirements of Contact in LV Switching Devices

For LV circuit-breakers, the same principles mentioned above are applicable. Distinction is essential between.

- — Main contacts having low contact resistance, high electrical conductivity.
- — Arcing contacts having high arcing resistance, high temperature withstand and low burning.

The low contact resistance material does not have the high arc-resistance properties. Hence separate sets of main contacts and arcing contacts in case of LV circuit-breakers. Alternatively the main contacts are provided with arcing tips.

15.39. CONTACT MATERIALS

Table 15 gives a list of contact materials used for main contacts and arcing contacts in LV Switching devices.

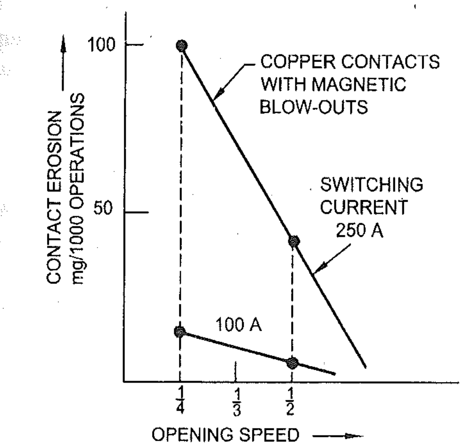
Table 15-C-4 List of Contact Materials

	Material	*Main Properties*	*Remarks*
1.	Main Contacts		
	Silver Silver Copper	High electrical conductivity.	Silver plated.
	Palladium alloy Palladium Gold alloy	Corrosion resistance	Sintered
2.	Arcing contacts		
	Tungsten-copper Tungsten Tungsten-silver	High arc resistance	Sintered

15.40. CONTACT SPEED DURING OPENING OPERATION

The speed of contact for opening stroke determines the time of arcing and contact erossion. For higher breaking current, higher contact speed is used. In LV switches the contact speed is in the range of 0.25 m/s and 0.5 m/s. Contact travel is a few mm. In MV switches contact speed is in the range of 1 m/s and 4 m/s. In HV switches the contact speed is 2 m/s to 6 m/s and contact travel is between 100 cm and 175 cm.

Fig. 15.17 (*a*) and (*b*) indicate the effect of opening speed and closing speed on contact erosion.



Switch with magnetic blow-out. Copper contacts, switching voltage 110 V d.c.
Fig. 15.17. (*a*) Effects of Opening speed on contact erosion for air-break.

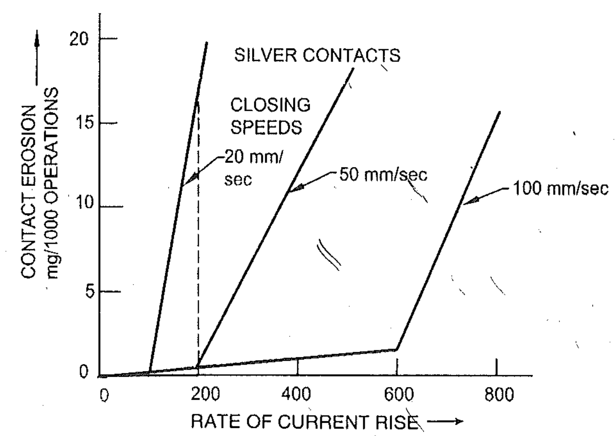


Fig. 15.17. (*b*) Effect of closing speeds on contact erosion for silver contacts.

15.41. AUXILIARY SWITCHES

Fig. 15.18 (*a*) shows schematic diagram of an auxiliary switch, connected with isolator mechanism. Fig. 15.18 (*b*) indicates the sequence of switching operations. An auxiliary switch has several pairs of contacts. The types of contacts include the following.

- — Normally-closed contacts
- — Normally open contacts
- — Changeover contacts
- — Fleeting contacts

Normally-closed contacts. These are closed when the main switch is open and open when the main switch closes.

Normally open contacts. These are open when the main switch is open and close when the main switch closes.

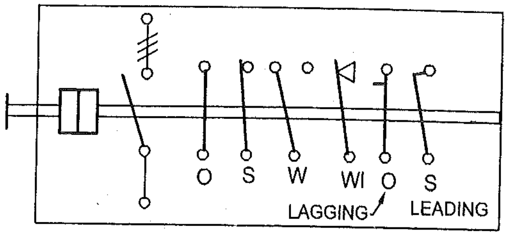


Fig. 15.18. (*a*) Schematic diagram of an Auxiliary Switch for an Isolator.

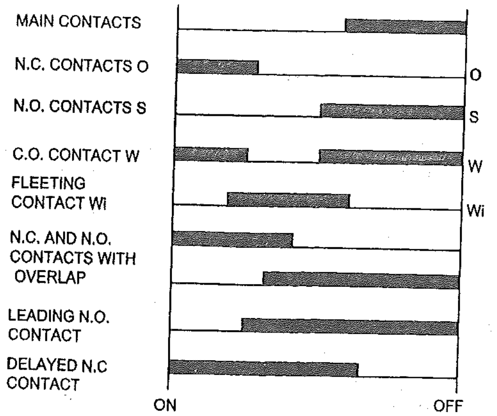


Fig. 15.18. (*b*) Contact positions of the auxiliary switch during operation.

Changeover Contacts. These have two separate fixed contacts for each position. They have one moving contact which closes with either fixed contact depending on the main switch position.

Fleeting contacts. These are closed briefly during the transition of the switching device from one position to the other.

Auxiliary switch operates with operating device, with the help of auxiliary switch, auxiliary circuits such as command, actuation, alarm and measurement circuits, are closed and opened in conjunction with the main circuit switchgear.

Auxiliary switches are of great importance, especially in extensive control and interlock systems and must therefore function reliably. Special attention must be given to the reliable making of contacts because auxiliary circuits often operate at low voltages and high currents.

15.42. TRIPPING DEVICE AND RELAYS

Tripping devices are components of switches which release them mechanically. Relays are control devices which electrically control other devices. Tripping devices are relays are operated by changing physical, predominantly electrical quantities.

These are measuring and non-measuring tripping devices. Table 15-C-8 gives list of tripping devices and relays.

Table 15-C-5. Tripping Devices and Relays

Function	*Abnormal condition causing operation*
Overload release	Over current above set value
Under current release	Under current below set value
Reverse current release	Current direction reversed
Under voltage release, no-volt release	Voltage value below set value
Fault current release	Fault current above set value
Fault voltage release	Fault voltage above set value
Over current in common conductor	Current in the common conductor above set value.

Fig. 15.13 (*b*) shows single line diagram of LV switch with (1) Electromagnetic over-current trip with auxiliary switch (2) Electrical of Electronic timed (3) Undervoltage or shunt trip (4) Switch latching mechanism.

Fig. 15 shows schematic circuit diagram of a three phase LV Motor Control Switch in Corporating (1) Open-Circuit trip (2) Undervoltage trip (3) Auxiliary switch unit (4) Connector block (5)

three-pole over current release. During abnormal conditions, the corresponding release is actuated and the switch mechanism is unlatched thereby causing opening of the main switching device.

Ref. Fig. 31.2, 31.4.

In case of MV switchgear, various protective relays are connected to the secondary of CT and VT. These relays operate in response to respective abnormal conditions and close trip circuit. Ref. Fig. 27.3. Overcurrent release, undervoltage release etc. are not provided in main circuit as in LV switchgear. Fig. 15.13 (*a*) and Fig. 15.13 (*b*) show components, with a typical LV switch.

15.43. DEGREE OF PROTECTION, IP CODE

LV and MV switchgear are installed indoor and need protection against ingress of dust, water, external bodies. The operators should be protected from accidential contact with line parts or moving parts. These aspects must be considered while designing the LV switchgear and MV switchgear. The enclosures should have adequate provisions of 'Protection'. The following protection are covered in the IEC 144, DIN 40050 etc. Specify various grades of Degree of Protection by IP code numbers. (P = Protection).

Standard degrees of protection by enclosures are applicable to respective electrical machines (IEC 34.5), LV switchgear and controlgear (IEC 144) etc. They specify design and testing requirements with respect to :

1. Protection against accidential contact of persons with live parts or moving parts inside enclosures and protections of internal parts against ingress of external solid parts such as dust, solid wires, objects. These two functional requirements are usually combined in a common numeral of the IP code.
2. Protection of internal parts covered by the enclosure against ingress of external water and liquids falling on the enclosure at various pressures.

The IP code is usually defined in the standard in four digits *e.g.*

Code letters IP are common. They indicates reference to the degree of protection.

First characteristic numeral disigrates degrees of protection provided by enclosure against contact by persons as well as against ingress of foreign bodies.

Second characteristic numeral designates degree of protection provided by enclosure against harmful ingress of water of liquids.

The LV switchgear enclosures are designed for achieving specific degree of protection and are tested in special laboratories as per test procedures for particularly specified degree of protection. The tests are simple and consist of showering talcum powder dust or water at spay of specified intensity for specified time. After the test the amount of ingress of dust/water into the enclosure is measured. It should be within specified limits.

Ref. Sec. 15.21 for standard numerals as per IEC 144.

15.44. MEDIUM VOLTAGE VACUUM CONTACTORS FOR 3.6 TO 12 kV

Courtesy : Siemens, West Germany.

Application

The vacuum contactors are particularly suitable for controlling AC loads with a high switching rate and unlimited on time.

They are used for the following functions :

— Switching of three-phase motors in AC 3 duty
— Inching in AC4 duty switching off of three-phase motors during run-up
— Switching of transformers
— Switching of capacitors

— Switching or resistive loads (*e.g.* electric furnace)

High voltage vacuum contactors are designed to meet IEC - 470, DE 066, BS 775-2, AS 1864 etc.

Construction and function (Ref. Fig. 15.19)

The vacuum contactor consists of a low-voltage section, a high-voltage section and an integral rocker as a dynamic link between the solenoid operating mechanism and the vacuum interrupters.

The LV section contains the solenoid mechanism, auxiliary switch blocks, centrally arranged terminal blocks, mechanical closing latch, and a mechanical lock-out.

The main HV parts are the moulded plastic housing with the three vacuum interrupters and the power terminals. The contactors are fitted with **vacuum interrupters** for the required particular voltage (3.6/7.2/12 kV). When the contactor closes the operating stroke of the solenoid is transmitted by the integral rocker to the moving contact of the vacuum interrupter. The contact gap is closed by the atmospheric pressure and an additional spring. When the solenoid circuit is interrupted the two restoring springs establish the contact gap by acting on the integral rocker. The contactor has a life expectancy of upto 2×10^6 operation cycle.

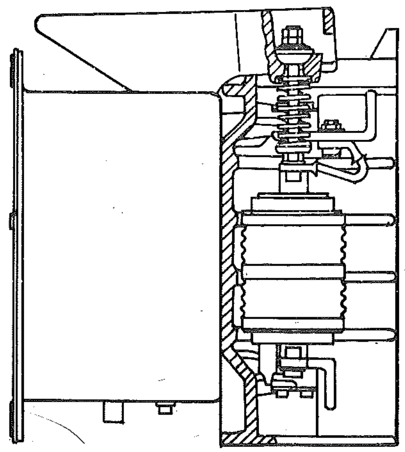


Fig. 15.19. Cross Section of Vacuum Contactor. Side View
Courtesy : Siemens, West Germany.

16

HVDC Circuit-Breaker and Metallic Return Transfer Breaker (MRTB)

16.1. INTRODUCTION TO HVDC SWITCHING SYSTEM

— HVDC Transmission Systems have become commercially successful in India and many other nations after around 1980. High Voltage Direct Current Transmission (HVDC) is an alternative to 3 Phase, 50 Hz, AC transmission in following applications :

— Bipolar Long Distance High Power Transmission from Super Thermal Power Plants/Super Hydro Plants to Mega-load centers. Typical Ratings of such HVDC Links ; single circuit 2 Pole ± 500 kV DC or ± 600 kV DC, 1500 MW, 2000 MW, 6000 MW, 750 km to 2000 km long, without any compensating substation in between. For example : Rihand Delhi HVDC Link : 820 km, ± 500 kV DC, 1500 MW. Chandrapur Padghe HVDC Link of same rating.

— System Interconnections (100 MW, 500 MW, 1000 MW, 2000 MW).

— Frequency conversion (50 Hz/60 Hz)

— Back to Back HVDC Coupling Station between two neighbouring AC Grids. National Grids with several such interconnections.

— Submarine Cable Transmission through oceans and lakes for feeding power to islands or for interconnection between two Grids separated by long ocean/channel.

— Multi-terminal interconnections between several AC Networks by Long High Power HVDC Transmission Bus.

Table 16.1. Particular Applications of HVDC Transmission Systems

Type	*Principal Criteria of Choice*
1. Long 2-Terminal Bipolar High Power HVDC Systems *e.g.* Rihand Delhi, India 1991 ; Chandrapur-Padghe (1997)	— Economy in capital cost, — Better power control, accurate, fast control of power flow (30 MW/min) through particular line, this is not possible with AC Line in a Network. — Lower transmission losses as no reactive power flow. — Energy Conservation — Higher Stability Limit

	Type	*Principal Criteria of Choice*
2.	Back-to-Back HVDC Coupling Stations between two independently controlled AC Networks *e.g.* Vindhachal Back-to-Back (WR/NR) 1989; Chandrapur Back-to-Back (WR/SR) 1998	— Technically Superior — Better Stability of AC Networks at both ends. — Excellent Interconnection which provides operational flexibility of power reversal, accurate fast power and frequency control, damping of power swings etc. — Large scale blackouts in Interconnected AC Networks are prevented.
3.	Long High Power Submarine Cable-Links (*e.g.* British Channel HVDC Link between France and UK, 1983)	— No continuous charging currents. Hence no upper limit of power and length of cable.
4.	Multi-Terminal HVDC interconnection System between three or more independently controlled AC Networks (*e.g.* New England-Hydro Quebek Canada-USA, 5-Terminal HVDC System)	— Accurate, Fast, control of power exchange between 3 or more AC Networks — No total Black-outs. — Higher Stability Limit — Lower losses — Energy Conservation

Modern Power Systems have a few HVDC interconnections and a few long 2TDC transmission links and a large 3 phase AC Network of transmission and distribution lines. These HVDC *Links transfer power in DC form from one AC network to another.* For rest of the generation, transmission and distribution, and utilisation, 3 Phase 50 Hz AC system shall continue. The 3-Phase AC system operates simply and automatically in synchronism. Design, expansion, operation etc. of AC Systems are simple, easy, of lower cost, AC Power Transformers and AC Switchgear can be used in several locations conveniently.*

More than 60 HVDC Transmission Systems have been installed in the world (1995) including 4 HVDC Systems in India. Several new schemes are under planning/execution. HVDC Technology has matured and has been accepted as an essential part of Modern Power Systems due to its several merits. HVDC is a solution to interconnected Power System Stability Problems.

The *protection and switchgear* requirements of HVDC Systems is quite different than that of 3 Phase AC Systems. Whereas in AC Transmission Systems the protective relays and AC Circuit Breakers are essential at every switching point and for every transmission line. HVDC Poles do not need any Circuit Breakers.

In HVDC Systems, Protection and Control functions are integrated with the Thyristor Convertor Control. There are no HVDC Circuit-Breakers. For normal operational control and for protection from abnormal currents and voltages etc. Thyristor control is employed. In the event of single-pole faults beyond the capability of the thyristor control ; the AC circuit breakers of the faulty pole are tripped after reducing power flow and the faulty pole is isolated. The healthy HVDC pole continues to be in service for such single pole faults.

All the present HVDC Systems are without HVDC Circuit Breaker in the DC Poles. Circuit Breakers are provided on AC Side of Converter Transformers. [Fig. 16.1 (*a*) to (*e*)].

The control of DC current, DC voltage and DC Power flow is achieved by Tap-changing of converter-transformers and simultaneous thyristor-control of converter valves take care of protective functions. Therefore, there is no need of any HVDC Circuit Breaker in Main DC Poles. Even if such breakers are provided, they will not be operated, as the Converter Controls and continuity of power flow would be adversely affected.

However, the HVDC Switching Devices in form of Metallic Return Transfer Breaker (MRTB) are necessary in the earth return path in present 2-Terminal HVDC Systems for interrupting earth return currents during change over from earth return to pole return (Metallic Return). DC Switching Arrangement are also used in HVDC parallel tapping for current reversal. These DC Switching

* The notion that HVDC will replace 3-phase AC is wrong. 3-Phase AC Network will continue for ever. HVDC is for a few particular applications listed above. HVDC Systems are between 2 or more AC Systems. HVDC has no independent stay.

Devices are rated for normal current breaking with low arc energy, (i.v.t.-joules). They are not true HVDC Circuit Breakers which would break HVDC Short-circuit currents or full load DC Currents at rated DC Voltage of poles. Such HVDC current interruption involves high energy arc switching (i.v.t-joules) which is difficult due to absence of natural current zeros.

Artificial Current Zero Arc Interruption Principle

Why is an HVDC Breaker different from an High Voltage AC Breaker ? Why is the low voltage DC Breaker different from an High Voltage DC Breaker* ?

AC breaker easily interrupts the arc at natural current zero in the AC wave. At current zero, the energy ($1/2\ Li^2$) to be interrupted is also zero. The contact gap has to cool and recover the dielectric strength to withstand natural TRV. With DC Breaker, the problem is more complex as the DC waveform does not have natural current zeros. Forced arc interruption would produce high transient recovery voltage and restrikes without arc interruption and ultimate destruction of the breaker contacts.

The artificial current zero principle must be employed in HVDC switching devices for interruption of DC arcs. The artificial current zeros are produced in the LC oscillatory circuit in the loop of circuit-breaker while opening the contacts. The arc is extinguished by the circuit breaker. A ZnO arrester in parallel limits the Transient Recovery Voltage and absorbs associated energy. The limit is imposed by the energy (i.v.t-joules) associated with the interruption. DC Current has *no natural current zeros* like in AC Current.

During circuit breaking, the current through the capacitor and parallel reactor produces oscillations and several artificial current zeros are obtained in the current. The breaker interrupts the arc during one of the current zeros. The subsystem for producing artificial current zeros requires large energy storage capacitor bank, trigger gap, ZnO arresters, reactors etc. The HVDC Breaker Pole has ZnO arresters in parallel with the main break for absorbing switching overvoltages. Artificial Current Zero Principle is employed in all the present medium voltage and high voltage DC switching devices. In these devices, the Arc is interrupted at artificially produced current zero and thus involves low arc energy dissipation. The Breaker Pole itself is airblast type or Minimum-oil type. The presently used DC switching devices are of lesser current rating and with medium DC Voltage. They are not true high power HVDC Breakers which would interrupt full rated DC Current/Short-circuit Current of HVDC Poles. During 1970s, research and development efforts were focussed on development of HVDC Circuit Breakers and HVDC Systems. These development have been technically successful but are not used in practice due to high cost and complexity of HVDC Breaker Systems.

The Original Objectives of HVDC Breaker Development

The development of HVDC Circuit Breakers was undertaken by CIGRE Working Group on HVDC Breaker during early 1970s. The converter control by thyristors was not yet fully developed then. HVDC Breaker development was with the following three *basic presumptions* :

Presumption 1. HVDC Circuit Breakers would be essential for protection during abnormal conditions and also for normal switching operations and lack of HVDC Circuit-Breaker Technology would be a bottle-neck in the use of HVDC Systems in Network. This presumption was based on the AC Breaker and Protection Principles and proved to be *wrong* for HVDC Systems by early 1980s. The HVDC Converters with thyristor control do not need of HVDC Circuit Breaker. The thyristor control itself regulates the DC current. Breakers on AC Side of Converter Transformers are enough. Fig. 16.1 (*a* to *e*) show the practical schematics.

* Refer Sec. 5.9 and Sec. 4.7.1 for Low Voltage DC Arc Interruption achieved by *high resistance arc interruption methods.* Arc is lengthened, cooled, split, to dissipate energy as heat. These methods are applicable only to Low Voltage DC Circuits Breakers. This method is not suitable for Medium DC Voltage (3.3 kV and above) switching devices due to high arc energy dissipation required. Artificial Current Zero Method is applicable.

Presumption 2. HVDC Circuit-Breakers would be essential in Multi-Terminal HVDC Systems. This presumption also proved to be *wrong* during late 1980s. The 5-Terminal New-England, Hydro Queback MTDC System with HVDC Converters has thyristor control of valves and no HVDC Circuit-Breakers. Fig. 16.1(*e*) shows a practical schematic.

Presumption 3. Development of High Power HVDC Circuit-Breaker may be technically impossible as flow of DC energy cannot be interrupted instantaneously. This presumption was also proved wrong by 1985 as *truly High Power High Voltage HVDC Circuit Breaker has been developed successfully by a group of companies under a CIGRE HVDC Breaker Development Project.*

Though HVDC Breakers could have been used after 1985, they have never been used in practical HVDC Systems due to following reasons.

— HVDC Circuit Breakers *are not necessary* as the control and protection functions are performed by thyristor control of converters. The short-circuit currents in HVDC System are controlled quickly and automatically by converter control and the switching is carried out by AC circuit breakers.

— If HVDC Breaker is used, each HVDC Circuit Breakers would need another Back-up Breaker. HVDC Poles would need two HVDC Breakers at each switching point (one for main and other for back-up) and in addition to the thyristor control for protection and automatic controls. *Such a system would be prohibitively costly and complex.*

— The breaking of full load DC currents (2 kA to 5 kA) at High Voltage (± 500 kV DC) and with large energy in inductance (0.5 LI^2), is a complex, costly process and unreliable. It requires a very costly and complex HVDC Switching System. Such a system is practically uneconomical. With such a HVDC Circuit Breaker the already costly HVDC Schemes would be *economically unacceptable as against alternative EHV AC Systems.*

The high cost and complexity of HVDC System with HVDC Circuit-breaker is not acceptable as against the alternative EHV AC System of proven simplicity and reliability.

HVDC Systems without any HVDC Circuit Breaker in Main Poles

Todays HVDC Systems [Fig. 16.1(*a*)-(*e*)] are without HVDC Circuit Breakers in main pole. AC Circuit Breakers are installed on AC side of converter transformers. *Current in DC Poles is controlled by thyristor valves quickly and accurately without need of DC Circuit-Breakers.* In the event of a fault on DC side or in converter transformers, the DC current is blocked quickly by several control actions from both the terminals and the AC Circuit breakers are the rectifier end and opened. Even if HVDC Circuit Breaker were present, the converter control and AC Circuit-breakers would be and essential for operational control and protection.

Metallic Return Transfer Breakers (MRTB) is installed in the neutral to earth return path in one terminal-substation. This MRTB DC breaker is rated for switching earth return currents at medium voltage DC.

16.2. SCHEMATIC OF A 2-TERMINAL, BIPOLAR LONG DISTANCE HVDC TRANSMISSION SYSTEM

Such Systems are used for Long Distance High Power Transmission due to economic line construction, reduced line losses, easy rapid and accurate power flow control through a particular high power transmission link (*e.g.* from Rihand (UP) to Delhi, ± 500 kV DC, 1500 MW, 820 km long Bipole Link, 1991).

The principle of operation of a typical 2-Terminal bipolar point-to-point HVDC System is explained by means of the schematic Fig. 19.1.(*a*) The two AC Networks are connected by an HVDC Link. The HVDC Link has two identical converter substations, one at each end. Each converter substation has the following :

— AC Circuit Breakers
— Converter Transformers
— Converter Valves
— AC Harmomic Filter Banks
— DC Harmonic Filter Banks
— DC Smoothing Reactors.

The HVDC Line has two pole conductors, Pole 1 and Pole 2. One pole is positive with reference to the earth and the other is negative. The neutral points of the 12-pulse-thyristor coverter bridge is earthed via the earth return transmission line and earth-electrodes. There is no HVDC Breaker in the system. The MRTB Metallic Return Transfer Breaker is provided between the neutral point of the rectifier and the earth.

One of the terminals acts in Rectifier mode and the other terminal in Inverter Mode.

The converter at sending end terminal (*e.g.* Rihand) is operated in Rectification Mode (AC → DC) by appropriate firing angle of thyristor-valves. The receiving end converter (*e.g.* Delhi) is operated in Inverter Mode (DC → AC) by appropriate firing angle of thyristor valves. The power is fed again into AC Grid at receiving end (Delhi). Thus the HVDC Link transfers power from one AC Network (1) to the other AC Network (2).

Smoothing Reactor in DC Poles reduces the current ripple from DC waveform. Smoothing Reactor has high inductance (*e.g.* 0.4 H) and carries DC Current. Therefore stored energy (1/2 LI^2) is high and pole current interruption is difficult and not resorted to.

DC Filters eliminate DC Harmonics from DC waveform and thus minimise telephone interference in neighbouring areas. DC Filter Capacitors also provide reactive power compensation to AC System for regulating AC Bus Voltage and for converter operation. Earth return currents in bipolar operation are usually small (< 3%) of rated DC current). Earthing of converter neutral is by an earth electrode about 15 km away from the terminal. The earth electrode line is installed between the neutral and the Earth Electrode. The earth return current can be interrupted by a specially designed MRTB. Full details of HVDC System are described in Chapter 47. Chapter 16 covers details about the HVDC Circuit Breakers.

During normal operation as well as during abnormal operation the DC current, DC voltage and power flow are controlled by controlling phase angle of thyristor firing of Rectifiers and inverters and by tap-changer control simultaneously, continuously and automatically. Tap changer control is slower (10 seconds) and thyristor control is faster (few tens of milliseconds).

During a *temporary fault* on DC Line, the following *operating modes* are tried :

— In the faulty pole, Converter at Rectifier Terminal is put to inverter mode, and voltage is reduced. This results in "starvation" of line fault current and fault dies out within a few tens of milliseconds.

— Meanwhile the other healthy pole conducts more power without any interruption.

— After a few tens of milliseconds, the converter of the faulted pole is put back to rectifier mode and the service restoration is attempted. Voltage is increased and normal Bipolar Mode is restored.

— If the line fault is permanent or if converter/valve is faulty, the converter control reduces the voltage and power, then the AC Circuit Breakers of that pole are tripped for protection.

— If the fault in one of the station poles is permanent, the HVDC System is automatically transferred from the usual Bipolar mode to Monopolar Mode and the DC power flow is made continuous without interruption. This Monopolar Mode is either to begin with, of Monopolar with Earth Return (MPER). But for long duration Monopolar Operation, Monopolar with Metallic Return is preferred. This is explained below.

The monopolar operation can have two operating modes

1. Monopolar with Earth Return. Full pole current flows through one pole conductor and return earth. The earth electrodes get rapidly consumed during the Monopolar earth return mode. The earth currents cause damage to substation earthing systems and gas/water pipelines if allowed to flow for long time.

2. Monopolar with Metallic Return. Full pole current flows through one pole conductor and returns through other pole conductor (Metallic Return). The Monopolar Operation with Metallic Return can be made continuous as there are no problems of earth electrode consumption and problems of galvanic corrosion of metallic pipes and earthing mesh due to heavy ground current.

The transfer from Monopolar Earth Return Mode to Monopolar Metallic Return Mode (and *vice versa*) is accomplished by the MRTB.

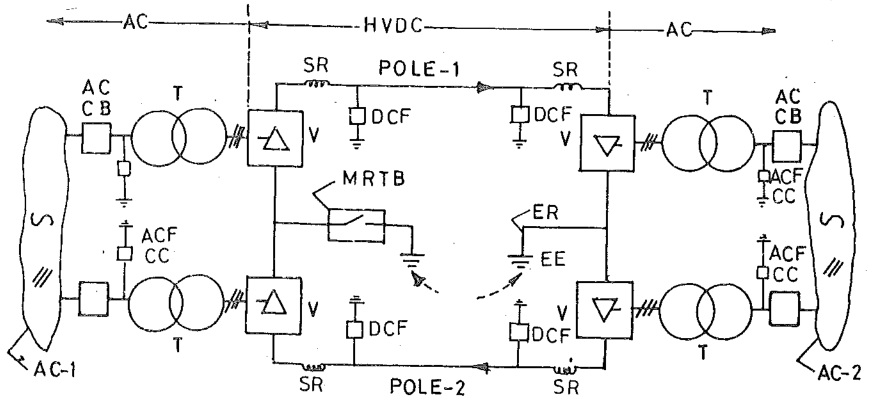


Fig. 16.1. (*a*) Schematic of a 2-Terminal Bipolar HVDC System indicating Circuit Breakers on AC Side.
(There are no HVDC Breakers in Main DC Poles)

AC-1 AC System 1 — V Thyristor-Converter Valves
AC-2 AC System 2 — MRTB Metallic Return Transfer Breaker
ACCB AC Circuit Breakers — T Converter-Transformer with OLTC
SR DC Smoothing Reactors — ER Earth Return Line — EE Earth Electrode
ACF-CC — AC Harmonic Filters and Compensating Capacitors
Pole 1 Path with say, positive DC Polarity with respect to earth
Pole 2 Path with negative DC Polarity with respect to earth
DCF DC Harmonic Filters

The MRTB is an HVDC Switching Device based on Artificial Current Zero. MRTBs are used in todays commercial HVDC Systems. But the HVDC Systems do not need/have any HVDC Breaker in the pole circuit.

Full details of HVDC System are described in Chapter 47. This chapter covers details about the HVDC Circuit Breakers.

16.3. BACK-TO-BACK HVDC SYSTEM

The interconnection between two independently controlled adjacent AC Networks is either by conventional AC Transmission Line (Interconnecting AC Line) or by an HVDC Back to Back Coupling Station (*e.g.* Vindhyachal Back-to-Back 1989) or an HVDC submarine Cable Link (England-France 1970s).

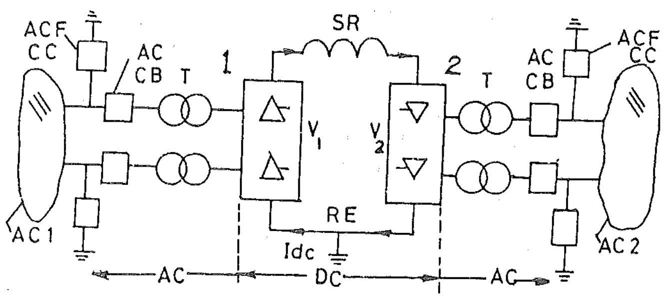
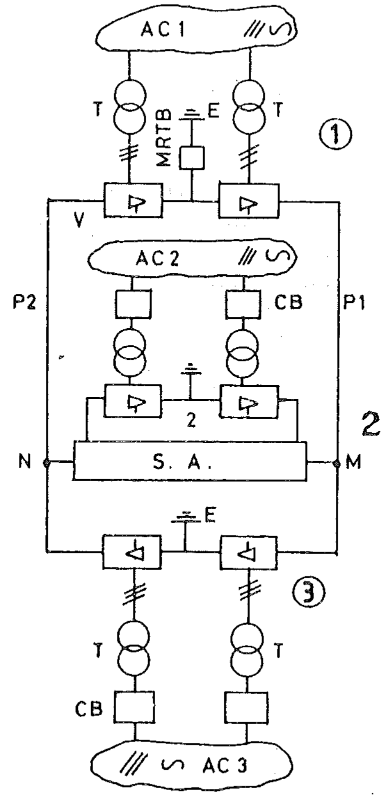


Fig. 16.1. (*b*) Back-to-Back Coupling System:
Interconnecting Substation between two adjucent AC Networks
(There are no HVDC Breakers in Main Poles)

AC-1 — AC System 1 — V — Converter Valves
AC-2 — AC System 2 — RE — Reference Earthing
ACCB — AC Circuit Breakers — T — Converter-Transformers with OLTC
ACF-CC — AC Harmonic Filters and Compensating Capacitors
SR — Smoothing Reactors
Pole 1 — Path with say, positive DC Polarity with respect to earth
Pole 2 — Path with negative DC Polarity with respect to earth
V_1, V_2 — Thyristor Converter bridge with several thyristors in series per arm



SA — Switching Arrangement [shown in Fig. 16.1 (*d*)]
M, N — Points of connection for SA
1, 3 — Terminal of 2-T HVDC System
2 — Additional Parallel Tapping at MN
P_1 — Pole-1, P_2 — Pole-2
MRTB — Metallic Return Transfer Breaker
CB — AC Circuit Breaker
V — Valve, T — Converter-Transformer

Fig. 16.1. (*c*) Additional Parallel Tapping with 2-Terminal HVDC System.

In India the neighbouring Regional Grids will be ultimately interconnected by small back-to-back HCDC Coupling stations rated about 500 MW each. Vindhyachal Back-to-Back (1989) couples Western Region with Northern Region. Chandrapur back-to-back (1998) couples Western Region with Southern. Three more HVDC Coupling Stations are in initial planning/execution stage (1998).

HVDC Coupling Stations enable rapid, accurate power exchange in either directions between the two AC Networks, improved stability of both AC Networks, better frequency control. Fig. 16.1(*b*) illustrates the essential parts in a Back to Back HVDC Coupling Station.

The principle of operation of a typical HVDC Coupling System is explained in Ch. 47.

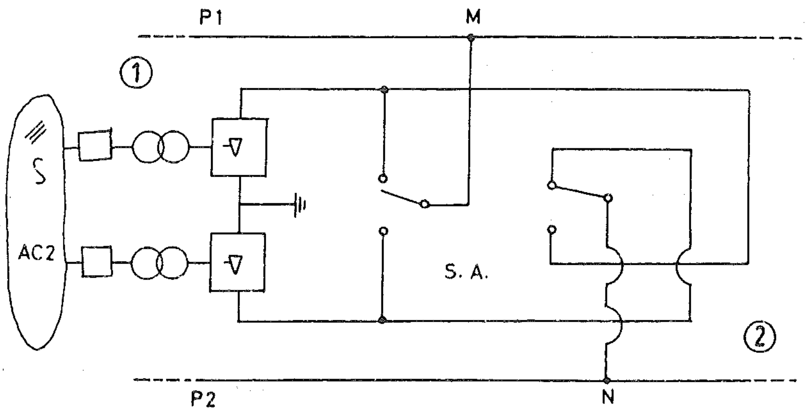
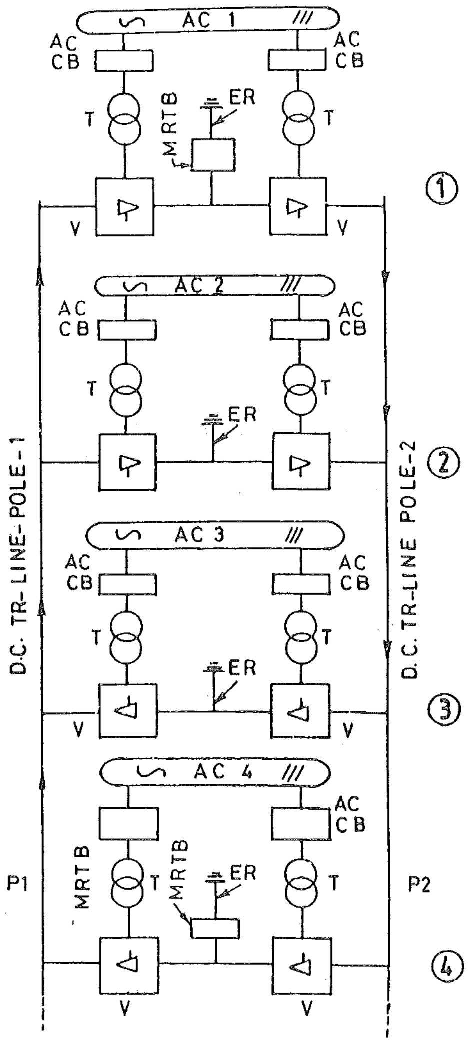


Fig. 16.1. (*d*) Switching Arrangement (SA) of Fig. 16.1 (*c*).
P_1 — Pole-1 P_2 — Pole-2

16.4. MULTI-TERMINAL HVDC SYSTEMS (MTDC)

An MTDC System interconnects three or more independently controlled AC Networks [Fig. 16.1 (*e*)-1, 2, 3, 4]. HVDC Systems are the solution to black-outs in Large Interconnected Power Systems.

The surplus AC Network (*e.g.* 1 and 2) can supply power into the HVDC Pole Lines *via* the converters operated in Rectifier Mode (AC → DC). The deficit AC Networks (*e.g.* 3 and 4) can draw power from the HVDC Pole Lines via the converters operated in Inverter Mode (DC → AC). The overall system stability is improved, the transmission losses are reduced, energy is conserved, large scale black outs in the total AC System are prevented. Such blackouts do occur in AC Networks interconnected by AC Transmission lines during cascade tripping of interconnecting lines. The first MTDC System in the world is the New England — Hydro Quebek 5 Terminal HVDC System (1996) in USA and Canada. The MTDC System does not need HVDC Circuit Breakers as each terminal has its Converter Controls for controlling DC voltage, power and current. The Circuit Breakers are provided on AC Side.



P_1	—	HVDC Transmission line Bus Pole 1
P_2	—	HVDC Transmission line Bus pole 2
V	=	Valves
ACCB	=	AC Circuit Breaker
ER	=	Earth Return Line
T	=	Converter Transformer
MRTB	—	Metallic Return Transfer Breaker

Fig. 16.1. (*e*) MTDC System with 4-Terminals.
(AC-1, AC-2, AC-3, AC-4 : AC Networks)

Metallick Return Transfer Breakers (MRTB) are provided in earth return circuits in Rectifier Terminals for the switching from Monopolar Earth Return Mode to Monopolar Metallic return Mode as described in Sec. 16.2.

16.5. SCHEMATIC OF DC SWITCHING SYSTEM AND WAVEFORM OF IDC WITH ARTIFICIAL CURRENT ZEROS

In Fig. 16.2 (*a*) the Main Break (MB) represents a Circuit-Breaker Pole which is capable of breaking the arc at artificial current zero. Single pole MOCB/Air-Blast CB have been used successfully. The DC Switching System has an additional LC-Circuit in parallel A. Triggered Vacuum Gap (TVG) is in this parallel path. The ZnO Arrester is in parallel for transient overvoltage absorption. Refer Fig. 16.2 (*b*). The DC current Idc starts rising from the instant of fault (t_1) on the DC side of the DC pole. The fault is sensed by the protection and control circuits. The tripping command is given to the MB and trigger command is given to the TVG.

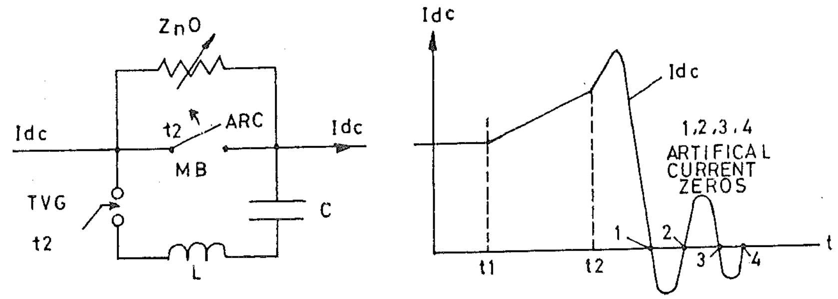


Fig. 16.2. (*a*) Schematic of DC CB Fig. 16.2. (*b*) Current Waveform

Idc	—	DC current through the pole and circuit breaker MB
MB	—	Main Breaker with interrupter
TVG	—	Triggered Vacuum Gap
ZnO	—	Zink Oxide Arrester (Ref. Sec. 18.5B)
L, C	—	Inductor and Capacitor in parallel with MB
t_1	—	Fault occurs on DC pole conductor, current Idc starting rising
t_2	—	MB opens and arc is initiated in MB contacts, TVG sparks over LC is brought into the circuit in parallel with MB

Time *t* is in milliseconds, (t_1) to (4) is about 100 ms.

As the Main Break opens (at t_1), the DC arc is initiated between the contacts. Idc flows through the arc in the MB. As the TVG sparks over, the parallel LC path comes into circuit and the Idc oscillates producing artificial current zeros (1, 2, 3, 4...). The MB interrupts the arc at one of these artificial current zeros. The transient recovery voltage (TRV) across the Main Break tries to produce a restrike between open contacts of MB. The ZnO Arrester limits the transient recovery voltage across the MB and parallel path. The ZnO Arrester absorbs the energy in the bypassed current associated with the TRV. The Idc is finally interrupted at one of the artificial current zeros.

16.6. CONCLUSION

From the experience of present HVDC Systems, the true HVDC Circuit Breaker is not necessary in HVDC Poles of 2TDC, MTDC, Back-to-Back HVDC Systems. All the control and protection functions are performed effectively by the converter controls without the need of HVDC Breakers in pole circuit. HVDC Circuit-Breakers/Switching Systems, though available are of no practical use as they are complex, costly and unreliable for practical use in the Main DC Poles. However Metallic Return Transfers Breakers. HVDC Switching Arrangement based on Artificial Current Zero Principle of arc quenching are used in present 2-TDC and 3-TDC Systems. The details about HVDC Switching Systems are covered in following sections.

16.7. ENERGY CONSIDERATION IN BREAKING DIRECT CURRENT IN HVDC CIRCUIT-BREAKERS

(Refer Secs. 3.2 and 4.5 for fundamentals of energy in L, C and difference between A.C. and D.C. arc interruption).

Forms of Current Zeros

In a.c. circuit-breaking, the current is interrupted at current zero of the alternating current wave [Fig. 16.3 (*a*)]. As the contacts separate, the arc is initiated. The arc has a tendency to disappear around current zero. The arc is quenched at current zero by removing the ionised medium from contact space by flow of quenching medium. The contact space filled with fresh dielectric medium has then to withstand the Transient Recovery Voltage. The arc provides a resilient transition between the current carrying state and the voltage withstanding state. The post zero conductivity of contact space assists in dampening the TRV.

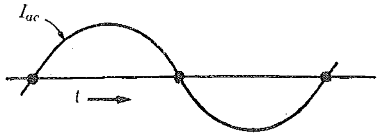


Fig. 16.3 (*a*). Current zeros in A.C. waveform.

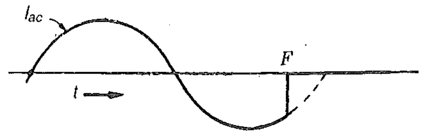


Fig. 16.3 (*b*). Forced current zero in AC wave (current chopped at instant F).

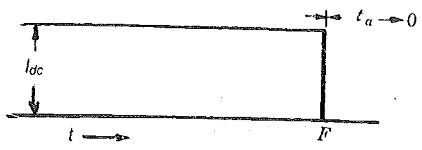


Fig. 16.3 (*c*). Abrupt forced current zero in D.C.

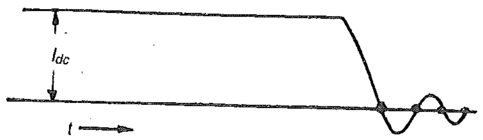


Fig. 16.3 (*d*). Artificial current zeros in DC by inserting LC parallel circuit across the circuit-breaker contact separation.

While breaking direct current, the natural current zero is not available. Hence the problem in D.C. circuit-breaker is to bring down the current from full value to zero, smoothly without chopping it abruptly. The abrupt current zero can be achieved by a high pressure blast on the arc zone. Such an abrupt forcing of current zero (current chopping) would result in excessive overvoltages [Fig. 16.4]. Hence, the switching system should bring down the direct current to zero artificially without chopping it [Fig. 16.3 (*d*)]. D.C. circuit-breaker should be capable of breaking all the values of currents from rated normal currents to highest short-circuit currents without excessive overvoltages.

This discussion can be visualised by comparing the flow of current with flow of water in a pipe-line (Fig. 16.4). If valve is suddenly closed, the flow of water is stopped and the pressure rises suddenly. The level of water in the surge tank thereby increases. Likewise, by interruption of current I by current chopping the energy in system inductance gets converted to capacitive charge, increasing voltage across system capacitance. If current is interrupted at zero value, the rise in voltage would be minimum.

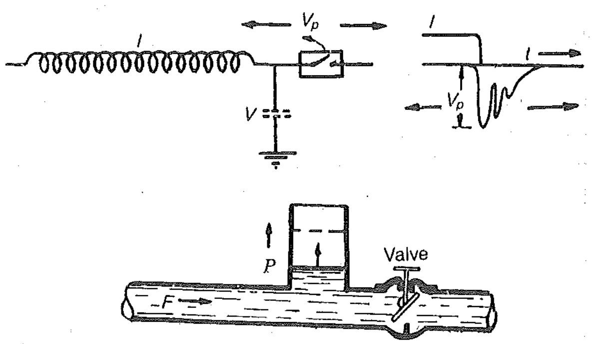


Fig. 16.4. Analogy between water flow and current flow.

Energy Equation

Refer Fig. 16.5 representing HVDC transmission system, let V_o = D.C. voltage at sending end, V_o is a function of i, t during transient switching condition.

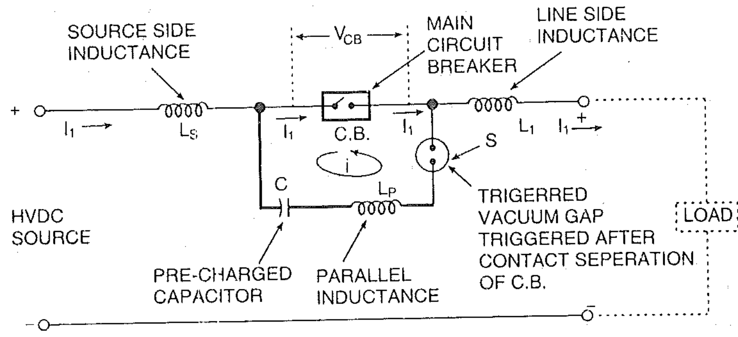


Fig. 16.5. Schematic of HVDC Switching System.

Before switching off, the steady direct current I flows through line induction L and resistance R and the d.c. circuit-breaker CB. The initial and final conditions are as follows :

$$t = 0, \quad i = I$$
$$t = ta \quad i = 0$$

Current decreases from initial value I to final value in time ta. The voltage equation can be written as–

$$L\frac{di}{dt} + iR + V_{CB} = V_0 \qquad \ldots(16.1)$$

where $L\frac{di}{dt}$ = Voltage drop across line inductor L ... Volts

iR = Voltage drop across resistance R ..., Volts

V_{CB} = Voltage across a circuit-breaker CB ..., Volts

V_0 = Sending end voltage, Volts

The energy (W) can be derived from simple relation given by

$$W = \int_0^{ta} iV \cdot dt \ldots \text{joules}$$

Multiplying equation (16.1) by idt and integrating with respect to time,

$$\int_0^{ta} V_0\, idt = \int_0^{ta} Li\, di + \int_0^{ta} i^2 R\, dt + \int_0^{ta} V_{CB} \cdot i\, dt \qquad \ldots(16.2)$$

rearranging the terms and simplifying

$$\int_0^{ta} V_{CB} \cdot idt = \frac{1}{2}LI^2 - \int_0^{ta} V_0 \cdot idt + \int_0^{ta} i^2 Rdt \qquad \ldots(16.3)$$

Total Switching Energy	=	Magnetic Energy in Inductance	–	Input Energy from Network	+	Total Joule Losses Converted into heat of arc

From equation (16.3) it can be seen that the switching duty is a question of energy. The total switching energy gets shared by the three component energies. The task of the switching system is to achieve the switching condition without abrupt change in magnetic energy.

As discussed in chapter 3, as per fundamentals, the current in inductance cannot be changed instantaneously (in zero time). Similarly the energy is capacitance cannot be changed instantaneously. If the current in inductance is forcibly chopped to zero in zero time, the energy in inductance has no way to dissipate except to get converted into energy in capacitance in form of charge, *i.e.* if $\frac{1}{2} LI^2$ in equation (16.3) is made zero instantaneously so as to interrupt the current, the component $\frac{1}{2} LI^2$ gets converted into $\frac{1}{2} CV^2$ the resulting overvoltage will stress the insulation and cause flashovers. To avoid this, the current I should vary with relatively low di/dt. In general, the value of time t_a varies between 10 to 30 milliseconds. The total switching energy can be increased quickly beyond the magnetic energy so as to quench the arc. The switching energy can be dissipated by charging capacitors (energy storage) or through resistors (energy dissipation).

Recently developed (1980's) Metal Oxide Resistors (ZnO) have superior voltage/current characteristic and energy absorption capability. Such resistors are used in HVDC switching-system.

In practical d.c. systems, the value of d.c. current is of the order of a few kilo amperes and the value of voltage across the circuit-breaker would be of the order of 10 to 200 kV. The switching power would be in the range of a few kilo-watts to a few megawatts depending upon the inductance of the line and smoothing reactors.

16.8. HVDC SWITCHING SYSTEM

In a.c. circuit-breakers, the arc is extinguished at natural current zero of the wave. Thus, the energy in system inductance at current zero is practically zero and current interruption is relatively easy.

In d.c. Switching system, a LC resonant circuit is introduced in parallel, just after contact separation of main circuit-breaker. Thereby oscillations are produced in the main current resulting in a few artificial current zeros. The main circuit-breaker catches one of the current zeros so as to quench the arc and break the direct current.

16.8.1. Commutation Principle of HVDC Circuit-breaker

The principle of a HVDC switching system is illustrated in Fig. 16.6.

The *Main Circuit-breaker* (CB) may be, MOCB or ABCB. The circuit-breaker should be capable of withstanding very high rate of rise of transient recovery voltage. It should also be able to dissipate the arc energy. It should be capable of opening consistently with precise opening time.

L_s and L_L represent the circuit inductance on either sides of the circuit-breaker.

C and L_p represent properly selected values of inductance and capacitance.

The capacitor C is pre-charged by a separate charging circuit (for obtaining current i in the loop).

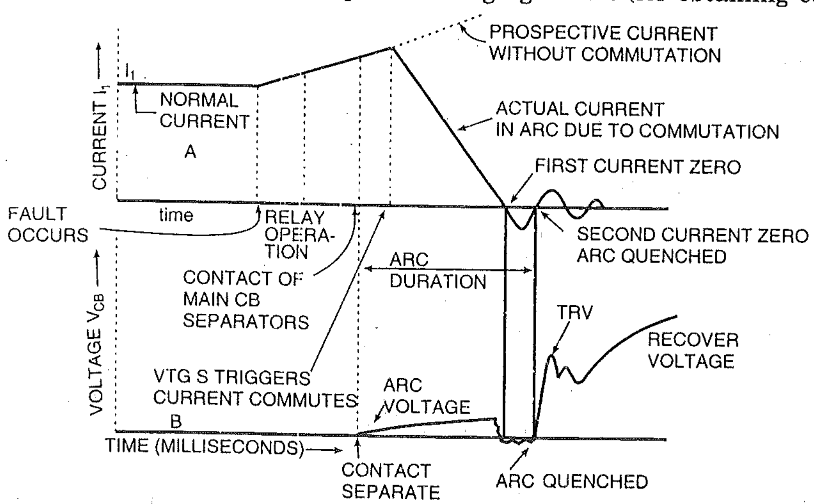


Fig. 16.6. Waveform of current zero achieved by commutation principle.

The parallel L_p-C circuit is switched immediately after opening of the contacts of Main Circuit-breaker CB. This switching is achieved by closing of a switch S or by triggering a vacuum gap or a thyristor in place of switch *S*.

When switch S is closed, the capacitor C discharges through the circuit-breaker causing current i opposite to current I_1. Current i is oscillatory, the frequency of oscillations depend upon value of L_p and C.

The oscillations of i are superimposed on the main current I_1, thereby producing several artificial current zeros in the main current I_1. These current-zeros are created during the arcing state in the main circuit-breaker (Fig. 16.6).

The current I_1 is interrupted by the main circuit-breaker at a suitable current zero (Fig. 16.6).

The rate of rise of TRV depend upon the dI_1/dt at current zero. The dI_1/dt is reduced by proper selection of C and L_p. The rate of TRV is also reduced by connecting ZnO arrester, and capacitors across the interrupters of the main circuit-breaker.

The final current zero in the main circuit-breaker (CB) does not stop the current. The current is now commuted to the parallel circuit. However, the capacitor C offers an open circuit to steady direct current and the direct current in the main path dies down on its own. The principle of HVDC circuit-breaker described above is called *Commutation Principle* as the current is commuted from main circuit to parallel path for achieving artificial zeros.

16.9. CONTROL OF dI/dt and dv/dt

Interruption of direct current is not simply a problem of creating artificial current zero. The circuit-breaker should be capable of withstanding the TRV. For comparison with A.C. circuit-breaker, the rate of change of current in an a.c. circuit-breaker for breaking 40kA is of the order of 20 A/μ sec. Whereas the rate of change of current in a d.c. circuit-breaker for interrupting 5000 A would be around 1000 A/μ sec.

To reduce dI/dt and dV/dt the following steps are taken in HVDC circuit-breaking system :

— Additional saturable reactor (L_{SAT}) is connected in series with the Main Circuit-breaker to reduce dI/dt prior to current zero.

— A combination R-C_1 is connected in parallel across the interrupter to reduce the dV/dt after zero.

— Resistance R is connected across load side through S. Each circuit-breaker has a limitation of withstanding the TRV stresses depending upon the properties of extinguishing medium and the flow pattern within the interrupter (Refer Ch. 4). Hence besides commutating circuit, there should be provision in the switching system to reduce dI/dt before final current zero and dV/dt. For reducing the severity of stresses on the circuit-breaker, switching stress factor F should be low. The interrupters which can withstand higher factor F are more suitable for HVDC main circuit-breaker.

$$F = \frac{dI}{dt} \times \frac{dV}{dt} \qquad \text{...(16.4)}$$

F = Switching stress factor (watt/sec^2)

where dI/dt = rate of change of current (A/sec)

dV/dt = rate of change TRV after final current zero, (V/sec).

Since the current in the inductance cannot change instantaneously, the saturable reactor reduces dI/dt, since the voltage across the capacitance cannot change instantaneously, the capacitance reduces the dV/dt.

16.10. TRIGGERED VACUUM GAPS (TVG)

Since the commutation process should be established immediately after contact separation, conventional make switches are not convenient for switch S. Triggered vacuum gaps are preferred. These are vacuum gaps with a third electrode (trigger). When a pulse is given to the trigger, the vacuum gap breaks down giving a conducting path (Fig. 16.7).

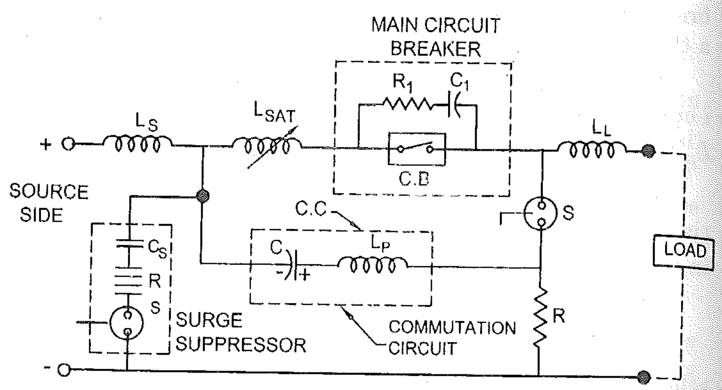


Fig. 16.7. Modification of basic circuit of dampen dI/dt and dV/dt.

16.11. SURGE SUPPRESSION

The current chopping by D.C. circuit-breaking (forced current zero prior to artificial current zero) can cause increase in voltage. To limit to such voltages, surge suppressor are necessary on both sides of the circuit-breaker. The *surge suppressor* is a combination of suitable non-linear resistor in series with capacitor and a vacuum gap. Now ZnO Arresters are used in addition to the surge suppressors.

16.12. COMPLETE CIRCUIT OF HVDC SWITCHING SYSTEM

Summarising, the complete HVDC circuit-breaking scheme comprises the following components (Fig. 16.7) :

— Main circuit-breaker (CB) with R_1 and C_1 in parallel with the interrupters for reducing dV/dt after final current zero.
— Saturable Reactor (L_{SAT}) in series with CB for reducing dI/dt before final current zero.
— Parallel series circuit containing triggered vacuum gap S, pre-charged capacitor C and reactor L_p for producing artificial current zero after contact separation in CB.
— Surge suppressor (SS) containing triggered vacuum gap in series with non-linear resistor, capacitor and parallel ZnO Arrester.

16.13. MAIN CIRCUIT-BREAKER FOR HVDC SWITCHING

The main circuit-breaker (CB in Fig. 16.7) has following functional requirements :

— It should be able to open and close the normal currents and fault currents in conjunction with the other components in the switching system.
— The short-circuit currents should be interrupted in minimum time.
— Overvoltages should be minimum.
— High switching stress withstand capability.

The main circuit-breaker is subjected to much more severe temperature stresses than conventional A.C. circuit-breakers because energy to be dissipated in the D.C. arc is much larger than A.C. arc (Refer Eq. 16.3). In A.C. circuit-breakers, the energy dissipated in the arc (Refer Ch. 4) is low as the arcing time is only of the order 10 to 20 milliseconds and during the period the current varies sinusoidally. Arc resistance is also not increased deliberately. Whereas in main DC circuit-breaker, part of the energy in inductance is dissipated in the arc.

DC circuit-breaker should be able to withstand high switching stress factor F (Refer Eq. 16.4). The following circuit-breakers have been successfully tried in HVDC experimental systems :

— Air-blast circuit-breaker. — Minimum oil circuit-breaker.
— Minimum oil circuit-breaker with pumping feature or with pressurised chamber (Refer Sec. 8.4).

Minimum-oil circuit-breakers can withstand high rate of the TRV and initial TRV. Hence they are suitable for HVDC. However, they have inherent disadvantage that the arcing time is dependent on current.

Vacuum circuit-breakers have basic advantage of very high rate of dielectric recovery. However, they have a limitation of lower voltage per interrupter. Hence they are not preferred for HVDC.CB.

SF_6 CB are sensitive to initial TRV (ITRV) during first microsecond after current zero. Hence they are not preferred for HVDC-CB.

16.14. SWITCHING DEVICES IN PRESENT BIPOLAR HVDC SUBSTATIONS

The change over from Bipolar mode to Monopolar mode necessitates both convertor control and switching arrangements on DC side. HVDC yards have following DC switching devices.

1. Medium voltage HVDC circuit breaker in neutral bus circuit to transfer earth return current to metallic return current. Such a circuit breaker has high normal current rating (1000 A to 2000 A) and medium DC voltage rating.

2. **HVDC Isolator Switches.** These are designed to open HVDC circuits after the current is brought to zero by convertor control.

3. **Earth switches.** For discharging dead circuits to earth for safety.

The DC voltage Ratings, Normal current Ratings, Breaking current rating and speed (time) of the above are quite different. But present systems do not have any HVDC circuit breaker in main pole to break full short-circuit in DC poles at rated DC voltage. Present schemes have following arrangements in the event of a fault on HVDC side.

If a fault occurs on HVDC pole side, the convertor control acts rapidly and the fault current is reduced rapidly by putting rectifier into invertor mode. The line is de-energized within about 120 ms.

After about 120 ms the re-energizing is attempted. If the fault is permanent, the complete faulty pole is removed from service by blocking the convertor bridges and tripping AC circuit-breakers feeding that pole.

This principle is followed in present 2 TDC and MTDC systems. Hence present 2 TDC and MTDC systems do not need HVDC circuit-breaker of high interrupting ability. Present HVDC systems use HVDC circuit breaker of low interrupting ability for transfer between earth return and metallic return.

As the DC fault current is rapidly and automatically controlled by convertor control, real need of HVDC circuit-breaker for interruption of HVDC fault currents is being questioned, debated and doubted. Even the recent MTDC systems are without HVDC CB for fault current interruption and depend on convertor control for operation and protection.

In case the pole is to be tripped, the tripping is from AC side by tripping AC circuit breakers on the AC network side of convertor transformers which feed the pole.

The bipolar HVDC system is divided into two poles for the purpose of protection and control. In the event of a permanent fault on one pole, almost half the rated bipolar power continues through the Monopolar operating Mode with either earth return or metallic return. The convertors of each pole are provided with on-line microprocessor based controls.

As the basic requirements of operation, control and protection are performed essentially by the convertor control system and tripping can be performed for the faulty pole from AC side by AC circuit-breakers associated with the faulty pole, *the lack of HVDC circuit-breakers has not posed any limitation to 2TDC systems or MTDC systems.*

16.15. TYPES OF HVDC CIRCUIT-BREAKERS

The types of circuit-breakers are identified with reference to

— switching time — current to be interrupted
— switching energy — voltage at which the current is interrupted
— voltage (TRV) after current interruption.

The current to be interrupted by HVDC circuit-breaker depends upon the (1) Switching time (2) Action of convertor control (3) Short-circuit ratio of HVDC system with respect to AC Networks.

Two extreme cases of HVDC circuit-breaker applications are

1. **Ideal high capability HVDC circuit-breaker** associated with ideal protection system which is so *fast* that the DC current is suppressed and interrupted immediately after occurrance of fault within shortest possible time (app. 15 ms) before the current has time to rise to full value (30 to 40 ms.)
2. Low capability HVDC circuit-breaker which is capable of interrupting lesser value of DC fault current at lesser voltage at the time when the DC fault current and DC voltage has been de-energized.

Practical HVDC Circuit-breakers (Proposed-1986)

The **Practical proposed HVDC circuit-breakers** (for which prototypes have been successfully tested) have a capability to interrupt DC currents at DC voltage; in between the two extreme cases that

— the breaker is not interrupting the current immediately on occurrence of fault.

— The breaker comes into action before the convertor control brings down the fault current and voltage to zero.

The proposed practical HVDC circuit-breaker have certain specified capability to interrupt HVDC currents at certain specified HVDC system voltage and Transient Recovery Voltage (TRV) such proposed practical HVDC circuit breakers are classified into two categories called A-type and B-type.

Type-A Breaker is fast and does not depend on converter control action.

Type-B Breaker is slow and depends upon convertor control to act before the current interruption is initiated. Type-B is further divided into Type **B1 and B2.** Type B-1 Breaker has full voltage capability and TRV capability. Type B-2 Breaker has limited capability with respect to system voltage and TRV withstand.

Table 16-1-B. Classification of Proposed Practical HVDC Circuit-breakers (1986)

Class of HVDC Breaker	*Operating time*	*Characteristics*
1. **Type 'A' HVDC Circuit-breaker**		
— High current and voltage capability and fast HVDC breaker. Breaker interrupts fault current before current peak. — Breaker does not depend on convertor control to reduce fault current.	— Less than 15 ms considerably shorter than usual AC breaker. — Breaker reduces fault current before the current reaches positive peak — Breaker quenches arc before the control of thyristor convertors bring down the DC current and voltage.	— Breaker capable of breaking peak DC fault current at rated voltage and rated TRV — Breaker requires very high energy absorption capability — The demand on convertor control is reduced.. — Breaker very complex and costly.
2. **Type 'B-1" HVDC Circuit-breaker**		
— Breaker with reduced current interruption capability and full voltage capability — Breaker operates after the current is brought down by convertor control — Breakers has full voltage capability and TRV capability	— 60 to 90 ms	— Breaker is simpler than type A breaker. — Breaker depends on convertor control to reduce fault current. — Breaker takes lesser time than Type B-2. — Compromise between complex control and complex breaker.
3. **Type 'B-2' HVDC Circuit-breaker**		
— Breaker with minimum voltage capability, TRV capability and current capability. — Breaker operates only after DC current and voltage are brought to low value by convertor control.	— 90 to 120 ms	— Breaker simpler and least costly. — Breaker least useful — Controls are costly and complex. — Time required for restoration of system after temporary line faults is very long (150 ms).

16.16. HVDC Circuit-breaker Capabilities and Characteristics

These include the following :

— Voltage capability

— Current interruption capability

— Switching time.

— TRV capability

— Energy absorption capability

Each of these characteristics has a significant influence on the performance of the circuit-breaker individually and simultaneously. These characteristics also influence the behaviours of the HVDC system at the time of the breaker action. Therefore the requirements of the characteristic of the optimum. Circuit-breaker are determined by the system operating strategy with respect to energizing and de-energizing sequence during and after a fault.

In DC circuit-breaker the current is artificially brought to zero since DC current has no natural current zero. The current suppression generates a voltage transient. The prospective peak value of voltage transient depends on the rate of suppression of current (dI/dt) and inductance L in the DC circuit.

Besides the current zeros, there is another major difference between AC and DC systems. *In HVDC system, current and voltage on DC side is routinely controlled by the convertor control.* The same controls can be used to assist the circuit-breaker in its interrupting process by reducing the DC voltage and DC current when the breaker operates. In the limit it is possible to open the DC circuit-breaker at zero current and zero voltage, after an elapsed time of the order 120 ms (Type B-2 Breaker).

The required voltage and current capability of HVDC circuit-breaker is therefore associated with the questions "whether the control is assisting the breaker or not?" and "to what degree are the controls assisting the breaker". *In other words "what is the sequence of time events with reference to occurrence of fault, action of controls to reduce fault current and pole voltage and operation of HVDC breaker ?".*

Therefore there are *opposite demands* on (1) complexity of controls and (2) complexity of HVDC breaker. The choice is made after making a *compromise* between them in economic and technical terms.

A closed HVDC circuit breaker is designed to carry maximum load current continuously and fault current for short-time. When a fault occurs on HVDC line or Tap-off, the DC current starts rising rather rapidly before the convertor control comes into action. The rate of rise of HVDC fault current (dI/dt) depends upon the value of prevailing system voltage and inductance (L) in the system. HVDC side has large inductance due to smoothing reactors and the series inductance of HVDC line. The convertor control acts and reduces the current to 5 per cent of rated current and reduced DC voltage to low value (LVDC). Therefore of opening of HVDC breaker is delayed, relatively low current interruption is required (5 to 15% of Normal Load Current).

Alternatively if the HVDC breaker operates fast enough (less than 15 ms) before the DC fault current reaches the prospective peak, the interruption rating can be modest. However for such a scheme, fast protective system (detecting time of only a few ms) and a fast circuit-breaker (less than 10 ms) must be used.

16.17. DEFINITIONS OF SWITCHING TIME FOR HVDC CIRCUIT-BREAKERS

Between the instant of occurrence of DC fault and final current interruption by HVDC circuit-breaker the switching time has following component times :

1. Time to sense the abnormal condition (fault) and to send trip signal to circuit-breaker. This is called relay time.
2. Time to open circuit-breaker contacts. This is called opening time of CB.
3. **Time to commute the current out of the arc and subsequently to reduce the current to zero.**

In some circumstances, time to restore the system on the healthy pole should be added to the above. If the circuit breaker has limited voltage capability, full power cannot be restored on healthy pole unless the isolators (disconnecting switches) open and isolate the breaker. In such a case, the following time must be added.

4. Time for opening disconnector switches. The healthy pole can be energized and full power can be restored after a total time given by addition 1 to 4 above.

16.18. SHORT-CIRCUIT RATIO (SCR) OF HVDC SYSTEM

Short-circuit ratio of HVDC system is defined as the ratio of fault MVA of the AC system at the connection point of HVDC system to the rated capacity of line.

$$\text{SCR} = \frac{\text{Fault MVA of AC system}}{\text{Rated MW Capacity of DC System}}$$

SCR indicates the strength of AC system at the point of connection of HVDC substation. (Ref. Sec. 20.14)

Effective Short-circuit Ratio (ESCR)

It is defined as the ratio which includes fault MVA including contribution of AC harmonic filters. ESCR is now more commonly used. The performance of HVDC link is associated with the strength of the connected AC systems. SCR and ESCR give a measure of the strength of connected AC system. The AC systems are called strong, weak etc. as follows :

AC system	*SCR*	*ESCR*
Weak system	< 3	< 2.5
Strong system	> 6	> 5

16.19. Conclusions

1. HVDC circuit-breakers are classified into four categories :

(*i*) Low voltage Metallic Transfer Breaker

(*ii*) Type A Breaker which does not depend on control actions

(*iii*) Type B1 Breaker which depends on control action but has high voltage capability.

(*iv*) Type B2 Breaker does depend on control action and has no high voltage capability.

2. HVDC Breakers are likely to be used for a switching off parallel taps.

3. Though the HVDC C.B. have been developed, their use in HVDC systems is not envisaged.

For Further Reading :

1. Book : "EHV AC and HVDC Transmission Engineering and Practice" Khanna Publisher, Delhi (2nd Ed. 1996).
2. Ch. 47, Fig. 47.19, 20, 21, and sec 20.14.

QUESTIONS

1. With the help of sketches, explain the principle of Artificial Current Zero Circuit adopted in DC circuit breaking.
2. Draw a schematic of a two-pole two terminal HVDC System indicating main components. Explain why HVDC Circuit Breakers are not necessary.
3. Explain the configurations of a multi-terminal HVDC System without a HVDC Circuit Breaker.
4. Explain the function of Metallic. Return Transfer Breaker in a typical Bipolar Two Terminal HVDC System.
5. Discuss why HVDC Circuit Breakers are not necessary in HVDC Transmission System.

17

Electrical Substations, Equipment and Bus-bar Layouts*

Introduction — Connections — Bus-bar arrangement — Single bus-bar systems — Duplicate bus — Ring bus — Sectionalizing — Generator connections — Classical system — Unit system — Direct generator switching — Multiple generator transformer units — Layout of switching yard — Bus-bar design — Summary.

17.1. INTRODUCTION

The electric power system can be divided into the following regions :

1. Generating stations 2. Transmission systems 3. Receiving stations
4. Distribution systems 5. Load points.

In all these regions need switchgear. Busbars are conducting bars to which a number of local feeders are connected. Bus-bar operate at constant voltage. Busbars are insulated from earth and from each other. Besides the bus-bars there are other equipment in the electrical schemes such as circuit-breakers, current transformers, potential transformers etc. These equipments can be installed according to various schemes depending upon requirements. The total plant consists of several equipment.

The Substations have following distinct circuits :

1. *Main Circuits.* Through which power flows from generators to transmission lines. The components *in series with the main circuit of power flow* include : Busbars, Power Transformers, Circuit Breakers, Isolators, Current Transformer CT, Line Trap Units, Series Capacitors, Series Reactors, Diode or Thyristor Rectifiers. The components *in shunt circuits connected phase to ground* include Shunt Capacitors, Shunt Reactors, Static VAR Sources, Harmonic Filters, Voltage Transformers, Surge Arresters.

1. *Bus-bar and conductor systems* are of following alternatives :

— Tubelar or Solid Aluminium or Copper Conductors supported on Porcelain or epoxy insulators.

— Isolated Phase Busducts

— Flexible ACSR stranded conductors.

— Single core or Multicore Power cables through trenches.

2. *Auxiliary Power Circuits* through which power flows to Substation Auxiliaries. The supply conductors are generally Power Cables.

3. *LV Control Circuits* Measurement, Protection, Control, Monitoring, Communication Circuits. SCADA and Computer/Microprocessors. The supply conductors are generally of Control Cables.

4. *Auxiliary Low Voltage AC and Low Voltage DC Supply Circuits.* The conductors are generally of power cables or solid busbars.

Main Circuit and Equipment are described in Sec. 17.2 to 17.28.

* Refer following books by Khanna Publishers for more details :
— Electrical Substation Engineering and Practice, S. Rao
— Power Transformers and Special Transformers, S. Rao,
— EHV AC and HVDC Transmission Engineering and Practice, S. Rao.

17.2. SUBSTATION EQUIPMENT AND OUTDOOR YARD LAYOUT

An outdoor switch-yard in a substation has several three phase equipment, three phase busbars. Their relative locations and connections are illustrated by

— Single Line Schematic diagrams,
— Single line layouts,
— Three phase layouts,

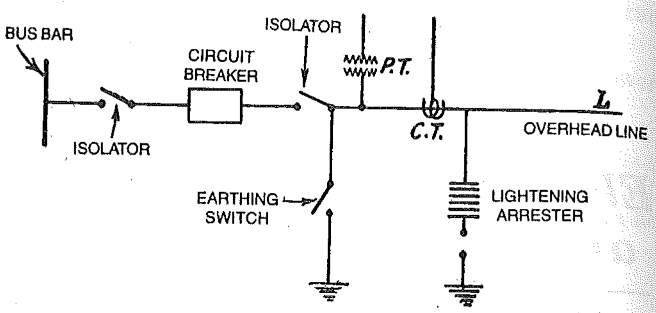
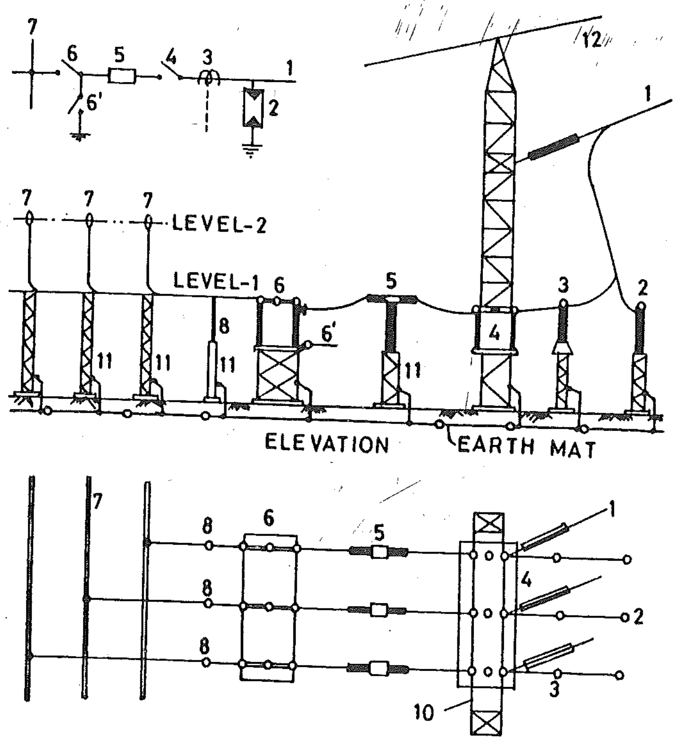


Fig. 17.1. Single Line Schematic Diagram of one bay in Switchyard.

The outdoor *busbars* are either *Rigid Aluminium Tubes* supported on Post Insulators or *Flexible ACSR Conductors* supported on Strain Insulators. The busbars are generally in *two horizontal levels* as shown in the 3-Phase Layout in Fig. 17.1 (*b*). The connections between the two levels are generally by vertical flexible ACSR (Aluminium Conductor Steel Reinforced) or AAAC (All Aluminium Alloy Conductors).

The relative locations of CB, isolators and busbars follow the general practice and particular switching requirement and maintenance and protection requirement. The reasoning should be understood and safety operation, maintenance, protection and control requirements must be satisfied.



1. Line
4. Isolator Line Side
7. Earthing Switch
10. Strain Insulator for 1
12. Shielding conductor (ACSR)
2. Surge Arrester 3.CT
5. Circuit-Breaker
8. Busbar Tubular Rigid
11. Gantry (Beam)11.Support Structure
6.Isolator (Disconnector)
9.Post-Insulator Support

Fig. 17. B Layout of a single bus

Each bay has several equipment connected in certain well defined pattern as shown in Fig. 17.1. Circuit breaker is connected between the busbar and each outgoing and incoming circuit. Isolator is provided on each side of circuit breaker. CTs are provided for measurement and protection. The protection zones should overlap and cover the circuit Breaker. Hence CTs may be necessary on each side of the Circuit Breaker. VTs are generally connected to busbars and incoming line side. Surge Arresters, (Lightning Arresters) are connected phase to ground, at the incoming feeder as the first apparatus and also at the terminal of Transformer, terminal of Capacitor Bank, terminal of Shunt Reactor, terminal of Generator, terminal of Large Motor for diverting Switching/lightning surges to ground. Power transformers are connected between of two voltage levels (Fig. 17.23, Sec. 17.11).

Shunt reactors are used with EHV lines to regulate voltage low during loads.

Fig. 17.3 illustrates the covering of circuit-breaker by the protective zones.

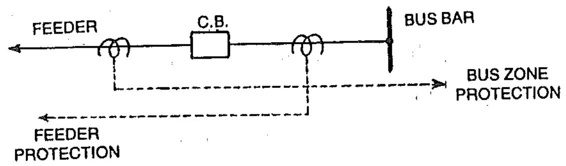


Fig. 17.3. The location of CT's should be such that CB is covered by protective zones.

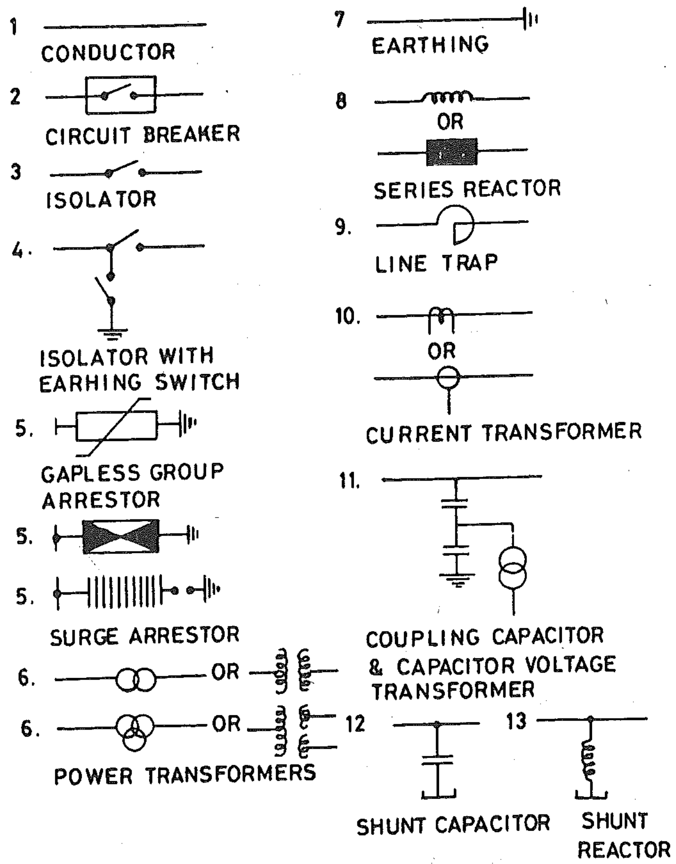


Fig. 17.4. Symbols of 3 Phase-Equipment.

Table 17.1-A. Substation Equipment and their Functions

	Equipment	*Function*
1.	Bus-bar	Incoming and outgoing circuits connected to bus-bars.
2.	Circuit-breakers	Automatic switching during normal or abnormal conditions.
3.	Isolators (Disconnectors)	Disconnection under no-load condition for safety, isolation and maintenance.
4.	Earthing Switch	To discharge the voltage on dead lines to earth.
5.	Current Transformer	To step-down currents for measurement, control, and protection.
6.	Voltage Transformer	To step-down currents for measurement, control and protection.
7.	Lightning Arrester (Surge Arrester)	To discharge lightning over voltages and switching over voltages to earth.
8.	Shunt Reactor in EHV substations	To provide reactive power compensation during low loads.
9.	Series Reactors	To reduce the short-circuit current or starting currents.
10.	Neutral-Grounding Resistor	To limit the earth fault current.
11.	Coupling capacitor	To provide connection between high voltage line and power line carrier current equipment.
12.	Line-trap	To prevent high frequency signals from entering other zones.
13.	Shunt capacitors	To provide compensations to reactive loads of lagging power factors.
14.	Power Transformer	To step-up or step-down the voltage and transfer power from one a.c. voltage to another a.c. voltage at the same frequency.
15.	Series Capacitors	Compensation of series reactance of long lines.

Main Data of a Typical 400/230 kV Outdoor AC Substation

Operating voltage	400 kV	230 kV
Rated current	2000 A	2000 A
Maximum Short-circuit current in busbars	40 kV	40 kV
Minimum phase to phase clearance	5.75 m	2.5 m
Minimum phase to phase clearance	3.65 m	2.0 m
Number of horizontal levels of tubular busbars/flexible busbars	– 2	2
Height of tubular busbars of first level above ground	7 m	6 m
Height of tubular busbars of second level above ground	13 m	4 m
Tubular Aluminium Busbar A1 ASTM B241	4" IPS*	4" IPS

* IPS = International Pipe Standard

Table 17.1-B. Various Subsystems in Substations and their Functions

	System	*Function*
1.	Substation Earthing (Grounding) system — Earth mat — Earthing spikes — Earthing risers	To provide an earth mat for connecting neutral points, equipment body, support structures to earth. For safety of personnel and for enabling earth fault protection. To provide the path for discharging the earth currents from Neutrals, Faults, Surge arresters, overheads shielding wires etc. with safe step-potential and touch potential.
2.	Overhead earth wire shielding or Lightning Masts.	To protect the outdoor substation equipment from lightning strokes.
3.	Illumination system (lighting) — for switchyards — buildings — roads, etc.	To provide illumination for vigilance, operation and maintenance.
4.	Protection System — protection relay panels — control cables. — circuit-breakers — CTs, VTs, etc.	To provide alarm or automatic tripping of faulty part from healthy part and also to minimize damage to faulty equipment and associated system.
5.	Control cabling	For protective circuits, control circuits, metering, circuits, communication circuits is a underground power cables.
6.	Power cables.	To provide supply path to various auxiliary equipment and machines.
7.	PLCC system power line carrier current system — line trap — coupling capacitor — PLCC panels	For communication, telemetry, tele-control, power line carrier protection etc.
8.	Fire fighting system. — sensors, detection system — water spray system — fire protection control panels, alarm system — water tank and spray system	To sense the occurrence of fire by sensors and to initiate water spray, to disconnect power supply to affected region to pin-point location of fire by indication in control room.
9.	Cooling water system — Coolers — water tank	This system is required for cooling the valves in HVDC substation.
10.	DC Batteries sets and Battery chargers	Auxiliary low voltage DC supply
11.	Auxiliary standby power system — diesel-generator sets — switchgear — distribution system	For supplying starting power, standby power for auxiliaries
12.	Telephone, Telex system, Microwave system.	For internal and external communication.

17.3. ISOLATOR AND EARTHING SWITCH

17.3.1. Requirement and definitions

Isolator (disconnecting switch) operates under no load condition. It does not have any specified current breaking capacity or current making capacity. Isolator is not even used for breaking load currents.

Circuit-breaker can make and break electric circuit under normal current or short circuit conditions.

Isolators are used in addition to circuit-breakers, and are provided on each side of every circuit-breaker to provide isolation and enable maintenance.

While opening a circuit, the circuit-breaker is opened first, then isolator. While closing a circuit, the isolator is closed first, then circuit-breaker. Isolators are necessary on supply side of circuit-breakers in order to ensure isolation (disconnection) of the circuit-breaker from live parts for the purpose of maintenance. Automatic switching of isolators is preferred.

Isolators used in power-systems are generally 3-pole isolator. The 3-pole isolators have three identical poles. Each pole consists of two or three insulator posts mounted on a fabricated support. The conducting parts are supported on the insulator posts. The conducting parts consist of conducting copper or aluminium rod, fixed and moving contacts. During the opening operation the conducting rods swing apart and isolation is obtained. The simultaneous operation of three poles is obtained by mechanical interlocking of the three poles. Further, for all the three poles, there is a common operating mechanism. The operating mechanism is manual plus one of the following :

(1) Electrical motor mechanism, (2) Pneumatic mechanism.

Pneumatic mechanism was preferred in substations with Air-Blast Circuit Breakers. Now, with SF_6 circuit-Breakers, motor-mechanism is preferred. Further the isolator can be provided with earthing switches where required. The earthing switch consists of conductor bar. When the earthing switch is to be closed, these bars swing and connect the contact on line unit of isolator to earth.

To prevent the mal-operation, the isolator is provided with the following interlockings :

1. Interlocking between three poles for simultaneous operation.
2. Interlocking with circuit-breakers.

Isolator cannot be opened unless the circuit-breaker is opened. Circuit breaker cannot be closed unless the isolator is closed.

Load Break Switches

In addition to isolators and circuit-breakers, there is one more device called Load Interrupting Switch, which combines functions of the isolator and a switch. These are used for breaking load current.

Earthing Switch

Earthing switch is connected between the line conductor and earth. Normally it is open. When the line is disconnected, the earthing switch is closed so as to discharge the voltage trapped on the line. Though the line is disconnected, there is some voltage on the line to which the capacitance between line and earth is charged. This voltage is significant in high voltage system. Before starting the maintenance work these voltages are discharged to earth by closing the earthing switch.

Normally, the earthing switches are mounted on the frame of isolator.

Sequence of Operation while Opening/Closing a Circuit

While opening : (1) Open Circuit-breaker
(2) Open Isolator
(3) Close Earthing Switch (if any).

While closing : (1) Open Earthing Switch
(2) Close Isolator
(3) Close Circuit-breaker.

17.3.2. Types of Construction of isolators

— Vertical Break type (Figs. 17.3 and 17.5)
— Horizontal Break type, either centre-break or double-break (Fig. 17.4)
— Vertical Pantograph type (Fig. 17.6).

The vertical pantograph type design is preferred for rated voltages of 420 kV and above. The other types of designs are used from 12 to 420 kV.

These are outdoor air break disconnecting switches of the gang-operated horizontal break type with rating of 7 kV and above. These isolators are designed for all outdoor applications including isolation of circuit breakers, transformer banks and surge arresters and line sectionalizing. Horizontal upright mounted switches can be equipped with arcing horns for interrupting small currents such as line charging or transformer-magnetizing currents.

Gang-operated earthing switches can be mounted on one side of the break jaw end of the main switches.

The grounding switches can be closed easily through a lever mechanism by use of the handle, but only when the main isolator is open, due to the provision of a mechanical interlock.

Horizontal Break Centre Rotating Double Break Isolator

This type of construction, has three insulator stacks per pole. The two on each side are fixed and one at the centre is rotating type. The central insulator stack can swing about its vertical axis through about 90°. The fixed contacts are provided on the top of each of the insulator stacks on the side. The contact bar is fixed horizontally on the central insulator stack. In closed position, the contact shaft connects the two fixed contacts. While opening, the central stack rotates through 90°, and the contact shaft swings horizontally giving a double break.

The isolators are mounted on a galvanised rolled steel frame. The three poles are interlocked by means of steel shaft. A common operating mechanism is provided for all the three poles. Fig. 17.5.2 shows one pole of a triple pole isolator in closed position.

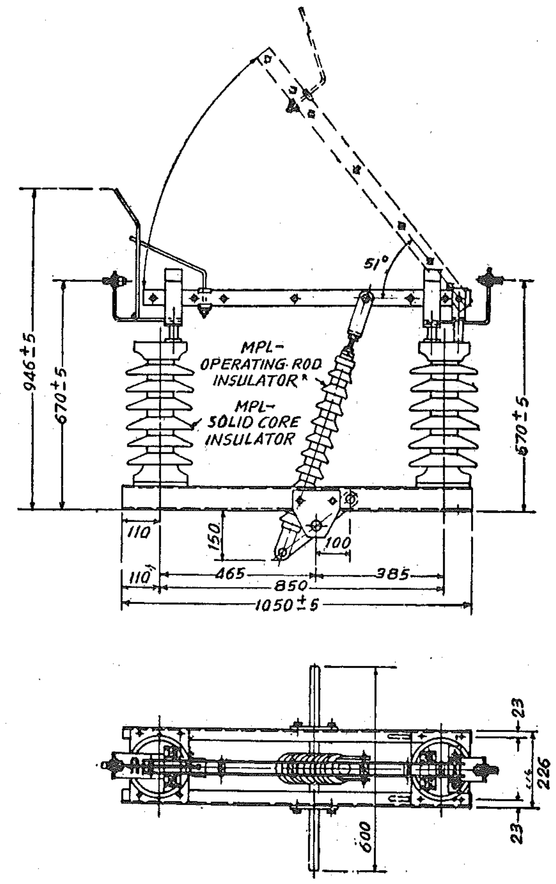


Fig. 17.5.1. Vertically Break 25 kV Isolator
(*Courtesy* : Hi-Velm Industries Pvt. Ltd., India.)

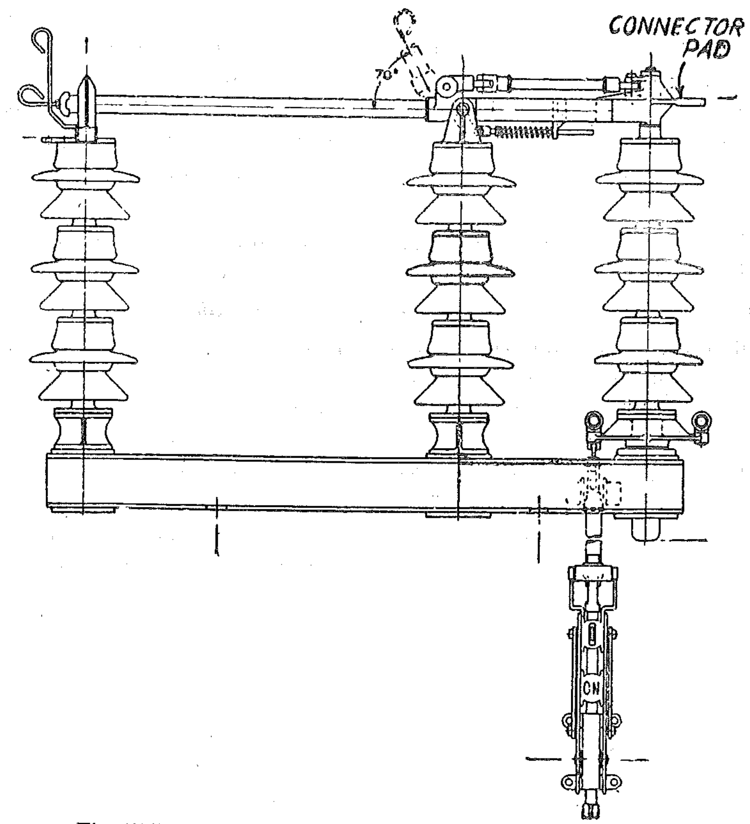


Fig. 17.5.2. Vertical Break Isolator (not described here)
(The insulator stack on right side swings about its vertical axis,
The contact pipe swings in vertical plane.)

17.3.3. Pantograph Isolator

Fig. 17.5.3 illustrates the construction of a typical pantograph isolator. While closing, the linkages of Pantograph are brought nearer by rotating the insulator column. In closed position the upper two arms of the pantograph close on the overhead station busbar giving a grip. The current is carried by the upper busbar to the lower busbar through the conducting arms of the pantograph. While opening, the rotating insulator column is rotated about its axis. Thereby the pantograph blades collapse in vertical plane and vertical isolation is obtained between the line terminal and pantograph upper terminal.

Pantograph isolators cover less floor area. Each pole can be located at a suitable point and the three poles need not be in one line, can be located in a line at desired angle with the bus-axis.

17.3.4. Ratings of Isolators and Tests

The definition regarding Normal Current Rating, Short time current rating, Rated voltage, Rated Insulation level for isolators are similar to the corresponding terms applicable to high voltage a.c. circuit-breakers (Refer Sec. 3.19). Isolators do not have breaking or making capacity.

The terms Type tests and Routine tests defined in Chapter 10 are applicable to Isolators also. The following *type tests* are conducted on Isolators :

— Temperature Rise tests (Refer Sec.10.12.2)
— Power frequency voltage withstand tests (Refer Sec. 12.10)
— Impulse voltage withstand tests (Refer Sec. 12.8)
— Mechanical Endurance tests (Refer sec. 10.2)

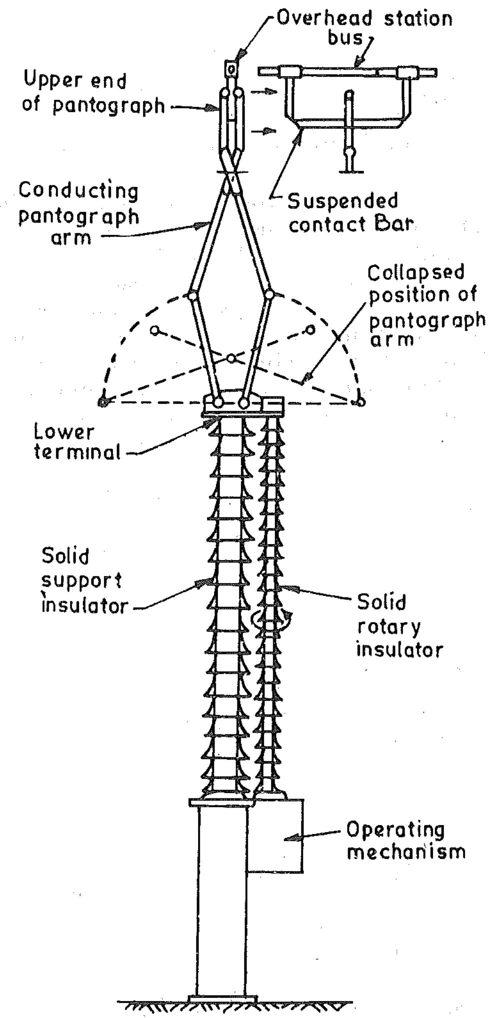


Fig. 17.5.3. Pantograph insulator for UHV sub-station.

— Millivolt drop tests (Refer Sec. 10.2.4)
— Short Time Current test (Refer Sec. 11.6)

Type tests are conducted on one or first few isolators to confirm the design and rating. Following routine tests are conducted on Isolators. These are conducted on each Isolator manufactured by the company before dispatch to site.

— Power Frequency Voltage Withstand Test
— Mechanical Operation Tests
— Measurement of Resistance.

17.4. BUS-BAR ARRANGEMENTS IN SWITCHYARDS

There are several ways in which the switching equipment can be connected in the electrical layout of generating station, receiving station or a switchgear in a distribution system. The selection of the scheme is in general affected by following aspects :

1. Degree of flexibility of operations desired.
2. Importance of load and local conditions. Freedom from total shut down and its period desired.
3. Economic consideration, availability and cost.

4. Technical considerations.
5. Maintenance, safety of personnel
6. Simplicity.
7. Provision of extension.
8. Protective Zones.

With these basic requirements there are several combinations, some of which are briefly described below.

For a small and medium sized station where shut-down can be permitted at times, simple, single bus-bar system can be favoured. For major plant such a large generating station or receiving station, bus-bar system is carefully designed and a costly system is always justified. Technical considerations are more important than economic considerations. In major plants, shut down results in disconnection of supply to a large area. Hence, to avoid shut-down, the major plants should have elaborate bus-bar system, with duplicate buses, sectionalization, alternative supply arrangements etc. The technical considerations include function of each equipment, its location, sequence of operation, relative location, interlocking, facility of periodic maintenance with alternative supply etc. Economy is most important. The extra-high voltage equipment such a isolator, circuit-breakers etc. are generally costly. Hence unnecessary equipment should not be provided.

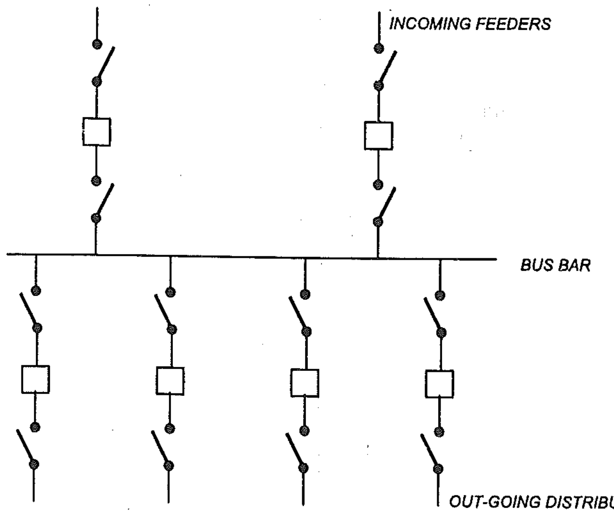
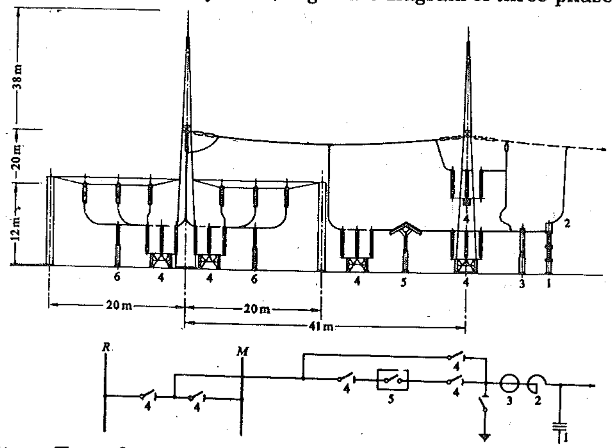


Fig. 17.6. Single bus-bar system (single line diagram of three-phase system).



1. Capacitive Voltage Transformer 2. Line Trap 3. Current Transformer
4. Isolators 5. Circuit-breaker 6. Post insulator
M–Main buses ; *R*–Reserve buses

Fig. 17.7. Section through a feeder bay in a 220 kV Switchyard.

(*a*) **Single bus-bar arrangement.** This simple arrangement consists of a single (three-phase) bus-bar to which the various feeders are connected. In case of a fault or maintenance of a bus-bar the entire bus-bar has to be de-energized and the total shutdown results.

Hence this type of arrangement provides least flexibility and immunity from total shut-down. However, this scheme is the most economical and simple. It is used for switch-boards, small and medium sized sub-stations, small power stations.

(*b*) **Duplicate bus-bar arrangement.** The duplicate bus-bar system provides additional flexibility, continuity of supply and permits periodic maintenance without total shut-down. In the event of fault on one bus the other can be used.

Fig. 17.8 (*a*) shows the duplicate bus-bar arrangement in a generating station. Each generator has only one circuit-breaker and between the circuit-breaker and each busbar there is one isolator. There are two buses called *main* bus and reserve bus. The coupler can be closed so as to connect the two buses. While transferring the power to the reserve bus, the following steps may be taken :

1. Close tie circuit-breaker, *i.e.* bus coupler. The two buses are now at same potential.
2. Close isolators on reserve bus.
3. Open isolators on main bus.

The power is now transferred to the reserve bus and main bus is disconnected. In more important stations, two circuit-breakers are used per generator, one for each bus.

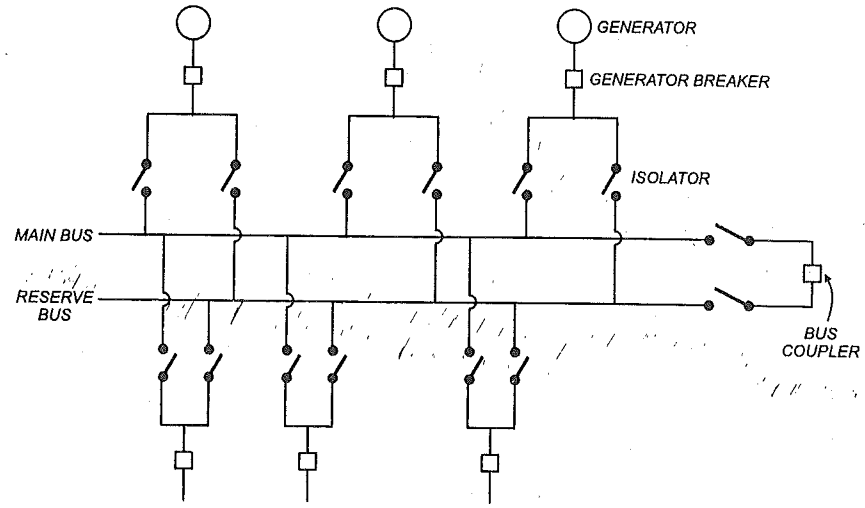


Fig. 17.8 (*a*) Duplicate bus-bar system (Single line diagram of 3-phase System)

For 400 kV Switchyards two Main Buses plus one transfer bus scheme is preferred. The transfer bus is used for transferring power from Main Bus I to Main Bus II.

(*c*) **Sectionalization of bus** (Fig. 17.9). Sectionalizing the buses has added advantages. One section can be completely shut down for maintenance and repairs while the other continues to supply. Secondly by adding a current limiting reactor between the sections, the fault MVA can be reduced, thereby circuit-breaker of lesser capacity may be permitted.

(*d*) **Ring bus** [Fig. 17.8(*b*)] Ring bus provides greater flexibility. The supply can be taken from any adjacent section. The effect of fault in one section is localised to that section alone. The other section continues to operate.

(*e*) **One-and a half breaker arrangement.** One-and-a-half breaker arrangement needs three circuit-breakers for two circuits. Any circuit-breaker can be switched-off for the purpose of maintenance, without the provision of bypass. (Fig. 17.10)

The number of circuit-breaker per circuits $1\frac{1}{2}$, hence the name.

Refer Fig. 17.10 having two bus-bar sets I and II. In $1\frac{1}{2}$ breaker arrangement, circuit I and circuit II can take supply either from bus-bar I or bus-bar II. Thus this arrangement gives high security against loss of supply. Such arrangement is particularly suitable for the switchyards in large generating stations in which very high power is to be handled by individual circuits. (Say 500

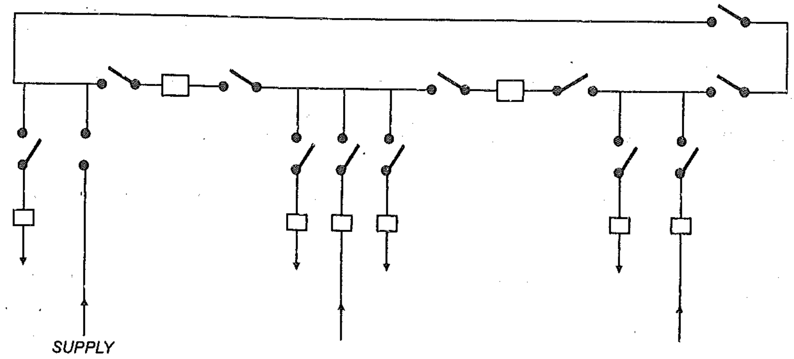


Fig. 17.8 (*b*) Ring bus.

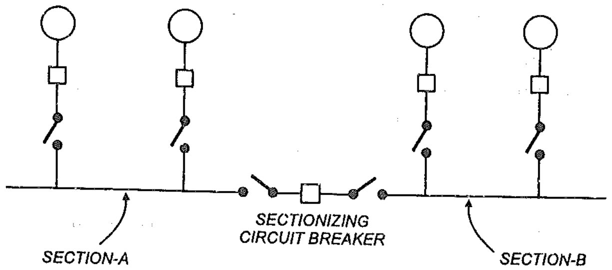


Fig. 17.9. Sectionalization of bus.

MW) $1\frac{1}{2}$ Breaker arrangement uses $\frac{1}{2}$ circuit-breaker per circuit. The higher cost is justified because of higher security and by passing facility obtained.

The $1\frac{1}{2}$ circuit-breaker arrangement has been used in important 400 kV, 750 kV sub-stations.

(*f*) **Mesh arrangment.** Another method of economic use of circuit-breakers in a sub-station is mesh-arrangement (Fig. 17.11). In mesh arrangement, the circuit-breakers are installed in the

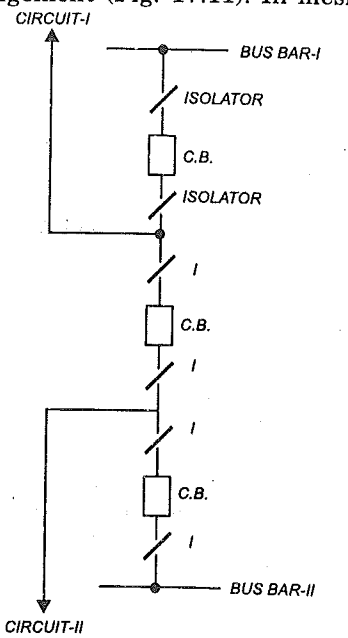


Fig. 17.10. One-and-a-half circuit-breaker arrangement.

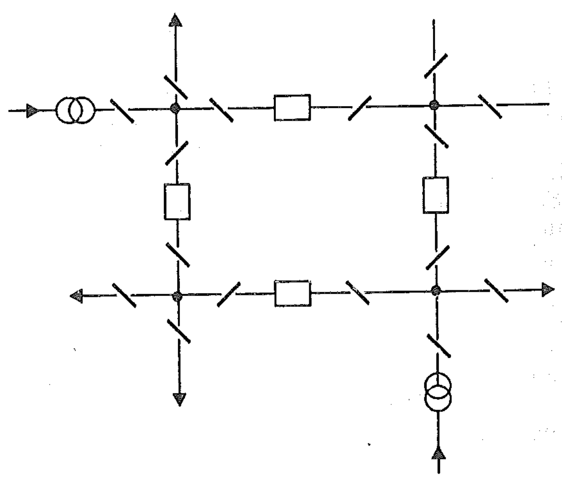


Fig. 17.11. Mesh Arrangement (Only four circuit-breakers control eight circuits.)

mesh formed by the buses. The circuits are tapped from the node points of the mesh. In the figure shown, four circuit-breakers are utilized to control eight circuits. In the event of a fault on any circuit, two circuit-breakers have to open, resulting in opening of the mesh.

17.4.1. Bus-bar System Recommended for Large Important sub-stations

— Duplicate bus-bar arrangement with additional transfer bus

— $1\frac{1}{2}$ circuit-breaker arrangement

— Mesh arrangement

Single bus-bar system is not preferred.

Duplicate bus-bar system is suitable for highly interconnected power network in which flexibility is important. It gives no security against bus-bar faults.

$1\frac{1}{2}$ circuit-breaker arrangement is preferred in important large stations where power handled per circuit is large.

Interconnected Mesh gives maximum security against bus-bar faults are requires minimum outage against busbar faults. It uses fewer circuit-breakers than $1\frac{1}{2}$ arrangement. It lacks switching flexibility. It is preferred in sub-stations having large number of circuits.

17.4.2. Maintenance Zoning

The sub-station layout should be designed with due considerations to maintenance zoning, *i.e.* grouping of various equipments such that they can be isolated and physically separated from neighbouring live parts for maintenance.

In simple *single bus-bar feeder circuit* the following three maintenance zones are required :

— circuit-breakers maintenance zone

— bus-bar zone including bus-bar isolator

— feeder zone including the feeder isolator and feeder-side equipment.

In *duplicate bus-bar arrangement* there are usually seven zones :

— circuit-breaker zones

— two bus-bar-isolator zones

— two bus-bar zones

— a circuit-breaker, isolator zone and circuit-connection zone

— a feeder zone including feeder isolator, bypassing isolator.

line side equipment.

17.5. USE A LOAD BREAK SWITCHES

In distribution systems, voltage upto 33 kV are used. The fault levels may not be high enough to justify the use of circuit-breakers economically.

In such cases, the load break switches are used in conjunction with H.R.C. fuses and circuit-breakers. Load break switches are capable of making breaking currents under *normal conditions.* They can carry the specified current of specified values for specified time. They are capable of making but not breaking, short circuit currents. Switch Isolators or Switch Dis-connectors combine the functions of switch and isolators. Load-break switches serve the following requirements :

— breaking rated currents.

— making rated currents.

— making specified S.C. currents.

— carrying specified short-circuit currents.

— interrupt small inductive, capacitive currents.

While selecting the schemes with load break switches, circuit-breakers or H.R.C. fuses should be provided at strategic locations so as to interrupt fault currents, since load break switches cannot do so. Fig. 17.12 illustrates typical uses of load break switches.

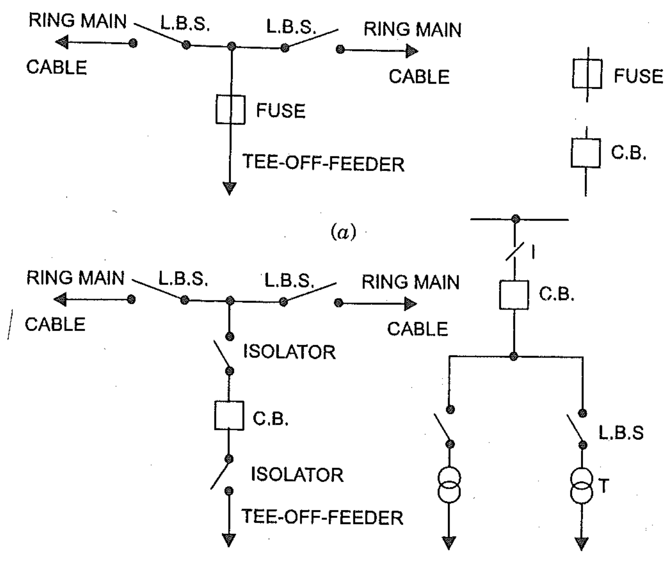


Fig. 17.12. Use of LBS (Load Break Switches) supplemented by CB or HRC Fuses.

17.6. SWITCHGEAR IN GENERATING STATIONS

The switchgear in generating stations can be classified as

— main switchgear — auxiliary switchgear

Main switchgear comprise circuit-breakers, isolators, busbars CT's, PT's etc. in the main circuit of generator associated transformers and transmission line. It is generally of EHV and outdoor type.

Auxiliary switchgear is generally indoor type and controls the various auxiliaries of the generator, turbine, boiler and the station auxiliaries. Auxiliary switchgear is at two or three voltage level such as 11 kV, 6.6 kV, or 3.3 kV, 415 Volts.

The ratings and requirements of main switchgear and auxiliary switchgear are quite different. Upto unit capacity of 200 MW, the auxiliary switchgear is generally at two voltage levels such as 6.6 kV and 415 V. For unit capacity of 500 MW. Three voltage levels are necessary, 11 kV, 6.6 kV, 400 V.

17.6.1. Main Switchgear Schemes

(*a*) Classical Method of Generator Connections

Generator voltage is less than 27 kV because of design considerations. The classical system consisted of connecting a number of generators to a common bus-bar through generator circuit-breakers. This system is used in many small medium sized stations and pumped storage schemes. With increase in the size of generator units, load and fault currents also increase and the classical system becomes technically unacceptable, and *unit system* is preferred.

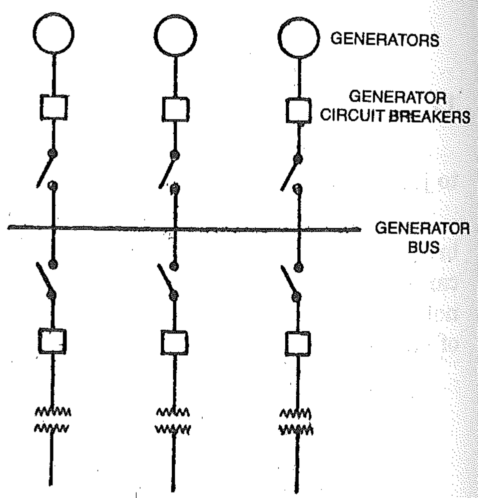
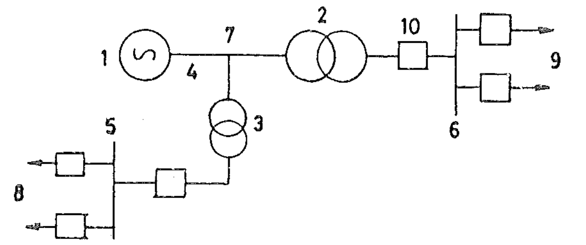


Fig. 17.13. Classical (old) system of generator connection, for small units.

17.6.2. Unit System of Generator Connections : (Scheme without Generator-Circuit-Breaker)

The standard ratings of generator-transformer units in Thermal and Nuclear Power Plants in India are : 200 MW, 236 MW (nuclear), 500 MW. Identical units are installed and are connected in parallel on HV side of main step-up transformer (generator transformer). *There is no circuit-breaker between the generator, generator-transformer and unit-auxiliary transformer.* Each unit has the following, (Ref. Fig. 17.14).



1. Main Generator
2. Main Unit transformer
3. Unit auxiliary transformer
4. Busduct between 1-2-3
5. Auxiliary Bus
6. HV Bus
7. T-off between 1, 2 and 3
8. Unit auxiliaries (motors etc.)
9. Transmission lines
10. Main C.B. Fig. 17.1.

Fig. 17.14. Unit system of generator connection.

Several identical units are connected to feed power to the EHV bus as shown in Fig. 17.19.

Each *Unit* has its own Boiler (Steam Generator). The various boiler auxiliaries, generator auxiliaries together are called *unit-auxiliaries*. The auxiliaries of the generator units are supplied power at 11 kV, 6.6 kV, 3.3 kV, 400 V AC. The power for the auxiliaries supplied by the same generator *via* the *unit-auxiliary transformer*.

The Auxiliary Switchgear in the power plant is an indoor metal clad drawout-type switchgear at 11 kV, 6.6 kV, 3.3 kV, 400 V AC.

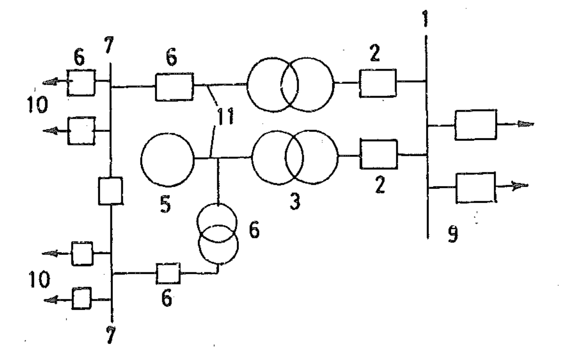
The main switchgear on HV side of the Main Unit Transformer is either 132 kV, 220 kV or 400 kV outdoor switchgear or a SF Gas Insulated Switchgear called GIS (Gas Insulated Substation).

In the conventional unit generator connection system (Figs. 17.14, 17.15 and 17.19, we do not need any circuit-breaker between the generator and main step-up transformer. The connection is direct by mean of Isolated Phase Busduct (Sec. 17.8).

The unit is started by taking auxiliary power from the main HV bus and the generator is brought to rated speed then rated voltage and then synchronized with the main HV Bus by closing the main circuit breaker.

Station Transformer

The *common station auxiliaries* like lighting, feed water pumps, air conditioning and cooling systems, battery-charging system, oil-filtration plants etc. are supplied power through the step-down station transformer (Fig. 17.15). The Starting power for unit auxiliaries is usually taken from the HV Bus *via* the station transformer. In some power plants, a quick staring gas turbine generator is provided for starting power and peaking power.

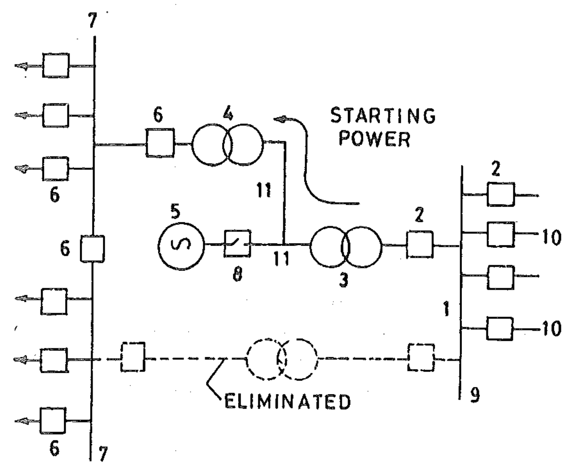


1. EHV bus
2. Circuit breaker
3. Main transformer
4. Auxiliary transformer of unit
5. Generator
6. Auxiliary C.B.
7. Auxiliary bus
8. Station service transformer
9. EHV yard
10. Auxiliary system
11. Isolated phase bus duct
12. Isolated phase bus-duct.

Fig. 17.15. Single line diagram-Unit system of generator-transformer connections in thermal power stations.

17.6.3. Unit Scheme Employing Generator Circuit Breaker

This concept was developed by European Companies during 1970s for unit ratings of 500 MW and above to minimise the installation cost. Fig. 17.16 is the schematic. The Gen. C.B. is connected between the Generator and the T-Off for Unit Auxiliary Transformer. The rating of Generator Breaker depends on MW rating and percentage impedance of the generator. The Generator-Breaker is either Air Blast Circuit Breaker or Puffer-type SF Circuit breaker. The three poles are enclosed in stainless steel or aluminium enclosures, and the enclosures are coupled axially with the bus duct.



1. EHV bus
2. Circuit breaker (EHV)
3. Main transformer.
4. Auxiliary transformer.
5. Generator.
6. Auxiliary transformer.
7. Auxiliary bus.
8. Generator circuit-breaker.
9. EHV-outdoor switchyard.
10. Transmission lines.

Note. Station Service Transformer (10) is eliminated.

Fig. 17.16. Scheme with Generator Circuit-Breaker.

With the generator breaker, while starting the unit, the generator breaker is kept open and the starting power for unit auxiliaries is taken from the HV bus *via* Main Unit Transformer.

The auxiliaries are started and the turbine is brought to rated speed. Then the excitation is increased till rated voltage of generator is reached. The generator is synchronised with the LV side of Main Unit Transformer by closing the Generator-Breaker. The input to turbine is increased and generator shares more load.

When generator breaker is switched off, the auxiliaries continue to get power from the main transformer. The Station Transformer is eliminated and this results in major reduction in capital cost.

Station Service Transformer is eliminated. Starting power for Auxiliaries is drawn from main HV bus.

Generator Circuit Breaker Scheme is not yet preferred in India as starting power is not easily available from other power stations *via* transmission lines.

17.6.4. Main Switchgear in Generating Stations

The power flow from the generator to the transmission system is *via* the main switchgear at 132 kV/220 kV/400 kV. The switchgear is either with outdoor SF_6 C.B. or with indoor SF_6 Gas Insulated Switchgear (GIS). Before 1980s the Air Blast Breakers and Minimum Oil Breakers were popular. They are not preferred any more and are found only in older installations (1985).

17.6.5. Single and Multiple Generator Transformer Unit

In single generator-transformer unit, transformer of almost same rating is provided with each generator. Three winding transformers are used where two values of high voltages are required (Fig. 17.17).

In multiple generator-transformer unit, two or three generators are connected to a generator

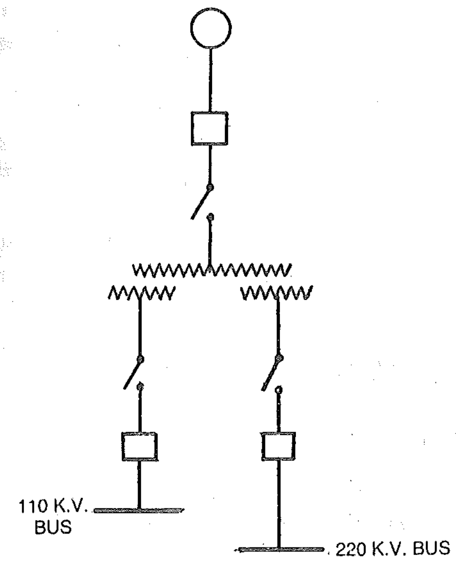


Fig. 17.17. Use of three winding transformer, single generator transformer unit.

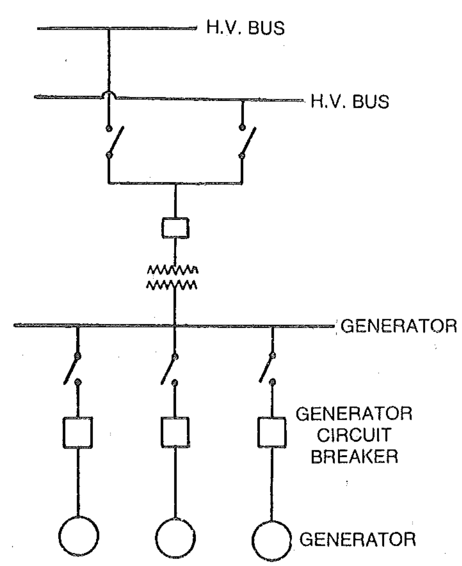


Fig. 17.18. Multiple generator transformer unit.

bus. Transformer is connected between the generator bus and high voltage bus (Fig. 17.18). Such scheme can be adopted in small hydro-electric power station, having unit size upto 15 MW and total transformer capacity upto 60 MW.

However, this scheme is not very common in modern thermal stations due to high capacity of modern turbo-generator (500 MW and above).

17.7. AUXILIARY SWITCHGEAR IN POWER STATIONS

The auxiliaries in thermal power station include boiler auxiliaries, condenser auxiliaries, generator and turbine auxiliaries, station auxiliaries, etc. The auxiliary motors are of rating, ranging from fractional horse-power to several thousand horse-power. The total power required by auxiliaries is of the order of 6 to 8 per cent of the station output. The purpose of auxiliary switchgear is to facilitate switching, control and protect of various auxiliaries. In 200 MW unit capacity class generating stations, the auxiliary system is generally at two voltage levels such as 6.6 kV and 0.415 kV.

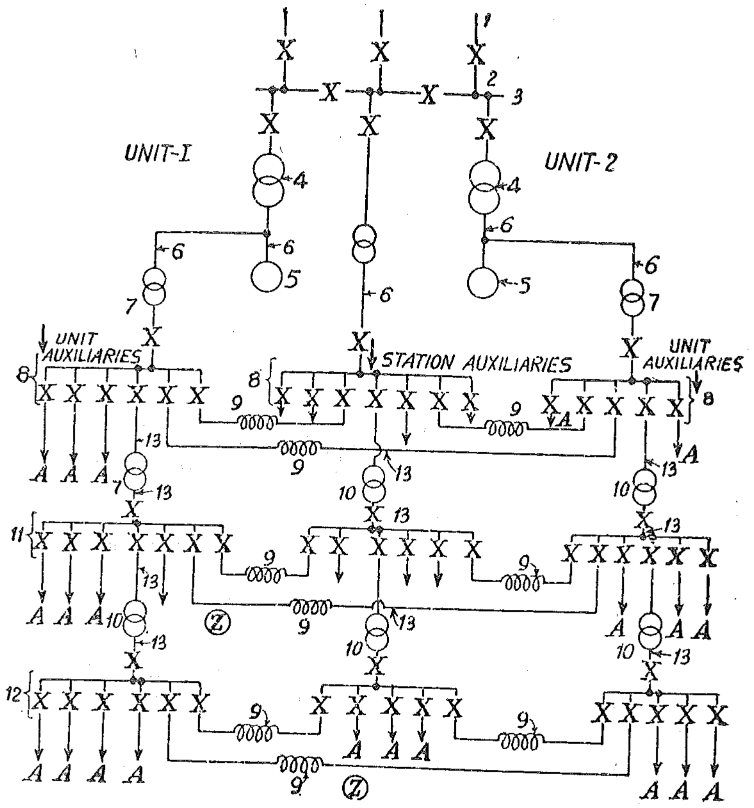
However, with 500 MW unit class power stations, three voltage levels, such as 11 kV, 6.6 kV, or 3.3 kV and 415 V are necessary, so that the auxiliary switchgear of enough breaking capacity can be installed. The auxiliaries concerned with the unit are called "Unit Auxiliaries", and are supplied by generator *via* the unit-auxiliary transformer, (Fig. 17.15).

The auxiliary of the station common to all the units are called Station Auxiliaries (Fig. 17.19).

To determine the rating of circuit-breakers in auxiliary system, the following aspects should be considered :

— Fault level at H.V. bus.
— Contribution to fault current from H.V. bus *via* the starting transformer.
— Contribution to fault current *via* the station service transformer. (Fig. 17.15)
— Contribution to fault current by the large auxiliary motors.

Typical rating of circuit-breakers in auxiliary system are as follows :



1 — EHV transmission line.
2 — EHV switchgear generally outdoor.
3 — EHV bus, generally outdoor, sectionalised.
4 — Main transformer of generator transformer unit (outdoor) Rating almost equal to that of 5.
5 — Turbo generator (indoor).
6 — Isolated phase buses, continuous type (Fig. 17.21).
7 — Unit auxiliary transformer (rating about 6 to 8%, that of 5).
8 — Auxiliary switchgear (say 12 kV).
9 — Current limiting reactors, switched during emergency or starting.
10 — Auxiliary transformers.
11 — Auxiliary switchgear (say 7.2 kV).
12 — Auxiliary switchgear (415 V).
13 — Metal enclosed conductor, Fig. 17.20.
A = To auxiliary equipment
X = Switchgear
Z = These interconnections are generally omitted.

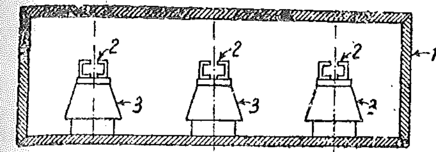
Fig. 17.19. Auxiliary switchgear for a thermal power stations.

Table 17.1

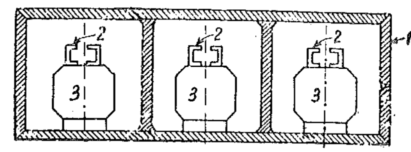
Rated voltage kV	*Breaking capacity MVA*	*Normal current ratings A*
12	1000 750 500 350	400, 800, 1200, 1600, 2000, 3000, 3500
7.2	500 350 250	400, 600, 800 1200, 1600, 2000, 2400
3.6	250 150	400, 600, 800, 1600 2000, 2400
0.415	31 26 15	400, 500, 800, 1200 2400

The auxiliary switchgear is indoor type. Similar units are installed side-by-side. The following type of circuit-breakers are used in drawout type metal enclosed indoor auxiliary switchgear (Refer Sec. 15.4).

— Air-break circuit-breaker, with magnetic arc elongation (for LV).
— Vacuum circuit-breakers with RC surge suppressors. (Refer Sec. 15.5)
— SF_6 circuit-breaker (Refer Sec. 15.27).



(*a*) Non-segregated bus ducts at 415 V.



(*b*)

1. Metal Enclosures Fabricated, Aluminium/Steel
2. Conductors, Aluminium Channels (or Flats)
3. Insulators (Porcelain or Resin Cast)

Fig. 17.20. Segregated enclosures of conductor used for auxiliary system at 6.6 kV or 11 kV.

17.8. ISOLATED PHASE BUS SYSTEMS (Fig. 17.21)

The conductors between generator, unit transformer, unit-auxiliary transformer are enclosed in hollow, tubelar aluminium enclosures. The enclosures are continuous* and are connected in star and earthed at each end. The conductors are supported on epoxy insulators within the enclosures. Such a system is called Isolated Phases Bus System, and is used in all thermal power stations having generator rating of 60 MVA and above. The eddy currents induced in the enclosures flow longitudinally in the enclosures. Thereby they produce associated magnetic-field outside and within the enclosures. This field interacts with the field of the main conductors. As a result, in case of isolated phase bus system, the magnetic-field is substantially reduced, outside the enclosures. Thereby the electrodynamic forces between main conductors during external short circuits are substantially reduced. (To about 5% of their value without enclosures.) Therefore, the insulator design is simplified. Heat is produced in the enclosures as well as in the conductors. Upto normal current ratings of 20 kA, air natural cooling may suffice. Between 20 kA and about 40 kA normal current rating forced air cooling is preferred. Above 40 kA conductors are water cooled. Maximum permissible temperature of conductors and enclosures is of the order 85°C. The design is such that the enclosure current is almost equal to conductor current. Aluminium conductors are of octagonal or double-channel or tublar cross-section. Enclosures are also aluminium [Refer Fig. 17.21 (*b*)].

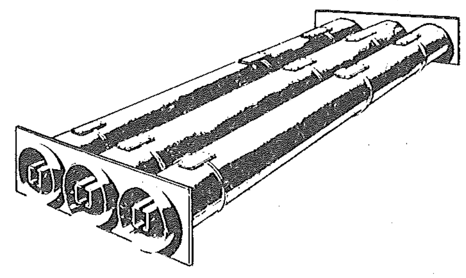
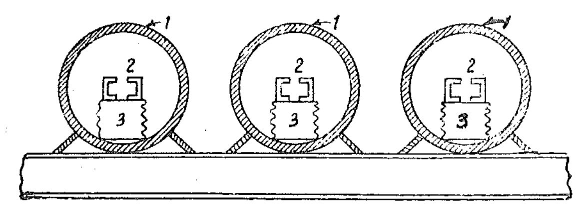


Fig. 17.21. (*a*) A view of isolated phase bus duct (continuous type enclosures)



1. Enclosures, Tubular Fabricated, Welded, Continuous Construction of Aluminium Earthed and Star Connected at both ends, Insulated from Generators and Transformers.
2. Aluminium Conductors
3. Insulators Support, Porcelain or Synthetic Resin Cast.

Fig. 17.21. (*b*) Isolated phase bus system for conductors between generators and main transformers.

* For normal currents above 4 kA, continuous type enclosure is preferred [Fig. 17.21 (*b*)]. For currents less than 4 kA discontinuous enclosures may be used.

In continuous type of design of bus-ducts, the sections of each enclosure are welded to get continuous run. In discontinuous type design, the next section is insulated from the previous one, see Note as below.

The advantages of Isolated Phase Bus System include :

— Reduced electrodynamic forces between conductors during short-circuit conditions, hence simplified insulator design.
— Almost, total absence of faults in bus section.
— Safety of personnel.
— Reduced maintenance.
— Magnetic shielding, no induced current in neighbouring metallic frame works, reinforcements, etc.

Generator circuit-breakers, discussed earlier, are also enclosed in continuous metal enclosures. Thereby the advantages mentioned above are inherited by the generator circuit-breakers too.

The conductors of auxiliary system are enclosed in segregated or non-segregated metal enclosures [item 13, Figs. 17.19 and 17.20]. Such enclosures are compact and minimise the phase to phase faults.

They are dust-proof, vermin proof water-proof, and ensure maintenance free and fault free service. The enclosures of segregated bus ducts are made of fabricated, rolled steel sections, to which steel sheets are welded or screwed. The construction is generally made of standard section of about 2 metres length connected lengthwise. The thickness of sheets should be above 2 mm.

17.9. CONTINUOUS HOUSING TYPE ISOLATED-PHASE BUSES

The high-capacity and high-safety, continuous housing-type isolated bus employed in power stations and substations represents one of the most reliable current buses.

As shown in Fig. 17.22, each phase conductor is separately enclosed in a metal housing, and the housing units are connected electrically. Housings of three phases are short-circuited on both ends to enable current to circulate sufficiently. Since the circulating current is approximately as much as 95% of the conductor current, it greatly reduces the external magnetic field produced by the conductor current. Accordingly, the larger the conductor current is, the greater effect is demonstrated.

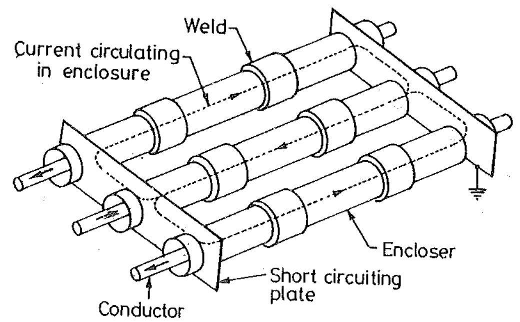


Fig. 17.22. Fundamental Principle of continuous Housing Type Isolated-phase Bus

ADVANTAGES

1. **Nonexistence of Phase-to-phase Faults.** Each phase conductor is enclosed by an individual metal housing separated from adjacent conductor housings by an air space. This design prevents phase-to-phase faults from occuring.

2. **Large Momentary Current Strength.** Since the metal enclosure has an electromagnetic shielding effect, the electromagnetic force on phase conductors is reduced to approximately 1% in an AC magnetic field, and to 3% in an AC magnetic field caused by short-circuit current with a maximum DC component, compared with electromagnetic force on a phase conductor without enclosure.

Furthermore, the bus conductors are a channel type, with a large section modulus, for this reason, and due to the high mechanical strength of insulators supporting the bus conductors, the buses have ample momentary current strength.

4. **Free from Electromagnetic Inductive Overheating and Inductive Interference.** The external leakage magnetic flux is very slight, rendering practically negligible inductive overheating on the peripheral steel structures and pipings and inductive interference on adjacent control wiring.

5. **High Current Carrying Efficiency.** Bus bar conductors are the channel type which displays very little skin effect and has a large cooling surface. The conductor surface and the interior of the enclosure are painted for efficient heat dissipation. As a result, temperature rise is small and current carrying efficiency is quite high.

6. **High Airtightness.** Standard connections between the housing units are welded, presenting a completely enclosed construction having a high airtight characteristic.

7. **High Dielectric Strength.** The bus conductors are supported on corrugated insulators with high dielectric strength to prevent insulation deterioration.

8. **Reduced Maintenance.** Construction itself is simple, and all standard joints are welded. Moreover, the metal housing prevents infiltration of dirt and dust. Actually, maintenance and inspection are practically unnecessary.

9. **Simpler Installation.** Each unit is shipped to the site in a completely assembled state, after having been fully built, factory-tested and packed, permitting the buses to be easily installed at the site and requiring little incidental construction work. Overall construction costs are thus reduced.

CONSTRUCTION

1. **Conductor Support.** The support used for each bus conductor is of high-strength construction which ably withstands large electromagnetic forces. To allow for free expansion and contraction of the conductor caused by temperature changes, one of the conductors in each unit is fixed, while the other is loosely supported in the axial line.

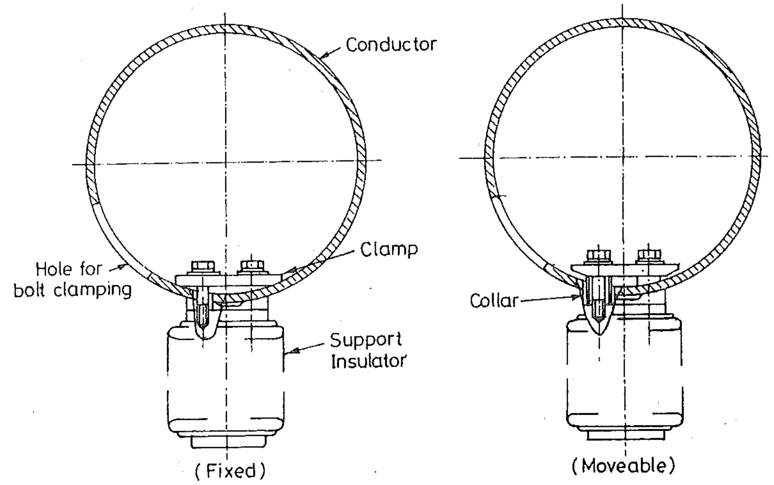


Fig. 17.23 Conductor Support (Rated current: 6,000 A and above)

2. **Inspection Cover.** A watertight inspection cover is provided on the enclosure for assembly and inspection. This inspection cover is a clamp-on type (shown in Fig. 17.25) for easy removal.

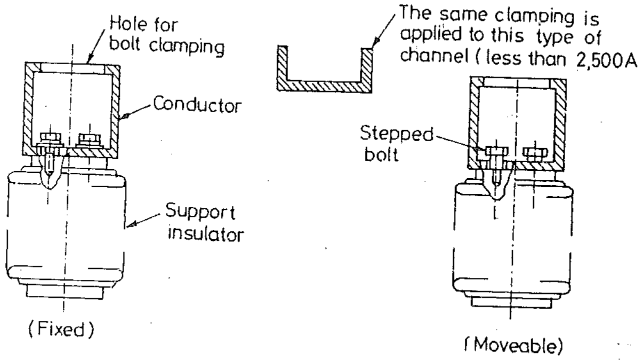


Fig. 17.24 Conductor Support (Rated current: Less than 6,000 A)

3. **Connectors.** An expansion connector composed of aluminium sheet layers is used as a connector between the conductors. One side is welded at the factory, and the other side is welded after installation to ensure completely welded construction. The enclosure is connected at the installation site after connection of the conductor, eliminating bothersome maintenance and inspection after operation.

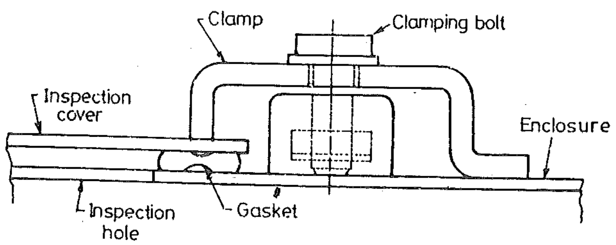


Fig. 17.25 Hinged part of inspection cover.

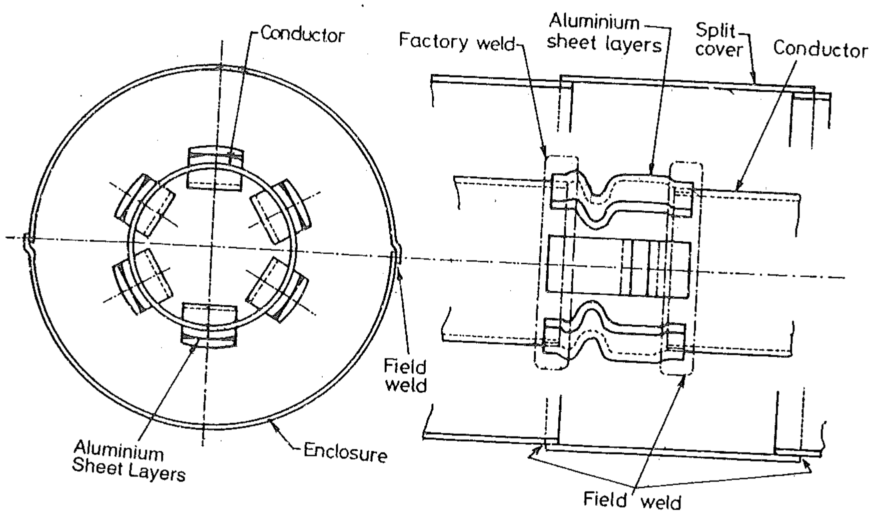


Fig. 17.26.

4. **Wall-penetrated Portion.** As shown in Fig. 17.28, the flanges of the enclosed buses are attached to the frame embedded in the building wall. A seal-off bushing is used (see Fig. 17.29) to close off air circulation.

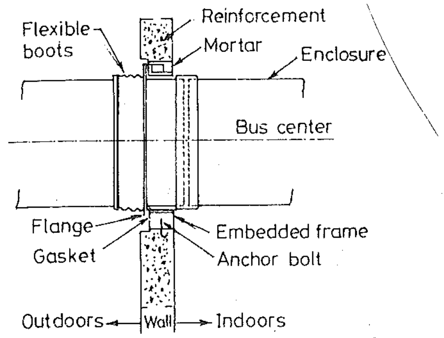


Fig. 17.27. Wall-Penetrated Portion

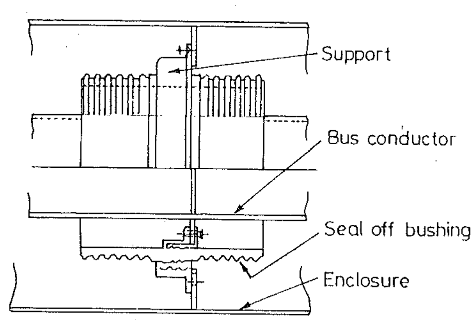


Fig. 17.28 Construction of Seal-off Bushing

5. **Flexible Connectors.** For protection against vibrations and possible foundation sinking the connections with generators and heavy transformers - as well as those in the wall-penetrated portion - are of special flexible construction. Flexible copper braids with adequate slack are used in the bus conductor connections to prevent undue stress from affecting the conductors and the terminals of machines.

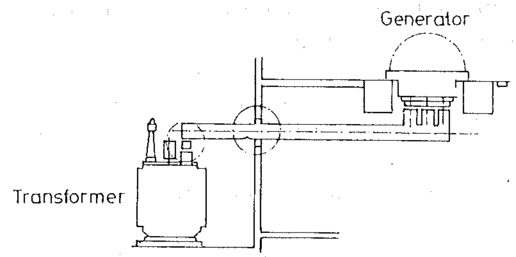


Fig. 17.29. Example of Installation of an Isolated-phase Bus

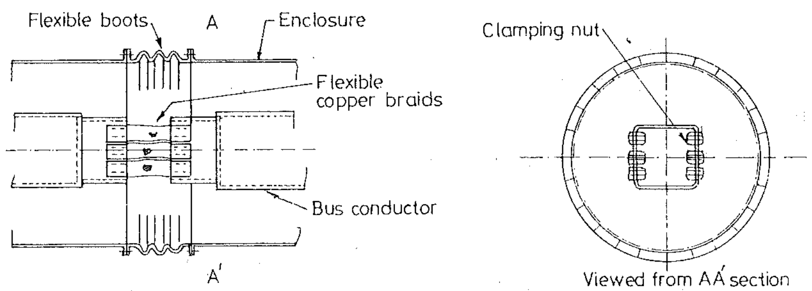


Fig. 17.30. Construction of Flexible Connector

BUS TRUNKING SYSTEMS

Busbar Trunking System is the modern factory built Electrical Distribution System designed not only as an alternative to cables but have many advantages over conventional cable distribution system is fast becoming Industry/building standard for future. Decentralized distribution is the main highlight of this distribution system *i.e.* each equipment/appaliance used in the installation is protected immediately by a protective device & can be maintained individually without disturbing other distribution networks thus reducing downtime. This system also eliminates separate requirement of distribution & panel boards. Loads can be fed from Plug-in Boxes unlike cables where each floor/machine is to be fed separately from the main switchboard. Furthermore, this system can be installed quickly with minimum technical expertise.

COMPACT LOW IMPEDANCE SANDWICH BUS TRACKING - TECHNICAL FEATURES

Insulated Sandwich Bus Trunking is prefabricated, pre tested system in standard length and shapes available in Copper and Aluminium in ratings from 500A to 5000A suitable for system voltages up to 1000V. These can be used as rising mains and for horizontal power distribution. It consists of three phases and neutral conductor with option of pre decided specifically located Plug-in points. The basic construction and assembly features of these systems make them different from other systems. Busbars are insulated from each other by electrical insulating materials throughout it's length except at joint and Plug-in points, and are tightly packed in enclosures (bolted at regular intervals).

STANDARDS AND SPECIFICATIONS

- Equipment is designed for low voltage power distribution as per IEC 60439 (1 & 2) and IS 8623 (1 & 2)
- System is designed for rated operational and insulation voltage - 1000VAc, rated impulse withstand voltage-12kV and rated frequency of 50 Hz.
- SBC: Copper bustrunking available from 800A to 5000A (3ϕ, 4W) and SBA: Aluminium bustrunking is available from 500A to 3600A (3ϕ, 4W).
- Bustrunking enclosure is made of CRCA/G.I. sheet of 1.6 mm (16 SWG) with anti corrosive coating and finally epoxy polyster powder coating of flint grey shade (RAL-7032).
- Busbars in SBC type are made of 99.9% pure ETP grade Copper, whereas busbars in SBA type are made of 99.5% pure, 19501 grade aluminium. Busbars are with full round edges for easy insertion/withdrawal of Plug-in boxes and joint blocks.
- Earthing: Internal earth of G.I/Copper of cross-section equal to 50% of phase (option-1) and External earth of Cu/Al of desired section can be provided, duly riveted/bolted along with bustrunking enclosure (Option-2).
- As a standard practice, degree of protection is IP-54 for Plug-in type and IP-55 for feeder type bustrunking.
- Individual busbars are covered with multi layers of F-class flexible insulation material to achieve excellent mechanical and electrical strength even at high temperatures and humid condition. Continuous insulation has low water absorption and no possibility of pin holes and insulation cracking.
- System is designed for ambient temperatures of 40°C with temperature rise of 55°C on bustrunking as per standards.
- Three plug-in outlets on front side of 3 mtr section can be provided as standard, (5nos. max on special request).

ADVANTAGES

- Close proximity of busbars doesn't allow mutual inductance between phases yielding low reactance, low impedance, low voltage drop and low power loss.
- Specially designed housing bolted at every 250 mm act as a heat sink to yield improved thermal characteristic, high mechanical and short circuit strength.
- Due to compactness system can be installed in lesser space.
- System is maintenance free and adds elegance to the surrounding.
- Due to elimination of air there is no rise of chimney effect, so no fire barriers are required.
- Automatic polarity is maintained during installation.
- System can be mounted edgewise OR flatwise, horizontally or vertically in any direction with all kinds of bends and tees etc.
- Flexible and safe distribution system leads to easy and fast installation. System is completely re-usable.

- Any section of bustrunking can be removed without disturbing adjacent sections.
- Joint assembly can be removed/installed at any time to isolate/join two sections of bustrunking in installed condition.
- Disc spring washer are used in Uniblock joint to uniformly distribute pressure. The disc spring washers accomodates the thermal expansion of the busbars and housing at joint area.
- Plug-in boxes with MCCB/SFU's/Fuse holders or load break switches can be provided with door interlocking and interlocking with bustrunking to ensure "Plug-in" and "Plug-out" possible only in 'OFF' condition.
- Extra safe cable connection in plug-in boxes without additional cable support.
- Plug-in boxes can be easily mounted, ensuring 100% automatic polarity.
- 4 Pole isolator is provided in Plug-in boxes upto 125A for extra safe connection on live bustrunking. All plug-in boxes are compatible with all ratings of bustrunking.
- Safe, easy and quick plug-in/plug-out is possible on live bustrunking. Earth contact of Plug-in boxes with bustrunking makes before phase and neutral and is last to break when removed.
- Each Plug-in box has three gland plates to connect cables from any three direction after providing cable glands.

OTHER COMPONENTS

1. **Reducer.** These are required to connect two dissimilar rating/type of bustrunking. Reducer may be designed with switching or isolating device.

2. **Sectional Isolator Unit.** These are required to isolate the bustrunking run in between, for various reasons. Section Isolator Unit can be fitted with Load Break Switches/SFU's/MCCB's.

3. **End Cover.** These are provided to close the open end of Rising main/bustrunking at the end and it provides necessary IP level.

4. **Vertical Support.** One set of Vertical Support is generally provided per floor per rising main along with rigid or spring hanger (as applicable) when the floor height is more than 3.5 mtrs to avoid horizontal swing in bustrunking sections.

5. **Wall/Floor Flange.** These are plates designed to cover the cut-out made for passing bustrunking through walls or floor. WALL/FLOOR flanges are required to be fitted to the both sides of wall or floor. When using the flange together with floor support in case of rising mains. These are placed between the floor and base channel.

6. **End Feed Box (Direct).** To feed bustrunking through cables, Direct End Feed Unit (EFU) is available with sufficient space for direct connection through lugs and bolts. MCCB, SFU, Isolators and Fuse Holders etc. can be fitted in End Feed Unit as per specific requirement. 375 mm length of bustrunking is integrally fitted (measured and charged with bustrunking) along with End Feed Unit as standard practice so that joint between End Feed Unit and bustrunking is exactly same as of two normal bustrunking lengths. Undrilled cable gland plate is provided for multiple cable feeding option. End Feed unit can be made LHS or RHS type as per site requirement.

7. **Flanged End Box (Adaptor Box).** Flanged End Box is used to accomodate Flange End and connect it to Panel or Transformer through flexible connections. It differs from End Feed Unit since it does not have any integral bustrunking length.

Flanged End Box may be provided with necessary busbar arrangement for phase matching of bustrunking with equipment and usually contains openings/window for busbar accessibility.

8. **Expansion Unit.** It is usually recommended to be installed after at every uninterrupted run of 50 mtrs to accomodate for composite expansion of complete bustrunking run. Expansion duct

is set by fixing bolts to prevent duct expansion during transit and installation. After complete installation, the fixing bolts are removed to allow thermal expansion of bustrunking at full load.

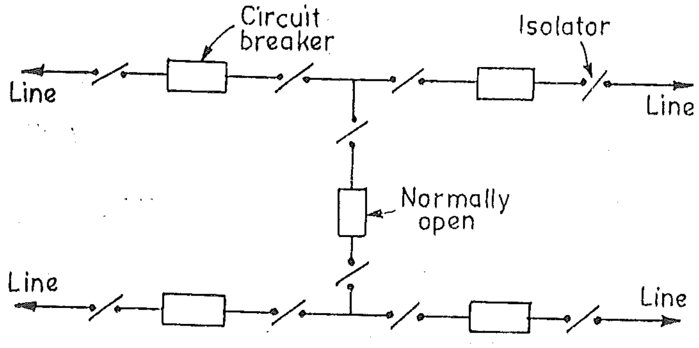
9. **Fixed Tap-off Provision (500-800A).** It is specially designed Tap-Off Point along with Tap-Off Box arrangement provided on main bustrunking as per the requirement ready to use MCCB/SFU etc.

TYPICAL APPLICATIONS

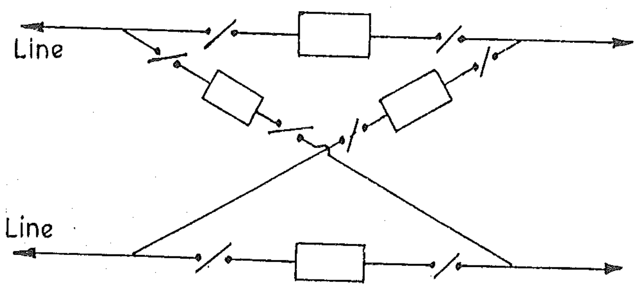
— Typical applications mainly includes Rising Mains, Horizontal Power Distribution, Transmission of power from Transformer to Switchgear, Generator to Switchgear & Switchgear to Switchgear as shown below :

17.10. SWITCHING SUB-STATIONS

There are several sub-stations between generating stations and final load points. They generally comprise step-down transformers and switchgear. In case no transformer is involved, the sub-station is called switching station (Fig. 17.22).



(*a*) With five breakers.

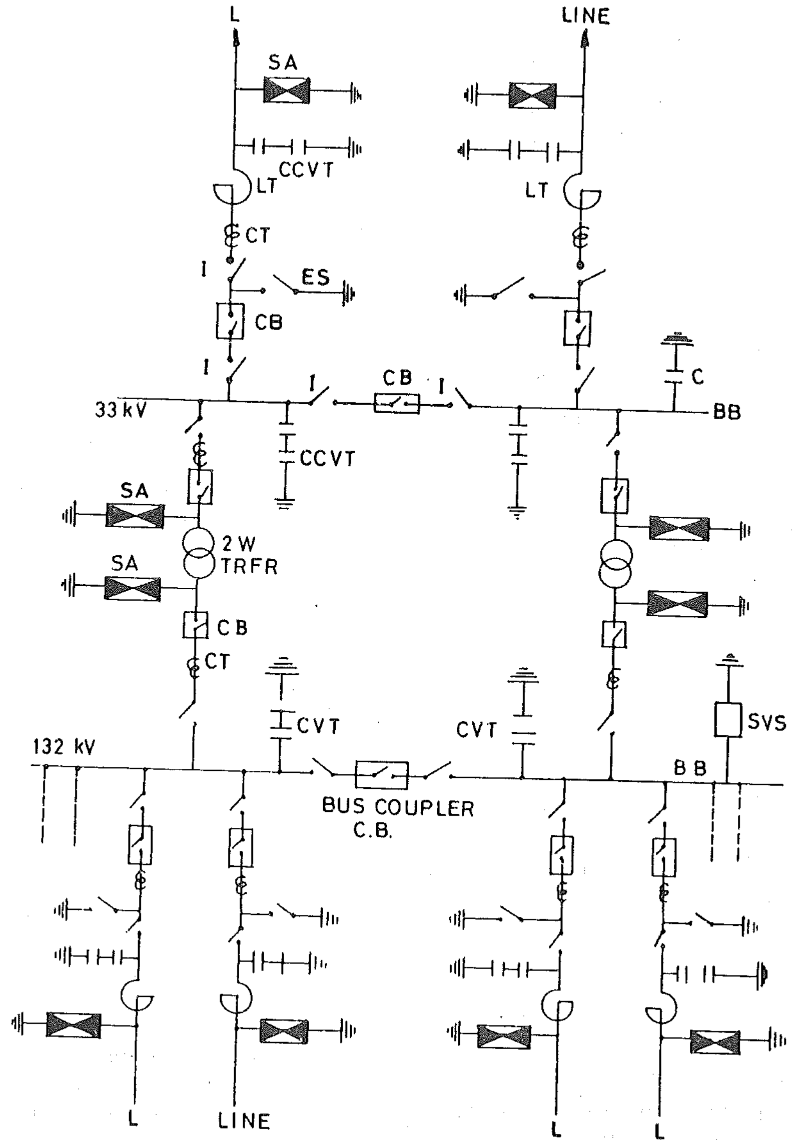


(*b*) With four breakers.

Fig. 17.22. Intermediate switching station with two incoming lines and two outgoing lines.

17.11. LAYOUT THE SWITCHYARD EQUIPMENT

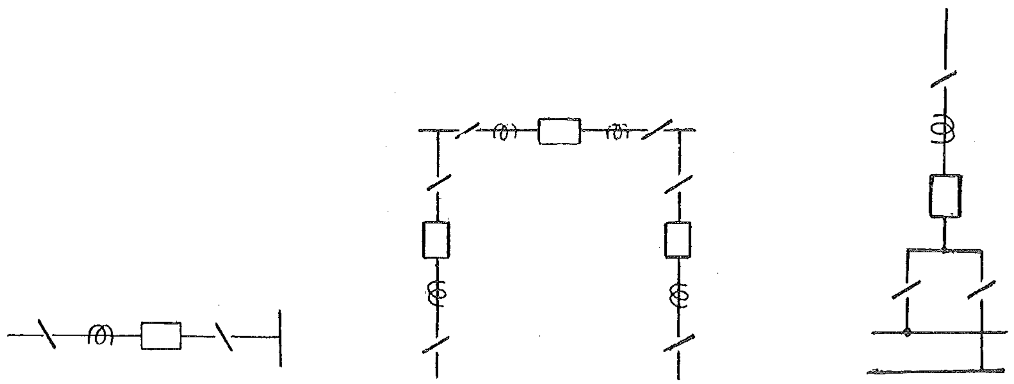
Fig. 17.23 gives the layout of switchyard equipment of a receiving station having two incoming lines and four outgoing lines. In this figure CT's and PT's are not shown. There can be several possible arrangements. The figure shows a single bus-bar arrangement [Refer Fig. 17.7 (*b*) for a typical side view].



L — Line
BB — Busbar
LT — Line trap
ES — Earthing switch
SA — Surge arrester
CB — Circuit-breaker
I — Isolator
CT — Current transformer
VT — Voltage transformer
CCVT — Coupling Capacitor and Voltage Transformer.
3W — Three-Winding Transformer CVT — Capacitor Voltage Transformer

Fig. 17.23. Single line diagram of a substation with single-busbar scheme.

17.12. LOCATION OF CURRENT TRANSFORMERS



(a) Single bus-bar arrangement.

(b) Sectionalised single bus.

(c) Duplicate bus.

Fig. 17.24. Location of CT's.

17.13. TYPICAL SUBSTATION IN DISTRIBUTION SYSTEM

In 11 kV distribution system, the cost of elaborate protection may not be justified for protecting transformers upto about 500 kVA. The sub-stations are generally unattended. In such cases H.V. Fuses such as drop-out fuses is the only protection provided on h.v. side. Hence the scheme for such sub-stations is very simple (Fig. 17.25). The fuses should be coordinated.

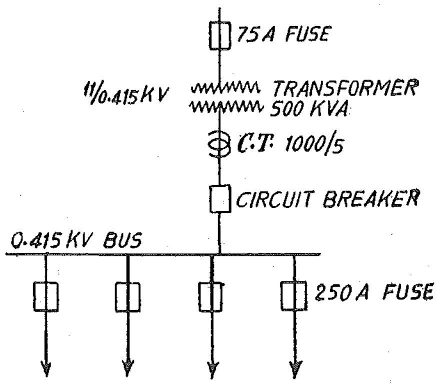


Fig. 17.25

17.14. SWITCHGEAR FOR A MEDIUM SIZE INDUSTRIAL WORKS

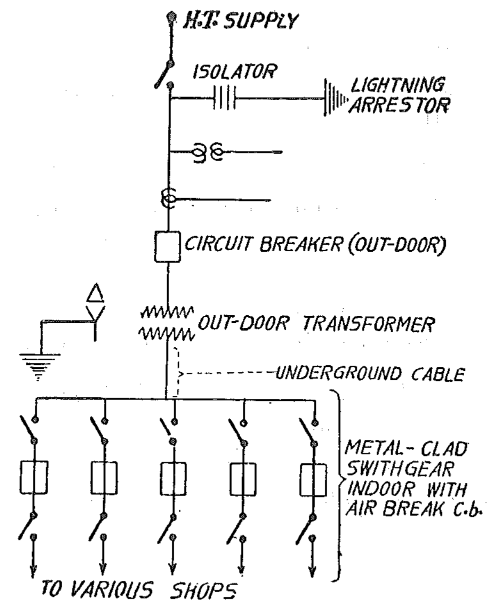
The switchgear in the sub-station of local points, such as industrial works, railway track-side sub-station, cinema houses, large buildings, foundries, etc. come in a variety of forms. Their requirements vary depending upon fault levels, kVA rating, voltage rating and other local requirements. In general the sub-station comprise the following :

— incoming line section — transformer section
— secondary switching section.

Incoming line section may comprise outdoor circuit-breaker or drop-out fuse, or it may comprise metal-clad switchgear. Draw-out type switchgear may be used for indoor installation. The secondary switching section can have one of the following forms :

— Draw out type switchgear with air circuit-breakers or vacuum or SF_6 C.B.
— Stationary moulded case or miniature circuit-breakers.
— Motor control centres.

Fig. 17.26 illustrates two typical schemes. Recently, SF_6 GIS has been introduced for 11 kV and 33 kV substations.



(a)

Fig. 17.26. Typical switchgear arrangement for medium size factory, incoming sub-station.

17.15. BUS-BARS

The 'Buses' concerned with switchgear do not have any wheels, not do they transport people. However, they all called buses, perhaps due to their commonness with omnibuses that they do have conductors and do transport electric current. Earlier, the conductors to which several local feeders or sources are connected were called Buses. Now the conductors carrying heavy currents are also called Buses. The standard definitions are given below :

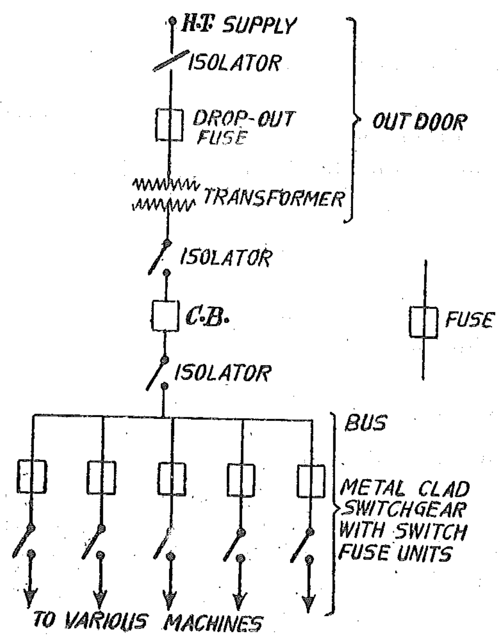


Fig. 17.27. Typical switchgear arrangements for medium size factory, incoming sub-station.

17.16. SOME TERMS AND DEFINITIONS

(a) *Bus-bars.* Conductors to which a number of circuits are connected.

(b) *Bus-bar connection.* The conductors that form the electrical connection between the bus-bars and individual piece of apparatus.

(c) *Open bus-bars.* The bus-bar which does not have protective cover.

(d) *Enclosed bus-bar.* The bus-bar that is contained in a duct or a cover of any material. The bus-bar enclosed in metal enclosures are called metal enclosed bus-bars. The enclosures are either of aluminium or sheet-steel.

(e) *Outdoor bus-bars.* An open or metal enclosed bus-bars designed for installation under open sky. Outdoor busbars are supported on glazzed porcelain insulators.

(f) *Indoor bus-bars.* The bus-bars designed for indoor use.

(g) *Compound immersed bus-bars.* Enclosed bus-bars immersed in liquid or semi-solid insulating materials.

(h) *Oil immersed bus-bars.* (i) *Solid-insulated bus-bars*

(j) *Compressed gas insulated bus-bars.* Bus-bars enclosed in enclosures filled with gas at a pressure above atmospheric pressure.

(k) **Ratings**

(i) *Rated current (Normal Current Rating).* The rms value of current which the bus-bars can carry continuously with temperature rise within specified limits. The standard values are the following.

200, 400, 600, 800, 1200, 1600, 2000, 2400, 3000 Amperes.

(ii) *Rated voltages.* The rms values of voltage, between lines for which the bus-bars are intended. Standard values are the following (in kV):

0.415, 0.6, **3.3, 6.6, 11,** 15, **22, 33,** 110, **132, 220, 400,** 500, 765 kVrms.

Note : The preferred voltages are printed in bold print.

(iii) *Rated frequency.* usually 50 Hz. (60 Hz. in USA).

(iv) *Rated short-time current.* This corresponds to the shortime current rating of circuit-breakers/switches/isolators. It is defined as the rms value of the circuit which the bus-bar can carry, with temperature rise within specified limits; for a specified duration.

The specified limits are :

Ambient temp. average	: 35°C
Ambient temp. peak (1 hr.)	: 40°C
Temp. rise permitted	: 40°C
Short time current duration	: 1 sec. or 3 sec.

17.17. MATERIALS FOR BUS-BARS

Copper and aluminium are used for bus-bars. Copper being scarce and costly, aluminium is being increasingly used for bus-bars. The material used for bus-bars should have low resistivity, higher softening temperature, good mechanical properties and low cost. During 1960's the need for substituting the copper with aluminium became very urgent, particularly in countries like India who import copper. Now aluminium is being increasingly used for various switchgear applications.

Table 17.2. Properties of Pure Aluminium and Copper*

	Property	*Units*	*Copper*	*Aluminium*
1.	Electrical resistivity at 20°C	$\frac{\text{ohm. mm}^2}{\text{m}}$	0.017241	0.02828
2.	Temp. Coefficient of resistivity	$°C^{-1}$	0.00411	0.00403
3.	App. softening temperature	°C	200	180
4.	Thermal conductivity	$\frac{\text{Cal}}{\text{cm. sec. C°}}$	0.923	0.503
5.	Melting point	°C	1083	657
6.	Density at 20°C	g/cm^3	8.94	2.703

Copper. The electrical and mechanical properties of copper are influenced by impurities and manufacturing process. The impurities increase the resistivity but are sometimes necessary to get desired properties. In many cases, where extreme mechanical properties are not desired, 'high conductivity electrolytic tough pitch copper' is used. 'Tough pitch' indicates that the oxygen contents are controlled within close limits. The conductivity of tough pitch copper with oxygen content of about 0.02 to 0.04 per cent is about 100 per cent I.A.C.S. (International Annealed Copper Standard). Electrolytic copper should have minimum 99.9 per cent copper by weight.

Copper is used in the form of rods, strips, various sections like angle, channel etc., the latter being preferred for high values of currents.

Copper starts becoming soft at 200°C. Hence the permissible maximum temperature short-circuit condition is 200°C. Copper oxides quickly at temperatures above 85°C. Hence, for normal currents, the maximum temperature permissible is 85°C.

At present, the trend is toward using copper where space required is minimum and quantity is not large. For large requirement of quantity, aluminium being preferred, as its use is economically justified.

Aluminium. Aluminium is used for bus-bars of indoor and outdoor switchgear.** Aluminium is also used for enclosures and conductors of Isolated Phase Bus Systems in generating stations. Aluminium is now being used for primary tubes of current transformers, current carrying blades of isolators, conductors in SF_6 switchgear, etc. Aluminium castings (5 to 12% silicon) are used in assembly bus-bar. Aluminium castings are used in the framework of circuit-breakers where weight should be minimum. Aluminium is used in form of strips (thickness above 2.5 mm), rectangular bars (width above 10 mm), round bars (diameter above 10 mm), for bus-bars applications. For heavy currents, channels and angle sections are used. While using aluminium for bus-bars, the difficulties arise due to the following aspects :

1. Higher resistivity, hence associated problems of temperature rise.
2. Lower tensile strength than copper.
3. Lower thermal conductivity than copper.
4. Higher coefficient of linear expansion than copper.
5. Higher joint resistance and associated problems about jointing.
6. Special welding techniques are necessary.

The following procedure is satisfactory for making bolted or clamped joints in bus-bar and connections of switchgear (between aluminium and aluminium) :

1. Clear the bus-bar joint surface with rough emery.
2. Apply an oxide inhibiting grease on the prepared joint surface immediately. The grease*** is applied to prevent the exposure of prepared surface to air and moisture.

* Properties vary with alloying and manufacturing process. The figures given in the table are for reference alone.

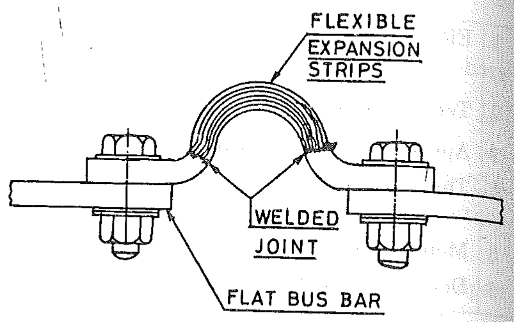
** Aluminium for bus-bars : EIE – M, IS 5082, E91E – WP, IS 5082.

*** Esso Multipurpose Grease H Caltex 2. Indian Oil Multipurpose Grease.

3. Make joint as early as possible, (within about 2 hours) by bolting or clamping.

Aluminium to copper joints present a problem that the resistance of joint increases with time, due to bimetallic corrosion. While making such joints copper bus-bar areas are tin-plated or silver plated. The aluminium bas-bar areas are prepared as described above. Then the joint is made.

Another method is to use bimetal strips with aluminium on one side and copper on the other. These plates are used for making A1-Cu joint. Such joints are used in Europe for outdoor constructions. The joints resistance after four days should be less than about 20 micro-ohms for busbars of indoor switchgear. The pressure between contacts should be adequate.



(Thin-aluminium strips welded to the bus-section.)
Fig. 17.28. Flexible joints.

The desired length of bus-bars is obtained by connecting required number of sections of standard length [2 to 6 metres]. The joints between neighbouring bus-bars sections are made either by welding or bolting or clamping.

Expansion joints should be provided when the length of bus-bars become significant. Flexible joints are necessary when the bus-bars terminate in switchgear or transformer terminals.

17.18. BUS-BAR DESIGN

(a) TYPES OF CONSTRUCTIONS

— Indoor or Outdoor
— Open or Enclosed
— Non-segregated metal enclosed bus ducts.
— Segregated metal enclosed bus ducts.
— Isolated phased bus ducts of continuous type or discontinuous types.
— Rigid Tubular
— Flexible ACSR

Enclosed bus-bars. The bus-bars are rigid conductors of aluminium or copper supported on support insulators. The assembly is supported on fabricated rolled steel sections and is enclosed by sheet steel or aluminium sheets.

Non-segregated Bus Ducts. The conductors of the three-phases are in a common metal enclosures with metal insulator barriers between them (Fig. 17.20).

Isolated Phase Bus Systems. The conductors of each phase is enclosed in a separated metal enclosures (Fig. 17.21 *a*, *b*).

Isolated Phase Bus System of Discontinuous Type. The Isolated Phase Bus System in which the enclosures are made up of units of standard length are jointed to get desired total length. The neighbouring enclosures are insulated from each other and are electrically discontinuous.

Isolated Phase Bus System or Continuous Type. The enclosures are electrically continuous throughout their length. The three enclosures are connected in star and earthed at each end. The enclosures are insulated from the terminal apparatus.

(b) TEST ON BUS-BARS

1. *Temperature Rise Test (Heat Run).* Rated current is passed and final steady temperature rise is noted. [Refer Sec. 10.22]

Temperature rise permitted	: 35°C/40°C
Ambient Temperature	: 40°C Maximum
	: 35°C Average.

2. *Rated short time current test.* This test is described in chapter 'Short-Circuit Testing of Circuit-Breakers'. [Ref. Sec. 11.6.]

3. *Rated Momentary Current Test.* This test verifies whether the busbars withstand the rated peak value of the first major cycle on short circuit. [Refer : Making Current, Sec. 3.19.5]

4. *High Voltage Test.* Power frequency voltage test; Impulse voltage withstand test, if necessary. [Refer Sec. 12.6]

(c) DESIGN CONSIDERATIONS

(*i*) *Materials.* Copper was used for electrical busbars and is now almost totally replaced by aluminium. Aluminium is now used for busbars in generating stations, sub-stations, transmission and distribution systems, indoor and outdoor switchgear. The aluminium used for bus-bars should have high conductivity, good mechanical properties, high softening temperature, etc. IS : 5082–1992. Wrought Aluminium and Aluminium Alloys for Electrical Purposes : Bars, Rods, Tubes and Sections specifies the requirements of aluminium for busbars.

(*ii*) **Forms.** The structural forms of bus-bars are generally selected on the basis of mechanical considerations of strength, supporting arrangement. When the spacing between bus-bars is small mechanical forces become significant. Typical bus-bar shapes include :

— Single flat rectangular sections
— Angles, channels
— Hollow tubelar sections
— Multiple rectangular sections
— Double channels
— Hollow rectangular sections.

(*iii*) **Current carrying capacity.** The various aluminium companies give regular tables of cross-sections and their current carrying capacities based on ambient temperature (40°C or 50°C) and temperature rise (35°C average, 40°C maximum). for various conditions and arrangements. The current carrying capacity varies with arrangement, cross-section, proximity, type of enclosure, ambient temperature, etc.

For preliminary calculations, Table 17.3 gives reference values.

Table 17.3
Approximate Current Ratings of Aluminium Bus-bars

Shape of Busbar	:	Rectangular, solid
Arrangement	:	With larger surface vertical
Material	:	E91E-WP as per I.S. 5082-1969
Ambient Temp.	:	35°C over ambient.
Condition	:	Still unconfined air without enclosures.

(mm)	*50 Hz, A.C. Current Rating, Amperes*			
	Single Bar (per phase)	*Two Bars (Per Phase)*	*Three Bars (Per Phase)*	*Four Bars (Per Phase)*
25 × 6	350	700	950	1000
50 × 6	675	1300	1700	1925
75 × 6	950	1750	2300	2600
100 × 6	1225	2150	2800	3200
125 × 6	1500	2500	3200	3700
50 × 10	825	1500	1950	2250
75 × 10	1180	2050	2650	3000
100 × 10	1500	2475	3150	3550
125 × 10	1850	2925	3600	4200
150 × 10	2100	3350	4000	4600
200 × 10	2750	4100	4900	5700
75 × 12	1350	2250	2800	3200
100 × 12	1750	2700	3350	3900
125 × 12	2100	3100	3900	4500
150 × 12	2400	2500	4450	5100
200 × 12	3050	4500	5300	6100
250 × 12	4 000	5010	6000	6800

Joints should be with oxide-inhibiting grease.

Derating Factors		*Derating Factor*
(*a*) Temp. rise of 40°C,	ambient 35°C	: 0.88
(*b*) Temp. rise of 35°C,	ambient 30°C	: 0.76
(*c*) Enclosure :	Outdoor,	: 85 to 0.95
	Indoor, Well-ventilated	: 0.6 to 0.8
	Indoor, poorly ventilated	: 0.5 to 0.6
(*d*) Rating factor for non-metallic back matt paint		: 1.2

A current density of 750 A/in^2 or 116 A/cm^2 can be considered as very safe choice in selecting cross-section for unenclosed bus-bars of copper.*

Table 17.4. A Appropriate cross-sections for various current ratings Single Bare Conductors in open air*

Continuous A.C. Currents ratings Amp. (r.m.s.)	*Cross-sectional Area*	
	Copper mm^2	*Aluminium mm^2*
100	20	25
150	34	40
200	41	56
225	47	63
250	53	71
300	68	122
350	79	145
400	94	145
450	115	165
500	125	187

(*iv*) **Temperature Rise During Short Circuit Conditions.** At temperatures about 160°C, aluminium becomes soft and loses its mechanical strength. This sets a limits on permissible temperature rise during short-circuit conditions. The calculations of temperature rise are complicated. Tables and graphs are generally available for difference bus-bars for the purpose of calculations of temperature rise. For preliminary calculations, the following expression can be used :

$$T = \left(\frac{I}{A}\right)^2 (1 + \alpha\theta) \cdot 10^{-2}$$

T = Temperature rise/sec. during short circuit condition (C)

C = 0.54 for copper 1.17 for aluminium

I = R.M.S. value of short circuit current

A = Cross–sectional area, mm^2

α = Temperature coefficient of resistivity at 20°C

0.00393 for copper

0.00403 for aluminium alloy (EIE-M)

0.00364 for aluminium alloy E91E-WP

* The figures are only for single rectangular conductors for more conductors in parallel, the current does not increase proportionately. For actual selection refer tables supplied by manufacturers. Refer : DIN 43670. The recommended current density for copper busbars is 165 A/cm^2 and for aluminium conductor is 118 A/cm^2 [VDE 4014/16].

θ = Temperature at the instant of short circuit, *i.e.*, ambient plus permissible temperature rise.

(*v*) **Oscillations.** The periodic variations in force results in oscillations in conductors and insulators. The nature of such oscillations at the time of short-circuit depend on characteristic frequency of the conductor system and operating frequency of circuit. Prolonged oscillations can cause of failure of structural parts by mechanical fatigue.

(*vi*) **Bending Load on Insulators.** As the conductors are supported on insulators. Insulators experience bending forces, due to the forces on conductors. The force is given by equation below. The cantilever strength of insulators should be more than F.

(*vii*) **Insulation Requirements of Busbars.** Insulation is required between phases and between phase and earth. Therefore, bus-bars are supported on insulators and necessary clearances are maintained between phases, and between phase and earth. For indoor metal clad switchgear upto 11kV, now, synthetic resin-bonded or cast parts are used for insulator supports. Formerly, porcelain, varnished papers, resin-bonded parts, densified resin bonded wood parts were more popular. The insulator supports for outdoor busbars are invariably, of glazed porcelain. Electrical clearances, line to ground (earth) and line to line, must be maintained. These clearances are more for outdoor busbar systems. Outdoor stations have a lattice steel structure for supporting buses, isolators, jumpers, etc. Outdoor buses are generally copper/aluminium bars, rods, pipes or thin walled tubing. Thin walled tubing is favoured because of higher stiffness. The clearances are more, to avoid faults due to birds. Simple ACSR standed conductor pieces are kept inside the tubes to prevent vibrations of tubular bus.

Table 17.5
Reference Values of Minimum Creepage Distances for Porcelain Insulators for Outdoor use

Highest system Voltage r.m.s	*Creepage Distance*	
	*Moderately polluted Atmosphere**	*Heavily Polluted Atmosphere***
kV	mm	mm
3.7	75	130
7.2	130	230
12	230	320
24	430	560
36	580	840
72	1100	1700
132	1850	2800
145	2250	3400
245	3800	5600
420	6480	9660

(*viii*) **Spacing of Support Insulators.** The spacing of support insulators is determined on the basis of the force on a span length of busbar under short circuit conditions.

$$F = 2.04\, i_s^2 \times \frac{L}{r}\, 10^{-2}\ \text{kgf}$$

i_s = peak momentary short circuit current (assymetrical), kA

L = span between insulator supports, cm

r = spacing between neighbouring conductors in three phase bus system, cm.

Distance r is determined by clearance considerations and by shapes of conductors selected. By increasing L, the value of F is increased necessitating insulators of high cantilever strength. The cantilever strength of insulators is first noted from the catalogue of insulators; on the basis of which the span L is calculated.

(*ix*) **Clearances between Phases and between Phase and Earth.** The minimum clearances are specified in standards Table 17.6 give reference values of clearances for various conditions.

(*x*) **Creepage distance.** The shortest distance along the contour along the external surface of insulators, from earth to the conductor [Refer Table 17.5]. The porcelain insulators are exclusively used for outdoor bus supports. They may be pin type, post-type or suspension type. For voltages upto 36 kV, pin-type of single post type insulator are used. Above this level, multiple post-type insulators (stack) are used for supporting air-insulated bus-bars above ground support, or the bus-bars are supported on suspension string insulators. Insulator surface is contaminated by soot, dust, salt layer near sea-shores, deposits of chemicals in industrial areas, etc. The insulators should be washed regularly as often as thrice in a year. In sea-shore areas, the station buses are over insulated, *e.g.* 24 kV insulators may be used for 12 kV buses.

(*xi*) **Ground Clearance.** Distance between the highest earthed part of the equipment and the ground. This should be minimum 2.75 metres (Ref. Fig. 12.1 sec 12.1). This is for safety of personnel moving in the sub-station.

Table 17.6. Indoor Bus-bars : Open or Enclosed Clearances for Voltages upto 33 kV

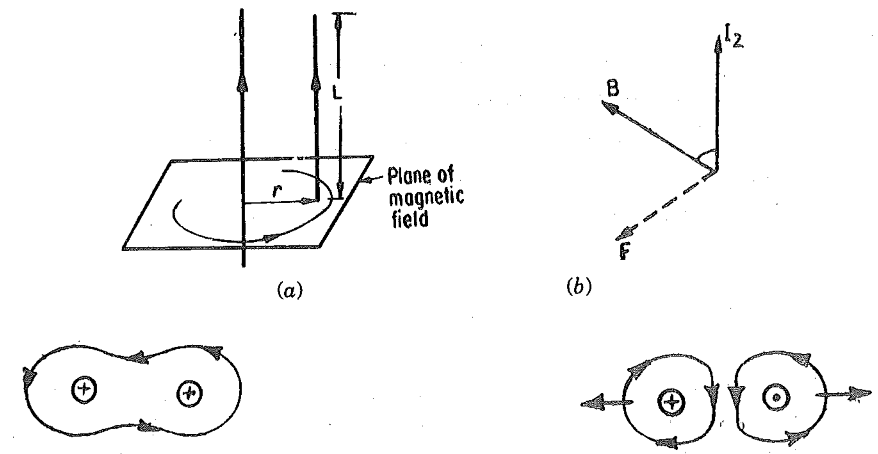
Rated Voltage, rms kV	*Minimum Clearance to Earth*		*Maximum Clearance between Phases*	
	Open mm	*Enclosed mm*	*Open mm*	*Enclosed mm*
0.415	19	16	26	19
0.5	26	19	12	19
3.3	51	51	51	51
11	77	77	127	127
15	102	102	165	156
22	240	140	242	242
33	223	223	356	356

Table 17.7. Clearances for Open Outdoor Bus-bars

Rated Voltage, rms kV (rms)	*Minimum Clearance to Earth*	*Maximum Clearance between Phases*
	mm	*mm*
6.6	140	178
11	178	229
15	216	267
22	279	330
23	381	431
66	685	786
110	1068	1219
132	1270	1473
220	2082	2361

17.19. ELECTRODYNAMIC FORCES ON BUS-BARS DURING SHORT-CIRCUITS

Current carrying conductors placed near each other experience electro-mechanical force.



(*c*) Force of attraction when current in same direction. (*b*) Force of repulsion.

Fig. 17.29.

The dynamic force occurs at the peak of first major loop, on short circuit. This force is given by the expression :

$$F = 2.04\, i_s^2 \frac{L}{r} \times 10^{-2} \text{ kgf}$$

where F = force between conductors

i_s = peak value of current, kA

L = length of conductors, cm

r = separation between conductors, cm

[1 newton = 0.101972 kgf].

From this force, required cantilever strength of the support insulator or span is determined.

Perpendicular conductors tend to straighten-out due to electromagnetic forces.

Bus-bar Design

The early sub-station were generally with *flexible bus* design. A flexible bus consists of flexible ACSR (Aluminium cable steel reinforced) or All-aluminium alloy stranded conductors supported by strain insulators from each end. The flexible bus is held at higher level above the various sub-station equipment. The connections between the flexible bus and the terminals of sub-station equipment are by flexible conductors held in vertical or inclined plane.

Rigid bus-bars are easy to maintain. They are at lower height. Connections to sub-station equipment are easy. Aluminium tubes are preferred for rigid bus.

A sub-station usually has a combination of Rigid Bus-bar and Flexible Bus-bars. ACSR conductors are preferred for flexible bus.

Configuration of Clamps and Connectors. Typical configurations of clamps and connectors used in sub-stations include the following:

1. *Tee-Connector* for connecting ACSR flexible conductor to ACSR tap conductor.
2. *Tee-Connector* for connecting with ACSR conductor to aluminium tubular bus.
3. *Parallel-Groove Connectors* for connecting two ACSR flexible conductors in parallel.
4. *Fixed type bus Post Clamps* for supporting tubular bus on post insulators.

5. *Sliding type Bus Post Clamp* for supporting tubular conductors on post insulators.

6. *Expansive type flexible Bus Post Clamp* for supporting and joining two busbars lengths on to a post insulator.

7. *Connector* between ACSR conductor and equipment terminal.

8. Connector between tubular bus section and equipment terminal

9. Spacers double-ACRS conductors and quadruple ACSR conductors.

10. Hardware for string insulator assembly.

Reference Data for Clamps and Connectors and Hardware Fittings

Conductor tension	1000 kg conductor
Wind load	560 kg
Forces due to short-circuit	1600 kg

Bus-bar Design

The bus-bars are designed to carry certain normal current continuously. The cross-section of conductors is designed on the basis of rated normal current and permissible temperature rise. The value of cross-section so obtained is verified for temperature rise under short time short-circuit current.

The bus-bar conductors are supported on *post insulators* or *strain insulators.* The insulators experience electrodynamic forces during short circuit currents. These forces are maximum at the instant of peak of first major current loop. These forces produce bending moment on separate insulators. The spacing of support insulators is decided on the basis of bending moment per metre.

The factors to be considered for bus-bar design are as follows :

1. Material
2. Cross-section of conductors.
3. Temperature rise during continuous normal current.
4. Temperature rise during short circuit current of 1 second or 3 seconds
5. Design of insulator-creepage distance and clearance.
6. Distance between phase conductors.
7. Force on insulators during peak short circuit current.
8. Span of insulator supports.
9. Enclosure design.

Example. *Design cross-section of an enclosed aluminium conductor for normal current rating of 1000 A, rms, 50 Hz and ambient temperature 30°C permissible temperature rise 35°C.*

Ans.

Derating Factor for Ambient Temp.	= 0.76
Derating Factor for Enclosure	= 0.5
Operating Factor for Matt-black paint	= 1.2
Total Derating factor	$= 0.76 \times 0.5 \times 1.2$
	= 0.46

Current rating 1000 A continuous aluminium conductor is selected cross-section to correspond to $\frac{1000}{0.46} = 2175$ A.

From the table :

Use one 150×10 mm Flat (2100 A)

Or one 125×12 mm Flat (2100 A)

Selection of support insulator. The insulators are selected by considering mechanical bending load occurring at that instant of peak short circuit current. During short circuit in the system, short circuit current flows through the bus-bars. The insulator supporting the busbars experience a bending force. The insulators should have enough cantilever strength to withstand the dynamic force occurring during short circuit.

Example. *The bus-bars are having phase-to-phase spacing of 24 cm. Their short circuit current rating is 25 kA$_{rms}$. Determine the minimum force on conductors during short circuit conditions.*

$$i_s = I_{rms} \sqrt{2} \times 1.8$$
$$= 2.55\, I_{rms} \quad \text{(Factor 1.8 is for assymetry).}$$
$$I_{sc} = 25 \text{ kA}_{rms}$$
$$i_s = \text{peak short circuit current}$$
$$= 2.55 \times 25 \text{ kA}$$
$$i_s^2 = (2.55)^2 \times 25^2$$
$$= 6.5 \times 6.25 = 4050 \text{ kA}$$
$$F = 2.04 \times i_s^2 \times \frac{L}{r} 10^{-5} \text{ kgf}$$
$$= 2.04 \times i_s^2 \frac{1}{0.24} \times 10^{-4}$$
$$= \frac{2.04 \times 40.50}{0.24} = 346 \text{ kgf per metre.}$$

Force on bus-bars per metre length = 346 kgf.

Cantilever load on insulator is given by $F \times H$ kg-metre

where F = Force, kgf per span length

H = Height of insulator, metre

Assume insulator height = 0.13 metre

Cantilever strength of insulator = S_k

Let S_k = 500 kg–metre from catalogue of insulators

$F \times H$ = cantilever load per metre run

$F \times H \times L$ = cantilever load per span length of insulator

$$F \times H \times L = \frac{S_k}{\text{Factor of safety}}$$

where F = Force on bus-bars per metre run

H = Height of insulator, metre

L = Span of insulators

S_k = Cantilever strength of insulator, kg–m

Factor of safety = 4

Substituting in given example,

$$346 \times 0.13 \times L = \frac{500}{4}$$

$$\text{Span of insulator } = \frac{500}{4} \times 346 \times 0.13 = 2.9 \text{ metres}$$

Let the span of insulators = 2.5 m.

17.20. IMPORTANT TECHNO-ECONOMIC CONSIDERATION FOR CONSTRUCTION OF SUB-STATIONS/SWITCHYARDS

A large number of Sub-stations/Switchyards, to meet the requirements of increasing demand for transmission and distribution networks, are being constructed involving huge amount of expenditure. In this era of competition, the aspect of exercising maximum possible economy while making no compromise on the operational requirements, safety & reliability aspects and the technical parameters should be known. Some of such techno-economic issues have been briefly described below :

17.20.1. Activities in Construction of Sub-station

Planning of sub-station starts with a system study. If there is a pocket of low voltage or a new load center is due to develop in the area or is already developed, the construction of sub-station is justified. The size of the sub-station to be constructed is based on power requirements as well as other environmental factors. The location of sub-station with regard to system improvement, vicinity to the load to be catered and configuration of incoming and outgoing line has to be properly envisaged.

Acquisition of land is yet another activity which demands good amount of exercise, as total cost depends much upon the selection of site. The amount of civil work within the sub-station and length of transmission network for the connection to the new sub-station depends upon the location of land. The location of land has also to be viewed from the angle of accessibility.

The design and layout is the next activity. Depending upon the nature of piece of land available, the layout can be made for different levels of voltage in the sub-station, incoming lines and outgoing lines. This exercise needs to be done on scale and also has to be in line with the statutory electrical requirement in vogue.

The civil design will depend upon the soil strata available at the site selected. There may be other parameters, which include local factors like high wind velocity, high temperature or low temperature etc. The structural design of gantry and equipment support will be the next item on agenda. This particular activity will include design and fabrication of structures. This has to be in line with the latest standard practice in the field as well as the experience gained from the past construction and the actual site requirement for accommodating equipments in the available space.

The selection of parameters of electrical equipments such as transformer, breaker, CT, PT, LA, PI, Isolator, earthing system has have to be meticulously done in accordance with the system requirement, protection and operational needs.

The procurement of equipments, which are specified, is one of the major activities as it involves drafting of specifications, tenderization, scrutiny of tenders, awarding of contract, execution of contract and receipt of materials. This activity is capital-intensive and has to be carefully planned out.

The actual civil work starts immediately after the land acquisition. The cutting and filling work is the first and foremost work to be done which is followed by protection wall, fencing, gates, watch and ward tower etc. The work of cable trench, control room, switchyard structure foundation follows the land leveling work and other important civil work. The roads, staff quarters, water supply and drainage system is also a part of the civil work.

The erection of gantry structures and equipment support structures is yet another important work. This is followed by equipment erection in the open switchyard and in the control room.

The commissioning of bays and commissioning of the sub-station is yet another activity. However, the receipt of transformer, its storage and erection of the same on the plinth is an independent job. The testing and commissioning of the transformer is a part of commissioning activities.

The final stage of the sub-station activity is the grooming of the sub-station by providing horticulture, painting, landscaping, sing boards etc.

Statutory clearance for the design and construction of sub-station has to be obtained from time to time.

17.20.2. Cost Effectiveness

Each one of the activities enumerated above has to be properly weighed for cost effectiveness. The cost effectiveness does not man avoiding expenses on need-based items of work or equipments. The reliability and availability of the sub-station has to be properly evaluated before arriving on cost effectiveness in construction. Cost effectiveness surely means avoiding wasteful expenses on material, labour, storage, transport and capital interest by proper Planning & Resource Management.

The cost effectiveness will vary from site to site. For example, the cost of land in and around metropolitan towns will be extremely high, whereas the load center will be close to each other. Besides, in this region, density of load will also be heavy and therefore the design of sub-station in electrical, mechanical and civil terms will be together a different proposition compared to the sub-stations to be constructed in rural sector.

The cost effectiveness in procurement may depend upon the market situation prevailing with a particular reference to the supply and demand during the process of tenderization. The cost may also depend upon the techno-commercial terms and conditions provided in the specifications.

The cost effectiveness of civil work will be very much an important factor. The labour and civil construction inputs (cement, wood, sanitary work, piping, sand, gravel, steel etc.) will be a decisive factor in the cost effectiveness of civil works.

Electrical erection testing and commissioning activities will generally depend upon the voltage rating of the equipment and cost of labour prevailing in the region.

17.20.3. Ways and Means of Economizing

(*a*) **Land acquisition.** The cost of land will depend upon the vicinity or remoteness of the proposed sub-station with reference to metropolitan, big towns or cities. Since the system study indicates the construction of sub-station in a particular location, the choice of type of switchgear has to be based on the land cost.

When the sub-station is to be constructed in the metropolitan or in the densely populated urban area, the cost of land matters much. To create a new load center is of prime importance and connection of the same to the existing/new transmission network is a next important activity. Besides acquiring such land in densely populated area has a very high cost benefit ratio due to high density of load around the sub-station and low cost of maintenance of lines (as new sub-station is meant to cater very heavy load in a radius of few of Kms.)

Creating a sub-station and the load center away from metropolitan and densely populated urban area is a matter of choice. Here, the cost of land is of prime importance along with the amount of cutting and filling to be done in the soil as well as nature of soil. In this category, there may be various techno-economic considerations as follows.

The land may be cheaper, but may need cutting, filling and leveling, but soil quality may be good.

The land may be levelled one, but susceptible to water logging, accessability may be difficult.

The land may be absolutely good in every sense such as levelled one, no likelihood of inundation, good quality of soil etc., but this piece of land may be much away from the thoroughfares and towns/cities. This proposition will prove costly from the angle of manning the sub-station, taking equipments to site, carrying out construction activities and later on maintaining sub-station. However, this may prove to be better for making the lines in and out.

The land may be very cheap, but may involve hill cutting. This will be a costly proposition.

In the densely populated areas under civil authorities, there may be a compulsion to locate a S/S in the heart of the town. The cost of land and the EHV cabling has to be weighed against the revenue return, system improvement and the customer satisfaction.

(*b*) **Layout drawings.** Making a lay out is the next important job. Optimization of lay-out will lead to better utilization of the available space at least cost. The number of bays to be accommodated on H.V. side and L.V. side will depend upon the maximum rated capacity of the S/S in MVA. Since the power transfer capability of each transmission line is almost fixed it is possible to calculate the number of H.V. and L.V. base at the S/S plannings stage only. However following points are vital while optimizing the layout.

Type and configuration of the equipments to be used for each voltage class.

Available land piece and shape.

The switching scheme. Whether it is single bus, two bus or three bus system. In case of two bus whether it is a main and auxiliary or main I and main II, whether sectionalization is required.

The affordable placement of transformer. Whether incoming lines and transformers are in the same horizontal axis or the transformers are placed between two voltage levels. If the transformers are placed between two voltage levels whether they are placed adjacent to each other or away from each other.

The position of incoming and out going lines of different voltage class is the factor, which will affect the lay-out. The positions of lines will depend upon the environment of the S/S. To be precise whether the S/S is situated in urban, sub-urban, rural area or industrial belt.

The control room sizing will depend upon the number of panels to be housed, which in turn will depend upon the number of voltage levels and nature of the S/S.

(*c*) **The earth mat design.** The earth mat design is one of the important area which needs optimization. The following needs to be taken care of.

(*i*) The resistivity of the earth is one of the important parameter of the earth mat design. It should be ascertained whether it is possible to get lower resistivity by penetration in to the lower levels of the soil or whether it is possible to improve (reduce) the soil resistivity by artificial means. For economic design of earth mat precise values of earth resistivity and short circuit current should be available, Tentative figures, usually lead to higher costs.

(*ii*) The short time current rating, fault level, touch and step potentials, are the other parameters affecting the design. It should be found out how and where the most realistic parameters can be applied/worked out.

(*iii*) The cost of the earth mat also depends upon depth of burial of the earth mat and depth to which the electrodes require driving.

(*iv*) If it is possible to artificially increase the conductivity of the earth fault current through earth mat and the electrode (use of bentonite etc.) to that extent the optimization can be achieved.

(*v*) The size of earth mat material and electrode material can be optimized by making trial and error on the spacings. The step potential can be reduced by spreading metal or gravel in the switching area.

(*d*) **Civil Engineering works.** Civil engineering works are the main and time consuming activity in the construction of S/S. Besides it is one of the most variable item of activity in terms of cost. The civil works include construction of boundary walls, water supply arrangement (making a bore, sump, overhead tank, piping etc.), drainage system (affluent, storm water etc.), cable trenches, structure foundations, control room building, stores, office building, staff quarters, recreation facilities, roads, culverts, fire protection, service room, A/C plant housing, generator room (where required) etc. There are many parameters as discussed below, which if taken care can help in cost reduction :-

(*i*) The boundary wall construction using locally available material such as stone, fly-ash bricks etc. can lead to economy and good strength. In case of black cotton and other poor types of soil if short piling is resorted to instead of deep excavation and stepped brick masonry, economy with high reliability can be achieved.

(*ii*) The water supply can be economically arranged by selecting proper location for the well, sump and the tank. The depth of the bore can be fixed by critically evaluating the water resource by means by hydrological tests.

(*iii*) The optimization and cost effectiveness of the drainage system can be achieved by choosing optimum location of the septic tanks and disposal of waste-water etc.

(*iv*) The cost of construction of the cable trenches can be minimized by preparing the cable schedules well in advance. The cable trenches can be categorized depending upon the maximum number of cables to be routed. The type of civil work (P.C.C., R.C.C., stone/brick masonry etc.) can be decided according to the type of soil/rock encountered at the site. The depth of the cable trench can be a decisive factor for selecting the structure of the cable trench.

(*v*) The foundations for gantry columns, equipment support structures, transformers and breakers can be economically constructed by critical evaluation of the forces acting on the equipments and structures (which are ultimately transferred to the foundation). Wherever possible, use of individual leg type footings for columns can bring in good economy. The under cut type of footings in the normal soil and soft rock/fissured rock can bring substantial economy with high reliability.

(*vi*) The architecture and design of control room building should be done very precisely for affording maximum flexibility as well as ease in control room operations at least cost. The space requirement considering the number of panels to be housed (including future expansions), office, store, conference room, toilet/bath, cable trench and cable entries, battery room, carrier room, computer room etc. should be assessed well in advance. The location of the control room should be so selected as to allow for future expantion. Wherever office building and store rooms are to be built away from the control room their locations and design should be done with an ascent on maximum floor space at minimum resource/cost. In seismic zone, extra care should be taken to provide framed structures approved by the concerned authorities.

(*vii*) Number and type of quarters to be constructed should be strictly in accordance to the staff set-up of the S/S. The location of the staff quarters should be such as to afford construction of minimum length of roads and convenient accessibility to the civic roads. The designs of quarters should be in accordance with the status wise space requirement with an ascent on good ventilation. If the S.S situated in seismic zone extra care should be taken to provide framed structures for staff quarters as per statutory requirements.

(*viii*) The other miscellaneous civil works such as recreation facilities, gardens etc. can be provided using minimum space and state of art horticulture and recreation equipments.

(*e*) **Switchyard structures.** The structural designs of gantry and equipment support structures should be based on realistic load requirements. The switching scheme should be as simple as possible. The statutory clearances should be kept to the requirement. The following points need be kept in view while optimizing the structure designs.

(*i*) The climatic conditions should not be considered excessive to what warrants as per the local situation and or meteorological data, since the wind pressure, rainfall, temperature, altitude, H.F.L. etc. governs the structural design.

(*ii*) The structures in the switchyard should be divided into various categories like beams, columns, equipment support etc. in accordance with the configuration. The division can also be in respect of their position in the switchyard. This includes structures in the line bays, bus bays, transformer bays etc. Again, the division can be made depending upon whether the structure is in the end position or the middle position. The structures with fly over and T configuration shall be designed with the loads in various directions and levels. With this type of exercise it will be possible to design structures in most economical manner.

(*iii*) The equipment support structures can be designed keeping in view the exact equipment dimensions, specified ground clearance and sectional clearance. The short circuit forces wherever required (Breaker, CT, PT, LA) should be accounted while finalizing these designs.

(*iv*) Cost of foundations for structures can be reduced considering the most probable loads on structures. The design of structures separately for each position in switchyard.

(*v*) The 220kV/400kV switchyard also have equipments like fire protection system, Air-conditioning plants, D.G. sets etc. The power transformers need protection from fire. There are alternative systems such as Fire Tender, mulsifyre system, Nitrogen bubble etc. The mulsifyre system needs many accessories and regular maintenance. Fire tender and nitrogen bubble are also effective systems. The transformer fire protection can also be arranged through fire tender using special foam meant to extinguish the fire. D.G. sets to be procured should be equivalent to the bare minimum emergency power required for s/s and control room, such as battery chargers, control room lighting, air-conditioning and fire protection gadgets.

(*vi*) In some of the 400 and 220kV sub-stations, air-conditioning system is provided for maintaining the temperature in the relay room. However it is observed that in some cases even control room and offices have been made air-conditioned by using central air-conditioning plant. This puts lot of financial strain on the sub-station in terms of construction and maintenance. It becomes mandatory to have a compressor room and cooling tower. Lot of water also is required to be arranged and water to be used needs to be of good quality. Besides, in case of any fault in the cooling plant the relay room is badly affected and in turn the operations are badly affected. If the relay rooms are designed in a compact manner, a special air cooling system which can maintain a temperature of the room from 22 to 24 degrees can save the situation. Even window air-conditioners can remedy the situation.

17.20.4. Construction activities

The economics of the s/s also depends upon the pre-planning of the construction activities. Time bound construction programme with all pre-defined and approved drawings goes a long way in cost cutting and reducing gestation period. Any delay in construction means loss of material, escalation in prices, loss of interest on the capital invested as well as continued overloading of the existing s/s.

The transformer which cannot be erected for want of plinth requires watch and ward and monitoring. Similarly other expensive equipments like Breakers, CTs/PTs/Isolators have metallic parts and are susceptible to theft. Planning of material procurement as per the PERT & CPM drawn at the project clearance stage and reviewed from time to time. This may help in reducing the cost incurred on storage, watch and interest on capital. There are large number of variables in the construction of EHV sub-stations and if they are tackled individually and handled in totality, substantial cost saving is possible.

The cost saving can be without jeopardizing safety norms in any way. However judicious and critical review of each one of the input of construction including procurement policies, construction management and quality control can bring about sizable saving which each one of the utility in this country needs to evaluate.

Proper planning and optimization measures would definitely result in appreciable cost saving.

It is reported that high intensity raids forms 80 to 100% of all the weather related failures.

17.20.5. Maintenance of over-head transmission lines

Major breakdowns of transmission lines can be prevented or the damages can be minimized by well defined routine preventive maintenance inspection and timely repair. Inspection should not

be confined to the transmission line proper but should also cover the neighbourhoods. The scope of inspection should cover all the elements of transmission line system to ensure safety as well as to enhance the reliability of power supply. Maintenance operations comprise the detection and removal of faults or abnormal conditions on the lines. Faults are detected by simple patrolling performed by single patrolmen, or by detailed inspections carried out by a crew of several men. Scope of inspection and different techniques presently being adopted in maintenance of transmission lines are briefly given below :-

A. Patrolling

The objective of routine inspections is not merely repair work, but to ensure prevention of outages, safeguarding against accidents, and detection of dangerous conditions along the line, such as inundation, soft soil, proximity of trees and building sites, conductor vibration, supporting structures exposed to lightning, etc.

Patrolling is done on foot, horse-back, by motorcycle, automobile and in mountainous terrain also by helicopters. The advantage of using a helicopter lies in the fact that a helicopter can fly low and slowly, giving the patrolman sufficient time to inspect the line from above, and that up to 300 km of lines can be inspected in a single day.

Extra-high-voltage lines are routine-patrolled at least once a month, high-voltage lines at least once in two months, and low-voltage lines at least once every year. Crossings and especially exposed sections of lines in densely populated industrial districts are patrolled more frequently. Once a year a night patrol should be carried out on extra-high-voltage lines to check up on corona formation in general and on joints in particular.

In addition to such regular patrols, there are also special patrols of the countryside before harvest time and after every major climatic disturbance, such as after heavy ice loadings, floods, cloud-bursts, gales, violent thunderstorms, line outages, etc. It is reported that high intensity winds form 80-100% of all the weather related failures.

During routine patrolling all the observations made, faults identified and the corrective actions (rectification carried out) taken subsequently is recorded in detail, since documented records are valuable data for effective future maintenance.

B. Scope of Routine Inspection

As far as maintenance of transmission line is concerned, it is an established rule that inspection should not be confined to the transmission line proper, but should also cover the surroundings. Attention has to be paid in particular, to soil around the supporting structures. Grass, bushes and other plants around poles and towers are removed. The supporting structures like pole or tower proper is inspected to detect any decay of wood or corrosion of steel or concrete and possible damage to the structure. The verticality of the supports is also checked. A detailed examination is carried out on the connection of the grounding wire with the grounding electrode, the grounding wire proper, bracings and anchor guys of the supporting structures. The pretension in the guys are monitored and adjusted if required. Crossarms are inspected to make certain that they are not loose or bent, insulator-pins are examined for bending, insulator strings are checked for their vertical position and possible damage. The overload ground wire attachment and sags of the conductors and overhead ground wire are also checked.

1. **Inspection of surroundings.** The neighbourhood of an overhead transmission line is checked to make sure that the original use of the grounds has not undergone changes due to construction of earth-work, setting up of a dump pile, or due to floods, building of a play-ground, wire-fence, etc. Utmost attention should be paid to forest stands or isolated trees below the line or alongside it, road-and river crossings, railway crossings and power or communication-line crossing and populated areas with protruding aerials & TV antennas.

2. **Emergency patrol.** In case of an outage, an emergency patrol is sent out with the object of speedy detection of the fault and instant reporting. For this purpose, the patrolman is usually equipped with a transceiver communication set.

The location of a fault on high-or extra-high-voltage lines due to short-circuit or broken conductor can be detected, within 0.5 km, by measurement from transformer substations. D.C. impulses are sent into the affected phase conductors of a disconnected line at a rate of e.g., 150 c.p.s. The emission and reflection of the impulses from the fault is observed on a cathode-ray oscilloscope, the distance of the fault is determined from the reproduced image.

In hilly terrains, materials required for repairs/replacement, such as insulators, conductors, clamps, etc. shall be stored in convenient, well-protected shelters, distributed along the line.

C. General Inspection

General inspections include examination of the soil near foundations, decay of wooden supporting structures at the ground-line, possible, corrosion of steel supporting structures at the ground-line and the state of the surface finish etc. In addition general inspections include climbing the supporting structures and checking the crossbeams, crossarms and braces, connection of overhead ground wires to the grounding wires, individual pin-insulator-ties (at least with the aid of a mirror attached to the end of a pole); During inspection attachment of conductors to clamps, conductor joints, dead-ending clamps, etc., are also checked.

Trimming of trees and bushes along the line and below it is also considered a part of the maintenance. The crew appointed to this work is equipped with proper tools and trained. Spreading of undergrowth also needs to be prevented.

1. **Inspection of Insulator Strings of EHV Lines.** In the case of an extra-high-voltage line, inspection also includes the testing of insulator strings. This is done by checking the voltage distribution between insulator caps of a live line. Many methods have been developed to inspect the insulator strings.

The highest voltage drop occurs across the insulator adjacent to the conductor. The magnitude of the voltage drop decreases gradually down to the third or second insulator unit, counted from the cross-arm. Irregular voltage distribution along the string indicates the presence of a faulty insulator. The voltage drop between insulator caps is generally measured with an electrostatic voltmeter (e.g., the Ferranti Line tester) attached to a long insulated pole.

The patrolman is often equipped with a high-frequency defectoscope, enabling him to detect defective high-voltage insulators by listening and measurement. The voltage-distribution is judged from the sound of the discharge at the double prongs, interconnected via. a well-insulated condenser, and fixed at the end on an insulated stick, the so-called buzz-stick.

As during such a test an insulator having the lowest voltage drop does not buzz, such an insulator is called a silent insulator. A faulty insulator is thus detected from the location of the silent insulator in string. For better results, these measurements should be performed when the relative humidity is not excessive generally below 70%.

During shut down, defective insulators are detected by measuring insulation resistance of insulators using light weight and portable meggars. In addition, live line measurement of the voltage and the electric field across the insulators is carried out to identify the punctured insulators. Ultrasonic Fault Detector to detect faulty insulators, insulators strings and other electrical equipments up to 800 kV under charged condition are now being employed. Various methods to find out the level of severity of pollution present on the insulators in a string are now being used. The measurement is done by using instruments like conductivity meter, leakage current monitor etc.

2. **Inspection of Conductors and Clamps.** During inspections of long spans, at least once in a year, bolt-clamps on suspension insulator strings are loosened and a check is made to ascertain that the conductors have not damaged due to vibration and that no strands have broken. At the same time, conductors near dead-ending clamps are examined to ensure that they are not corroded or otherwise damaged.

Location of defects are all clamps and joints in which two different metals are in contact, particularly branching-off clamps. The same applies also to low-voltage lines. Joints and branching-off clamps are tested under load at least once every two years with the aid of a paraffin stick to make certain that these do not get heated under load, or by means of a voltmeter connected, via a well-insulated condenser, to the prongs of a long insulated stick to the end of which the active parts of the apparatus are attached.

Until recently the only way to measure sag was to climb a tower and take a sighting with a theodolite to the next tower. Today handheld laser range-finders offer a very efficient way to directly measure sags and ground clearances.

3. **Special Inspections.** Special inspections are carried out to examine the surface finish of steel-towers or checking the corrosion of structures below the ground-line. The latter is generally followed by coating the endangered sections with asphalt & checking the ground resistance of individual groundings, and of the line as a whole. Power utilities in U.K. have begun using polarization resistance measurements to assess the corrosion risk to overhead tower foundations.

The schedule of the various inspections, for a transmission time is given in Table 17.8,

Table 17.8 - Typical Schedule

Sl. No.	*Type of inspection*	*Inspection schedule (in years)*			
		EHV	*HV*	*LV*	*Crossings*
—	—	—	—	—	—
1.	General Inspection	1	2	4	1
2.	Surface finish of steel structures	3	3	3	3
3.	Corrosion of steel structure below GL	5	5	5	5
4.	Test on strain Insulators	1	—	—	1
5.	Test on suspension Insulators	2	—	—	—
6.	Insulation resistance measurement*	—	1	1	1
7.	Ground resistance measurement*	2	5	4	1
8.	Overall grounding resistance of over head ground wire system*	1	1	1	1

Note : Inspection marked with an asterisk must be carried out before a new or repaired transmission line is placed into operation.

17.20.6. Maintenance & Repair

In addition to the above listed inspection, the maintenance and repair jobs e.g. re-connection of broken conductors, readjustment of conductor and overhead ground wire sags, replacement of insulators, repair of joints, clamps and grounding wires, tensioning of anchor-guys, addition of dampers in locations where vibration occurred, reduction of grounding resistance, etc. are also performed. After the repair of every fault, the repair job must be thoroughly checked and, whenever necessary, an insufficiently performed repair job must be properly completed, as a repair is often made in haste, or carried out only as a temporary repair job.

1. **Major Repairs of the Line.** Major repairs of the line consist of replacement of conductors, increasing the spacing between conductors on towers, addition of overhead ground wires, relocating or adding individual towers, re-locating entire sections of transmission lines, increasing the size of the conductors or raising the voltage. In the case of over-dimensioned structures, the line capacity is increased by adding an additional conductor to each existing one, *i.e.*, creating two-conductor bundles.

2. **Training for Personnel.** Maintenance and repair require experienced and well-trained crews, excellent technical equipment, fast, sufficiently spacious but light-weight vehicles especially

equipped for the purpose with dirigible spotlights, a portable spotlight powered by a portable storage battery, and a transceiver communication set. Maintenance and repairs are speeded up when good telephone communication and mechanical ladders or insulated work baskets are available.

3. **Live-Line Maintenance.** In Russia, U.S.A., Canada and Sweden, live-line maintenance has been successfully practiced for a number of years. Live-line maintenance tools make it possible to perform repairs on high- and extra-high-voltage lines without interruption to service. Live-line tools are fastened to the ends of insulated poles, sticks or rods, of late made generally of plastic tubing reinforced with glass-fibres.

The main types of live-line work on high-voltage lines are : replacement of fuses; connection and disconnection of pole- or tower-mounted transformers, condensers or switches; replacement of insulators, crossarms, braces, footings, poles and towers; addition of new lines; replacement of wood poles or their mounting on footings. In Russia, such operations are performed on live lines upto 110 kV operating voltage. In other countries, live-line work on extra-high-voltage lines is limited to replacing insulator strings and mounting vibration dampers. In Sweden, such work is carried out even on 400 kV lines. All such work are generally performed only in dry weather.

Live low-voltage lines are repaired with the aid of rubber gloves and special protective work suits. In all types of hot line work, the workers' heads should be protected by helmets made of insulating material.

QUESTIONS

1. Draw a scheme of receiving station incorporating the single bus-bar and associated equipment.

2. Design a bus-bar system for an 11 kV indoor, enclosed switchgear, normal current 800 A. Short time current 20 kA for 1 second. Permissible temperature rise 50°C. Material : Aluminium bars, Ambient temperature 35°C.

3. Describe the main switchgear arrangement in a generating station.

4. Explain with the help of neat sketches the following :
(*a*) Non-segregated bus-ducts (*b*) Segregated bus-ducts.

5. Explain the principle and construction of isolated phase bus-system.

6. Calculate maximum force between two parallel bus-bars per span length for following conditions :
(*a*) Peak instantaneous current : 50 kA, in both conductors.
(*b*) Spacing between bus-bars : 20 cm.
(*c*) Span between support insulators : 75 cm.

7. Calculate with the help of tables given in this chapter, the cross-section required for the bus-bar.
Given : 1. enclosed bus ; indoor, well ventilated room.
2. rated normal current 1900 A, r.m.s.
3. rated short-time current 30 k A, 1 sec. Obtain the cross-section on basis of 1 and 2 above and then check the temperature rise (ambient 35°C) for 3.

8. Give detailed of auxiliary system in a thermal power station with reference to auxiliary switchgears.

9. State the various equipment and auxiliaries in a substation.

10. Write detail note on the use of aluminium in switchgear.

11. Which tests are necessary on station bus-bars ?

12. Define : (*a*) Creepage (*b*) Clearance.
How can the porcelain insulators be cleaned ?

13. Explain the use of isolator and earthing switch.

14. Distinguish between the functions of isolator, circuit breaker earthing switch.

15. Describe construction of any triple pole isolator.

16. Why interlockings are necessary between isolator, circuit breaker and earthing switch?

17. State the sequency of operation of circuit-breaker, isolator and earthing switch.
(*a*) While opening (*b*) While closing.

18. In a 110 kV/32 kV sub-station the following equipment is to be connected. Draw a diagram of electrical scheme.
Items : (1) Two overhead 110 kV lines, (2) 110 kV circuit-breakers, 4 No. (3) 110 kV/33 kV. Transformers, 2 No. (4) 33 kV circuit-breakers, 6 No. (5) Lightning arresters 110 kV, 2 No. (6) Lightning arresters 33 kV, 4 No. (or 6 No.) (7) 33 kV overhead lines, 4.
Show isolators and earthing switches where necessary. Mark zones of protection.

19. What is the bus Trunking System.

20. What are the advantages of the bus-bar Trunking system.

21. What is the importance of Patrolling in maintenance of a HV Transmission line.

22. What is Live-Line Maintenance of Transmission lines.

18-A

Transient Overvoltage Surges, Surge Arresters and Insulation Co-ordination

Introduction — Principle of Insulation Co-ordination — Lightning Surges and Surge Arresters — Switching Surge — Insulation Co-ordination.

18.1. INTRODUCTION

Each electrical equipment should have long service life of more than 25 years. The conductors are supported on insulators/embedded in insulation system. The internal and external insulation of every electrical equipment is exposed to continuous normal voltages and occasional abnormal over voltages. The equipment insulation should be designed such that the equipment *withstands* the highest power frequency system voltage, occasional temporary power-frequency overvoltages, occasional lightning/switching surges reaching the equipment (after the interception by surge arresters). The terms related with rated insulation levels are defined in the relevant IS/IEC Standard Specifications. Each equipment has assigned Rated Insulation Level, the capability is proved by Type tests/Routine tests for that equipment. (*e.g.* Table 16.1).

The insulation system is protected against abnormal p.f. overvoltages, lightning surges and switching surges.

— The *insulation requirements* are determined by considering the following :

— *Highest power frequency System voltage* (continuous)

— *Temporary Power-Frequency Overvoltages* (a few mill-seconds to seconds) caused by load throw-off, faults, resonance etc.

— *Transient Overvoltages Surges* (few hundred microseconds). caused by Lightning, Switching, Restrikes, Travelling waves etc. The Surge Arresters intercept the surges and protect the installation.

— *Withstand Levels of the equipment.* The BIL is specified and other withstand levels are then selected from relevant tables in standard specifications.

Basic Impulse Insulation Level (BIL) is reference level expressed in peak (crest) voltage value with standard 1.2/50 μs lightning impulse wave. Apparatus should be capable of withstanding test waves above BIL.

— *Protective levels of Surge arresters* and available *Protective Margin* against Lightning/Switching Surges.

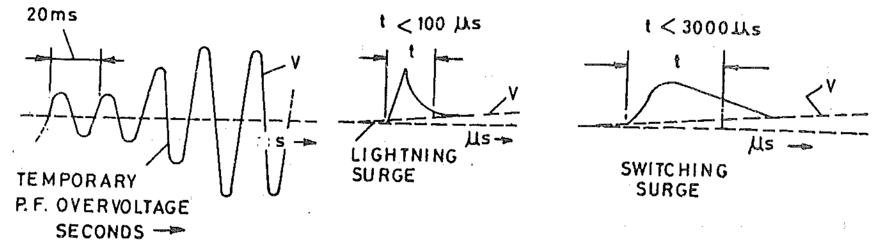
$$\text{Protective Margin} = \begin{bmatrix}\text{Withstand Level}\\ \text{of Equipment}\end{bmatrix} - \begin{bmatrix}\text{Protective Level by}\\ \text{Surge Arrester}\end{bmatrix}$$

— Co-ordination with other equipment connected to same voltage level.

— Co-ordination between various voltage levels in the Network.

— System Neutral Earthing.

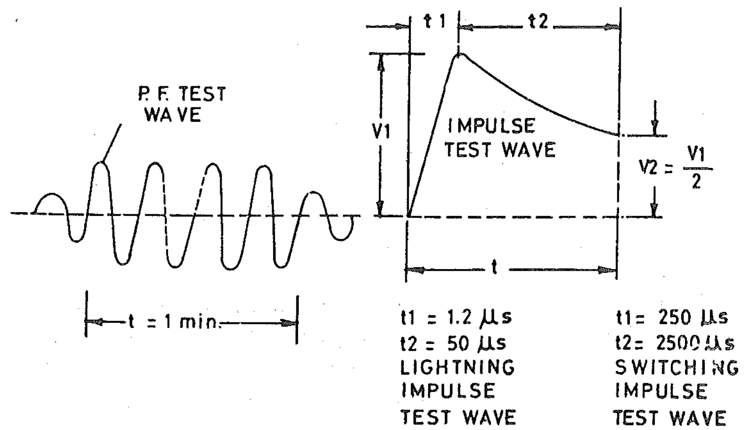
Fig. 18. A-1 illustrates the range of waveforms and durations of Power-frequency Overvoltage, Lightning Surges and Switching Surges. The time durations, rate of rise, peak values of these over-



Temporary P.F. Overvoltage Lightning Surges

Fig. 18 A-1. Three Representative Wave forms⁺ of P.F. Overvoltages and Surges occurring in Network.

voltages of actual overvoltages in the system differ widely. Hence stresses on insulation are also quite different. Power frequency overvoltages are of low overvoltage factor but longer duration. Lightning and Switching Surges are of higher over voltage factor and of lesser duration. The standard test waveforms have been obtained from field studies from several locations, over several years and are used as representatives for laboratory tests of equipment for proving the withstand *capabilities.*



P.F. Overvoltage Impulse Voltage Wave

Fig. 18 A-2. Standard Test Waveforms for Laboratory Tests.
(Word "Impulse" used for "test wave," "Surge" for "wave" in network)

Table 18.1. Example of Rated Insulation Characteristics of an Outdoor Busbar

Nominal voltage*	132 kV rms, 50Hz
Highest system voltage**	145 kV rms, 50 Hz
1 Min. 50 Hz Withstand***	300 kV rms
Lightning Impulse Voltage Withstand	450 kV peak
Switching Impulse Voltage Withstand⁺	380 kV peak
Lightning Surge Protective Level	390 kV p
Lightning Surge Protective Margin by S.A.	60 kV

* Rated voltage

** Design voltage for continuous withstand

*** Test voltage for 1 min. power frequency voltage withstand test

⁺ Switching overvoltage factor K, not specified for 132 kV busbars

Basic Protections against Overvoltages

The protection against Transient Voltage Surges is provided by *Surge Arresters*. The surge arresters, coordinated spark gaps, surge suppressors, overhead ground wires, neutral earthing, shunt capacitors etc. are located strategically to intercept the lightning surges or to reduce the peak and rate of rise of Surges. Protection against Temporary Power Frequency (50 Hz) Overvoltages is by Inverse Definite-Minimum Time Overvoltage Relay (IDMT). Overvoltage relay is connected to secondary of Voltage Transformer. During p.f. overvoltage beyond permissible limit; the overvoltage relay acts and sends appropriate command to busbar/line C.B. and the circuit breaker opens. The transformers and other equipment are protected against temporary power frequency overvoltages.

The Coefficient of Earthing co-relates the Insulation Levels with the Type of Neutral Earthing, the details are described in Ch. 18-B.

Protections against Overvoltages and how fast they act ?

Temporary Overvoltage (ms or s) |	*Lightning Surge (μs)* |	*Switching Surge (μs)* |
↓	↓	↓
Overvoltage	Surge Arrester	Surge Arrester
Relay & CB < 70 ms	1.2 μs	100 μs

The overvoltage protection against *Voltage Surges* is provided by Surge Arresters which act within microseconds. The surge is diverted to earth by the Surge Arrester.

Highest Power Frequency Voltages

The AC Network has different nominal power-frequency voltage levels (*e.g.* 400 V, 3.3kV ; 220 kV, 400 kV rms continuous, at 50Hz). During low loads, the power frequency voltage at receiving end of transmission line rises. In a well voltage-regulate system, the permissible maximum system voltage allowed is called Highest System Voltage. Each nominal voltage level has certain corresponding Highest System Voltage (440 V, 3.6 kV ; 245 kV, 420 kV rms continuous). Each equipment is designed and tested to withstand the corresponding Highest Power Frequency System Voltage of that voltage level continuously without internal or external insulation failure.

Protection against Temporary Power Frequency Overvoltages

There is a difference between the characteristics of Power-Frequency Overvoltage and Transit Voltage Surges and the corresponding stresses on equipment and surge arresters. The temporary P.F. Overvoltages are of 50 Hz and of lesser peak, lesser rate of rise and of *longer duration (seconds or even minutes)*. Every time a change in tap changing by one step-up may cause slight temporary overvoltage. In absence of proper voltage control (Ch. 45) the power frequency voltages go much beyond permissible highest system voltage values. Transformers are worst affected by temporary overvoltages above 1.1 pu. (due to high V/f and overfluxing.) Solid insulator supports are least affected. The protection against temporary P.F/Overvoltages is provided by Inverse Definite Minimum Time IDMT Overvoltage Relays connected to secondary of Bus VT and Circuit Breakers. The relay and breaker action is within several tens of milliseconds to a few seconds. The Overvoltage Relays connected to secondary of Voltage Transformer respond to the overvoltages and give tripping command to circuit breakers. The Circuit Breakers open and the Equipment (*e.g.* Transformer or Busbar) is protected against the temporary overvoltage.

Protection against Transient Surges

Surges in the Power System are of comparatively high peak, high rate of rise and last for a *few tens/hundreds of micro seconds* and are therefore called transients. During 1950s, Lightning Surges have resulted in failures. Several Transformers and Generators failed due to direct Lightning stroke on overhead lines near the substation/power station. By 1980s, the ZnO arresters were perfected. The failure rate due to Lightning and Switching has been minimised by proper insulation coordination and Surge Arrester Protection.

During 1960s and early 1970s, *Switching Surge Phenomena* were investigated, the Circuit-Breakers with low Switching Overvoltage Factors (K < 2) were developed. Surge arresters capable of diverting/absorbing switching surges were also developed.

Surges can cause spark over and flashover at sharp corners, flash over between phase and ground at *weakest point,* breakdown of gaseous/solid/liquid insulation, failure of transformers and rotating machines.

Several defensive-device are installed in the Network to intercept Lightning Strokes and minimise the peak/rate of rise of surges reaching the equipment. Ultimate and important protection is by ZnO Surge Arresters.

Strategy of Insulation Co-ordination

Following methods are applied to solve the problem of overvoltages and Insulation Co-ordination :

— Each Equipment has specified power frequency *Withstand Level and Impulse Withstand Levels.*
— The *Withstand Levels* of Equipment/Machines are co-ordinated with the *Protective Level* of nearest Surge Arrester. *Protective Levels* of Surge Arrester at each voltage level shall be coordinated.
— Every equipment is well protected and overall economy and reliability is achieved. In the event of occurrence of severe voltage-surge the damage is to least costly equipment (Spark Gap).
— Duplicate surge protection is provided in Substations, one surge arrester per phase at income bus and another surge arrester at Transformer terminal, for each phase.
— Rotating machines are provided with R-C Surge suppressors at the terminals.
— System Neutral is Earthed at every voltage level to reduce Coefficient of earthing and to discharge the surges.

Insulation co-ordination covers the following aspects :

— The causes and effects of Transient Overvoltages (Surges) and the Protection of Electrical Equipment Insulation.
— Standardisation of Nominal Voltage Levels, Highest Voltage Levels in the Network.
— Choice of Power Frequency withstand values for equipment insulation.
— Choice of BIL and Switching Impulse Withstand Levels for Equipment Insulation.

Basic Impulse Insulation Level (BIL) is the reference level expressed in kV peak (crest) voltage value with standard 1.2/50 μs Lightning impulse wave. Apparatus should be capable of withstanding test waves above BIL.

— Choice of Switching Impulse withstand levels for equipment insulation.
— Temporary power frequency overvoltage protection by overvoltage relays and circuit breakers.
— Co-ordination between the *Withstand Levels* of Equipment and the *Protective Levels* provided by surge arresters and the *Protective Margin* at various voltage levels for each equipment.

Power Frequency Overvoltages

The Power Frequency (50 Hz) overvoltages are the 50 Hz Overvoltages of value more than the Highest System voltage. For example in a 132 kV system, 145 kV is highest system voltage, and 150 kV rms is power frequency overvoltage. Such voltages are called temporary overvoltages.

The power frequency voltage withstand level of an equipment denotes the capability of the equipment to withstand p.f. overvoltage for a specified short duration (*e.g.* 1 min). The system experience occasional temporary power frequency over voltages arising during load-throw-off, wrong OLTC Operation, insufficient shunt compensation, resonance etc. Surge Arresters are not designed and installed for protection against the P.F. Overvoltages.

Overvoltage Relays are connected to bus-bars *via* voltage transformers and provide the protection against Temporary P.F. Overvoltages. The overvoltage relays respond to power frequency overvoltage and trip the circuit breakers against temporary overvoltages above permissible limits (*e.g.* 150 kV for a 132 kV System) within a few tens of milliseconds or seconds (with inverse characteristic). The insulation of transformers/generators/motors etc. connected to busbars is protected.

Lightning Surges

The equipment connected in the network are subjected to occasional *Lightning Surges* of high peak value, sharp rate of rise and short duration. The protection against lightning surges is given by *Lightning Arresters (Surge Arresters)*. The equipment has certain assigned *Lightning Impulse Voltage Withstand Level,* which is proved by conducting Lightning Impulse Voltage Test. The lightning a surges are simulated in High Voltage Test Laboratories by a representative 1.2/50 μs Lightning Impulse Wave obtained from an Impulse Generator.

Switching Surge

The *Switching Voltage Surges* occur during opening and closing unloaded EHV AC lines, breaking inductive loads, breaking capacitive loads etc. The switching surges are of comparatively longer duration (2500 μs), lower rate of rise and are represented by standard switching impulse test wave of 250/2500 μs. The peak value of switching surge is expressed in terms of Switching Overvoltage Factor. *Switching Impulse Withstand Level Test* is applicable to equipment rated 275 kV and above. The motor switching, reactor switching are special switching duties. (Ch. 18, Sec. 18.23 to 18.26), which generate switching surges.

The switching surges are simulated in High Voltage Test Laboratories by a representative 250/2500 μs Switching Impulse Wave obtained from an Impulse Generator.

The protective devices against Switching Surges are :

— ZnO surge arresters with high energy absorbtion capability, installed near the apparatus.

— RC Surge Suppressers, installed near the rotating machine terminals, circuit-breaker terminals.

Preventive Measures against Switching Surges are :

— Use of Circuit-Breaker with Low Switching Overvoltage Factor *K*.

— Use adequate phase-to-ground capacitance in the supply circuit to absorb the switching overvoltage.

Equipment Insulation. Each equipment has certain *internal* and certain *external* phase to ground insulation, and phase to phase insulation, creepage distance, clearances, insulation grading etc. The voltage grading rings improve the voltage stress profile and give high withstand values. These insulation requirements of AC electrical equipments are determined by the voltage stresses occurring during :

— Continuous Highest Power Frequency System-Voltage

— Occasional Temporary power frequency overvoltage caused by load-throw-off, oscillations, faults.

— Occasional Transient Lightning Surges

— Occasional Transient Switching Surges particularly due to switching of inductive/capacitive loads or EHV lines.

The dielectric stresses are imposed on internal and external, gaseous/solid and liquid insulation systems insulation systems of each equipment. The dielectric stresses depend on the peak vale, rate of rise, durations, of the voltage waveforms etc.

According to standard specification, each substation equipment has certain specified *withstand levels* of power frequency, lightning impulse and switching impulse voltage waveform. The withstand level is proved by relevant type tests and routine tests. The specified voltage withstand levels are :

— High Power Frequency Voltage Withstand Level for a short duration (U kV rms, 50 Hz for 1 minute).

— Lightning Impulse Withstand Level (Up kV peak, 1.2/50 μs lightning impulse test wave)

— Switching Surge Withstand Level (Up kV peak, 250/2500 μs switching impulse* test wave)

Definition of Insulation Level of the equipment. The combination of Rated Voltage and Specified one Minute Power Frequency Withstand level, Lightning Impulse Withstand Level, Switching Impulse withstand Level for the Equipment together are called *Insulation Level of the equipment.*

The grading between the Insulation Level of the equipment, Protective Level of Surge Arrester and the insulation levels/protective levels of the other equipment and surge arresters at the same voltage level, the grading between various voltage levels in the Network is called *Insulation Co-ordination.*

Steps in Insulation Co-ordination

1. Decide Equipment Insulation Level.
2. Decide Protective Level of Surge Arrester.
3. Co-ordination 1 and 2 for each equipment.
4. Co-ordination 3 for various equipment at the Voltage Level.
5. Co-ordination 3 between at various Voltage Levels.

The withstand levels of the equipment are co-related with the rated voltage of the equipment and the test values for type test and routine test and with the protective levels provided by the protective device (surge arrester, spark gap, surge absorbers, overvoltage relays, etc.) It is not economical/possible to design each equipment to withstand full lightning surge/switching surge/temporary overvoltage occuring in the network. Certain protective devices like Surge Arresters, Spark-gaps, Surge Absorbers, Overvoltage Relays are provided. These protective devices have certain protective levels against specified voltage waveforms.

Surge Arresters divert the switching surges/lightning surges above the protective level to earth within a few microseconds and protect the equipment against insulation failure. Spark gaps (coordinating gaps flashover externally during a voltage surge and protect the equipment insulation.

Table 18.2. Overvoltages and Protective Devices

Temporary-Power-frequency overvoltages

— Lasts for a few seconds to a few minutes

— Magnitudes approximately over 1.1 pu, phase to ground, rms

— Protection by inverse-overvoltage relay and opening of breakers

— Neutral earthing at each voltage level is necessary to avoid overvoltages in healthy phases single line to ground faults and arcing grounds.

Switching Overvoltage Surges*

— Occur during circuit breaker operation while breaking of inductive currents, restrikes in C.B. while breaking capacitive currents, closing unloaded EHV AC lines, etc.

— Represented by standard 250/2500 μs Switching Impulse Test wave. Each EHV Equipment should have withstand capability against Standard Switching Impulse of specified peak and test conditions.

— Magnitude of test voltage are taken from standard tables.

— Circuit-breakers should be suitable for switching duty so that switching overvoltages are within specified limits (*e.g.* 2 pu peak).

— Surge arresters and Surge Suppressors are used for protection.

— Neutral Earthing dissipates overvoltage to earth and helps the system insulation.

* The word *Impulse* is used for test waves produced in laboratory by means of an impulse generator. The word *surge* is for the wave in power system.

Lightning Overvoltage Surges

— Occur due to lightning strokes or discharges on overhead lines, outdoor equipment and surges travel through conductors.

— Represented by 1.2/50 μs Impulse test wave

— Magnitude of test voltages are taken from standard tables.

— Protection by Overhead Shielding Wires, Surge Arresters

— Neutral Earthing dissipates the voltage surge to earth.

— Each substation equipment has assigned value of Lightning Impulse Withstand Level. (above the Protective Level of SA.

*The word *Surge* is used for the transient voltage waves occuring in the network.

Basic Approach to Insulation Coordination In Power Systems

The rated voltages, withstand levels of equipment insulation are coordinated with the protective levels of the surge arresters such that protective levels are *less than* the withstand level with *certain protective margin.* This co-ordination between Insulation Levels of the equipment and protective levels of surge arresters is further coordinated for various equipments at the same voltage level and further for equipment at various voltage levels. Such a grading of withstand values and the protective levels of surge arresters at various voltage levels is called *Insulation Coordination.*

IEC (International Electrotechnical Commission) and IS (Indian Standards) Specification on Insulation Co-ordination on High Voltage Equipment; High Voltage Testing specify the values of

1. Nominal Power Frequency System Voltages
2. Highest Power Frequency System Voltages
3. Required Lightning Impulse Voltage Levels
4. Required Switching Impulse Voltage Levels
5. Protective Levels by Surge arresters
6. Withstand Levels of the Equipment against 2, 3, 4

System Designers/Consultants select the Insulation Levels at each voltage level from the Standards. These are coordinated for the entire Network having various voltage levels. The Equipment Insulation and Surge Arrester Protection Levels are graded (coordinated). The Equipment specifications are based on the coordinated values.

18.2. TERMS AND DEFINITIONS

1. **Insulation Level of an Apparatus.** A combination of withstand values both power frequency and impulse voltages which characterise the insulation of that apparatus with regard to the capability of withstanding dielectric stresses.

2. **Highest Voltage of Equipment/Apparatus.** The highest phase to phase voltage for which the equipment/equipment is designed; it corresponds to the Highest Power Frequency Phase to Phase System Voltage (U_m rms).

3. **Over Voltage.** Any time dependant voltage (U) exceeding the value ($\sqrt{2}/\sqrt{3}\ U_m$) instantaneous, phase to ground or ($\sqrt{2}\ U_m$) instantaneous phase to phase.

$$U > \sqrt{2}/\sqrt{3}\ U_m \text{ instantaneous, phase to ground}$$

$$U > \sqrt{2}\ U_m \text{ instantaneous, phase to phase.}$$

4. **Phase to Phase per unit overvoltage.** The ratio of peak of phase to phase actual voltage (Up) to peak of highest phase to phase voltage of the equipment

$$\text{PU Overvoltage} = \frac{U_p \text{ phase to phase}}{\sqrt{2}\ U_m \text{ phase to phase}} \text{ p.u.}$$

5. **Protective Level of the Protective Device.** The highest peak value of voltage that should not exceed at the terminals of the protective device when standard impulse voltage wave is applied to the installation under specified conditions of test.

6. **Withstand Level of Apparatus/Equipment.** The value of Standard test wave (power frequency/ or impulse) which the Equipment/Apparatus is assigned to withstand under specified test conditions.

7. Protective Margin $= \begin{bmatrix}\text{Protective Level}\\ \text{of Surge Arrester}\end{bmatrix} - \begin{bmatrix}\text{Withstand level}\\ \text{of the Apparatus}\end{bmatrix}$

8. **Surge Arrester (Lightning Arrester).** A protective device which discharges excess voltage surges to earth and provides protection to the power system apparatus/equipment subjected to overvoltage surge.

Types : 1. Gapped SiC Arresters (Valve Type Arresters)
2. Gapless ZnO Arresters (Metal Oxide Arresters).

9. **Insulation Coordination.** Grading of Withstand Levels of Apparatus/Equipment with the Protective Levels of Surge Arresters and co-ordination at the entire voltage level and various other voltage levels.

10. **Switching Overvoltage Factor K of the switching duty**

$$K = \frac{\begin{bmatrix}\text{Actual } U \text{ peak phase to ground voltage}\\ \text{value during switching duty}\end{bmatrix}}{\text{Peak rated Highest System Voltage phase to ground}}$$

$$K = \frac{\text{Actual voltage phase to ground, peak}}{\text{Rated Highest System Voltage, phase to ground, peak}}.$$

11. **Switching Overvoltage.** The overvoltage surge produced in the system inductance/capacitance by opening/closing operation of circuit breaker.

12. **Temporary Power Frequency Overvoltages.** The overvoltage of 50 Hz waveform produced by load throw-off, faults, resonance, poor voltage regulation by OLTC/Shunt Compensation etc.

13. **Spark Gap, Co-ordinating Gap.** An adjustable air gap with lower flashover value than the insulator and placed in parallel with the equipment insulator for protection against voltage surge. [Spark gap was the basic protection before 1960s when Surge Arresters were not under development. Spark Gap characteristics are *not exact* and can have variation of ± 30% depending upon weather conditions and shape of surge].

14. **Overhead Shielding Wire.** A stranded and earthed galvanised steel conductor located above the transmission line conductors/outdoor busbars/outdoor equipment etc. with sufficient clearance. The Overhead Shielding conductor is connected to earth electrode via another earthing connector at each galvanised steel structure/transmission tower.

15. **Underground Earthing Mat (Mesh).** The horizontal underground mesh of welded steel rods and vertical earth electrodes which together gives low earth-resistance earthing system for Substations/Power Stations/Towers/Installations.

16. **BIL-Basic Impulse Insulation Levels.** Reference levels expressed in kV peak (crest) of 1.2/50 μs standard lightning impulse wave. The apparatus withstand characteristics should be above the BIL.

17. **Critical Flashover Voltage (CFO).** Peak impulse voltage for a 50% probability of flashover for a particular apparatus.

18. **Impulse ratio** for flash over or failure of insulation

$$= \frac{\text{Peak value of impulse voltage}}{\text{Peak value of power frequency voltage wave}}$$

to cause the flash over or failure of insulation.

18.3. CHOICE OF INSULATION LEVELS OF SUB-STATION EQUIPMENT

The insulation of substation equipment should withstand the over-voltages occuring due to internal and external causes.

The over-voltages are two categories :

— Power frequency voltages

— Impulse voltage surges due to lightning and switching.

The temporary power-frequency over-voltages occur due to regulation, Ferranti, effect, load throw, etc.

The performance of insulation is verified by power frequency tests and impulse tests.

The surge arresters (lightning arresters) divert the transient overvoltages to earth and protect the sub-station insulation.

To achieve the desired insulation levels in the sub-station, following conditions should be satisfied :

1. Clearances should be as per recommendations of standards. These clearances are based on specified impulse withstand levels.
2. Each equipment should have specified impulse withstand level.
3. Surge arresters should be of specified protective level.
4. The protective ratio and protective margin should be correctly selected such that equipment design is economical and flash over/damage does not cause major damage to costly and important equipment.

Table 18.3. Insulation Levels of Sub-station Equipment

Normal Voltage line to line U_m	*Highest system voltage (line to line) kV r.m.s. U_m*	*Impulse withstand test dry with standard full wave, + ve and negative polarities kV (crest)*	*1 minute Power frequency withstand under standard condition kV r.m.s.*
kv r.m.s			
3.3	3.6	45	21
6.6	7.2	60	27
11	12	75	35
15	17.5	95	45
22	24	125	55
33	36	170	75
47	52	250	105
66	72.5	325	140
88	100	450	182
110	123	550	230
132	145	650	275
150	170	750	325
220	245	1050	460
400	420	1550	680

18.4. PROTECTIVE RATIO, PROTECTIVE MARGIN

The protection of equipment against impulse voltages waves by means of Surge arresters is expressed in terms of Protective Margin.

$$\text{Protective Ratio} = \frac{\text{Impulse Withstand Level of Equipment, kVp}}{\text{Protective Level of Surge Arrester, kVp}}$$

Separate protective ratio is specified for

(1) Lightning Impulse wave. (2) Switching Impulse wave.

Protective Ratios are usually above 1.2.

$$\text{Protective Margin} = \begin{bmatrix}\text{Equipment withstand} \\ \text{level}\end{bmatrix} - \begin{bmatrix}\text{Protective level of} \\ \text{Surge Arrest}\end{bmatrix}$$

Protective Margin may be expressed in terms of per cent of Equipment Withstand level

Protective levels are different for Lightning Impulse and Switching Impulse, *e.g.*

$$\frac{\text{Lightning Impulse Voltage withstand level}}{\text{Switching Impulse withstand level}} = 1.2$$

PART I. Lightning Over-voltages

18.5. LIGHTNING

Benjamin Franklin (1706-90) performed his famous experiment (1745) of flying kite in thunder cloud. Before his discovery the lightning was considered to be "Act of God". Frankling proved that the lightning stroke is due to the discharge of electricity. Franklin also invented lightning rods to be fixed on tall buildings and earthed to protect them from lightning strokes. Hence Franklin is a pioneer scientist in this field. *The large spark accompanied by light produced by an abrupt, discontinuous discharge of electricity through the air, from the clouds generally under turbulent conditions of atmosphere is called lightning.*

Representative values of a lightning stroke :

Voltage	2×10^8 volts 200, MV (peak)
Current	4×4^4 amp.
Duration	10^{-5} sec.
kW	8×10^9
kWh	22

$$\text{Energy} = \int u \cdot t\, dt = 22 \text{ kWh}$$

Static induced charges. An overhead conductor accumulate statically induced charge when a charged clouds come above the conductor. If the cloud is swept away from its place, the charges on the conductor is released. The charge travels on either sides giving rise to two travelling waves. The earth wire does not prevent such surges.

Another curious phenomenon is the unpredictable paths of lightning strokes. Normally they try to reach the earth and are therefore intercepted by lightning rods, trees, tall structures etc. Empire State Building of New York has been hit by several strokes. However some lightning strokes do not observe any rules. It has been reported that some strokes have travelled horizontally in all sorts of haphazard fashion.

B type stroke [Fig. 18.3 (*b*)] occurs due to sudden changes in charges of the cloud. If cloud 1 suddenly discharges to cloud 2, there is a sudden change in the charge on cloud 3. A discharge between cloud 3 and earth is called *B* stroke. Such stroke does not hit lightning rod, or earth wire. Therefore, no protection can be provided to the OH line against such strokes.

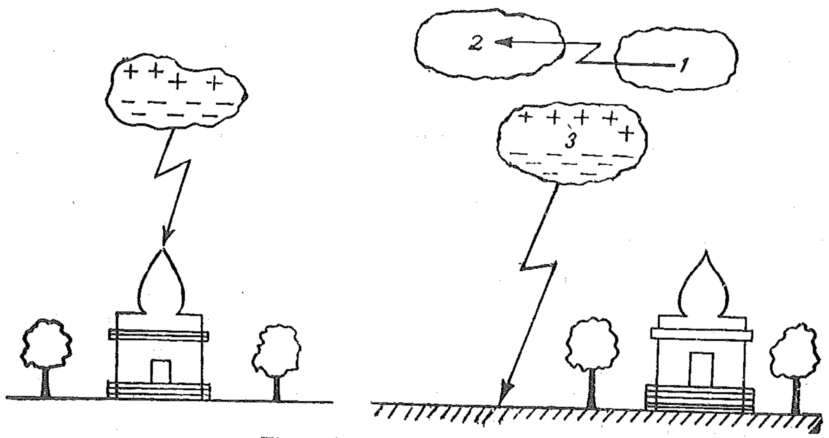


Fig. 18A-3. *A* stroke *B* stroke.

(*a*) A stroke occurs between charged cloud and earth. The lightning conductor or earth wire attracts such stroke.

(*b*) *B* stroke occurs because of sudden change in charge conditions in the clouds. Lightning conductor, or earth wires do not attract such strokes.

Attractive effect of OH Ground Wire and Earth Rods (MASTS). Earth rods (also called lightning rod) are placed on tall buildings. These are connected to the earth. The positive charges accumulate on the sharp points of the lightning rods, thereby the lightning strokes are attracted to them. The earth wires are placed above the OH transmission lines. At every tower this wire is grounded. The positive charges accumulate on this wire. The negatively charged strokes are attracted by the earth wire. In absence of the earth wire the lightning stroke would strike the line conductors causing a flashovers in transmission line.

Earth wires do not provide 100% protection. Weak strokes are not attracted by earth wires. *B* type strokes are also not attracted. However for the most dangerous "direct strokes" earth wire has proved to be a very good solution.

Practical experience has shown that earth wires have a shielding angle. The conductors coming in the shielded zone are protected against direct strokes. Shielding angle is between 30° to 40°. An angle of 35° is supposed to be satisfactory and economical for OH lines.

18.6. OVERHEAD SHIELDING SCREEN (*Earthed*)

The sub-station equipment are protected from direct lightning strokes by one of the following :

1. **Overhead shielding screen** (***Earthed***). Covering the outdoor sub-station and the overhead lines approaching the sub-station.

2. **Lightning Masts** installed at strategic locations in the switchyard. The tower-top is earthed. Mast is an independant structure.

Both the above methods are being used in India.

Lightning masts are preferred for outdoor switchyards upto 33 kV. For 66 kV and above, the lightning masts become too tall and uneconomical. The overhead shielding wires are preferred because they give adequate protection and the height of structures in the sub-station provided with overhead shielding wires is comparatively less than that with the of lightning masts.

Overhead shielding screen (*Earthed*). The entire switchyard is provided with earthed overhead shielding screen. The size of conductor is usually 7/9 SWG, galvanised steel round stranded conductor.

Transmission line conductors are protected by over head shielding conductor (earthed). The shielding angle (α) defined as follows. A vertical line is drawn from the earth wire. Angle α is plotted on each side of this vertical line. The envelope within angle 2α is called zone of protection.

The shielding angles are as follows :

American practice : 30°

British practice : 45°

The clearance between phase conductor and overhead shielding wire should be more than minimum phase to earth clearance.

OH = Overhead, above the conductor/apparatus. Ground = Earth.

18.7. LIGHTNING STROKE ON OH LINES (OVERHEAD LINE)

These can be the following :

(1) Direct strokes on line conductor. (2) Direct stroke on Tower Top.

(3) Direct stroke on Ground wire. (4) Indirect stroke or B stroke on OH lines conductor.

Direct Strokes on OH conductors. These are most harmful. The voltage being of the order of several million volts, the insulators flash-over, puncture and get shattered. The wave travels to both sides shattering line insulators, until the surge is dissipated sufficiently. The wave reaches the sub-station and produces stress on equipment insulators. Luckily, these strokes are prevented from striking the line conductor. All high voltage OH lines are protected by earth conductors. The outdoor switchyards are provided with overhead mesh of earth conductors. This mesh covers the complete switchyard.

Direct strokes on tower-top

Let, L = Inductance of tower. i = Current in tower.

R = Effective resistance of tower. e = Voltage surge between tower-top and earth.

$$e = L\frac{di}{dt} + Ri \text{ volts}$$

Let $\frac{di}{dt} = 10$ kA/μs.

$R = 5$ ohm. $L = 10$ μH

Then $e = 200{,}000$ V. This surge voltage appears between the tower-top and earth. The line conditions are virtually at earth potential because of neutral grounding. Hence this voltage appears between line conductors and tower-top. If this surge voltage exceeds impulse flash-over level, a flash-over occurs between tower and line conductor. Hence R is kept low for each tower.

A direct stroke on earth wire in the mid-span can cause a flashover between line conductor and earth wire or line conductor and tower.

Indirect strokes on line conductor can have the same effect as direct stroke on conductor. Indirect strokes are more harmfull for distribution lines but are not significant for EHV lines. Other factors are low tower footing resistance insulation level of lines. For lines rated 110 kV and above, the line insulation is high and back flashovers are rare. For line between 11 kV, 33 kV the insulation of lines is relatively low and back-flashovers are likely to occur.

18.8. PROTECTIVE DEVICES AGAINST LIGHTNING SURGES

Table 18.4

Device	*Where applied*	*Remarks*
Rod gaps	Across insulator string, bushing insulators. Support insulators	— Difficult to co-ordinate — Flashover voltage varies by ± 30% — Create dead shot circuit — Cheap
Overhead Ground Wires (earthed)	— Above overhead lines — Above the sub-station area	Provide effective protection against direct strokes on line conductors towers sub-station equipment.
Vertical Masts	— In sub-stations	— Instead of providing overhead shielding wires
Lightning Spikes/Rods (earthed)	— Above tall buildings	Protect Buildings against direct strokes. Angle of Protection α = 30° to 40°
Lightning Arresters (Surge Arresters)	— On incoming lines in each sub-station — Near terminals of Transformers and Generators — Pole mounted on distribution lines.	— Diverts over-voltage to earth without causing short-circuit — Used at every voltage level in every sub-station and for each line — Phase to ground
Surge Absorbers	— Near rotating machines or Switchgear — Across series reactor, valves.	Resistance Capacitance Combination absorbs the over voltage surge and reduces steepness of wave.

18.9. ROD GAPS OR SPARK GAP

The simplest protection of line insulators, equipment, insulators and bushings is given by Rod Gaps or Coordinating Gaps. The conducting rods are provided between line terminal and earthed terminal of the insulator with an adjustable gap. The medium of gap is air. The rods are approximately 12 mm dia or square. The gap is adjusted to breakdown at about 20% below flash-over voltage of insulator. The distance between arc path and insulator should be more than 1/3 of the gap length, *i.e.* $l_1 > l/3$ (Fig. 18.4). Refer Table 18.4 for gap-settings.

Precise protection is not possible by rod gaps. The breakdown voltage varies with polarity, steepness and wave-shape, weather. The power frequency currents continue to flow even after the high voltage surge has vanished. This creates an earth fault only to be interrupted by circuit breaker. Operation of rod gap, therefore, leads to discontinuity of supply. The advantage of gap is low cost and easy adjustment on site. For more precise operation, surge arresters are used.

Horn Gap. The gap between horns is less at the bottom and large at the top. An arc is produced at the bottom during high voltage surge. This arc commutes along the horn due to electromagnetic field action and length increases. The arc may blow out.

Impulse Ratio. Impulse ratio of a protective device is the ratio of breakdown voltage on specified impulse wave to breakdown voltage at power frequency.

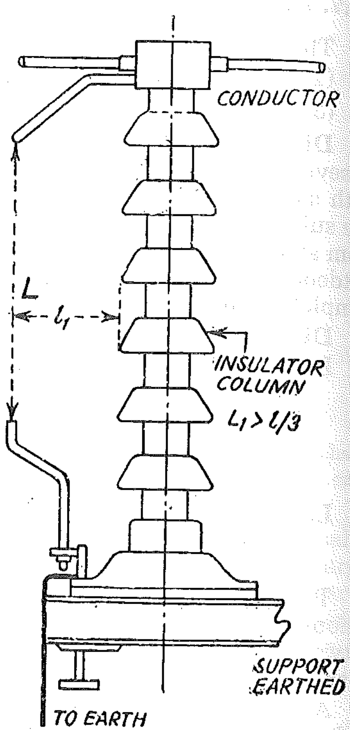


Fig. 18.4. Rod gap.

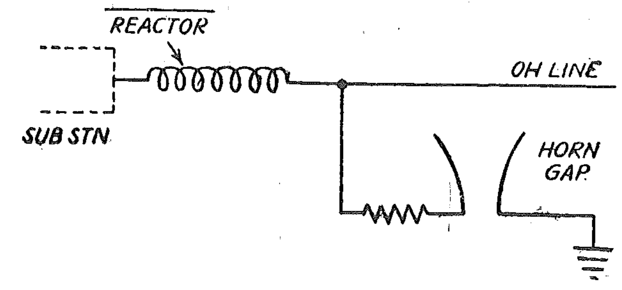


Fig. 18.5. Hom gap.

Typical impulse ratios :

Sphere Gap	:	1
Rod Gap	:	1.6 to 3
Horn gap	:	2 to 3.

18.10. SURGE ARRESTERS (LIGHTNING ARRESTERS)

Surge Arresters are usually connected between phase and ground (Fig. 17.1) in distribution system ; near the terminals of large medium voltage rotating machines and in HV, EHV, HVDC sub-stations to protect the apparatus insulation from lightning surges and switching surges.

The resistor blocks in the surge arrester offer low resistance to high voltage surge and divert the high voltage surge to ground. Thereby the insulation of protected installation is not subjected to the full surge voltage. The surge arrester does not create short-circuit like rod gaps and retains the residual voltage across its terminals.

Surge Arrester discharges current impulse surge to earth and dissipates energy in the form of heat.

After discharging the impulse wave to the earth, the resistor blocks in the surge arrester offers a very high resistance to the normal power frequency voltage and the arrester acts as open circuit. Surge arresters are not against temporary power frequency over voltages. They provide protection against surge voltage waves.

At present the following types of surge arrester are used :

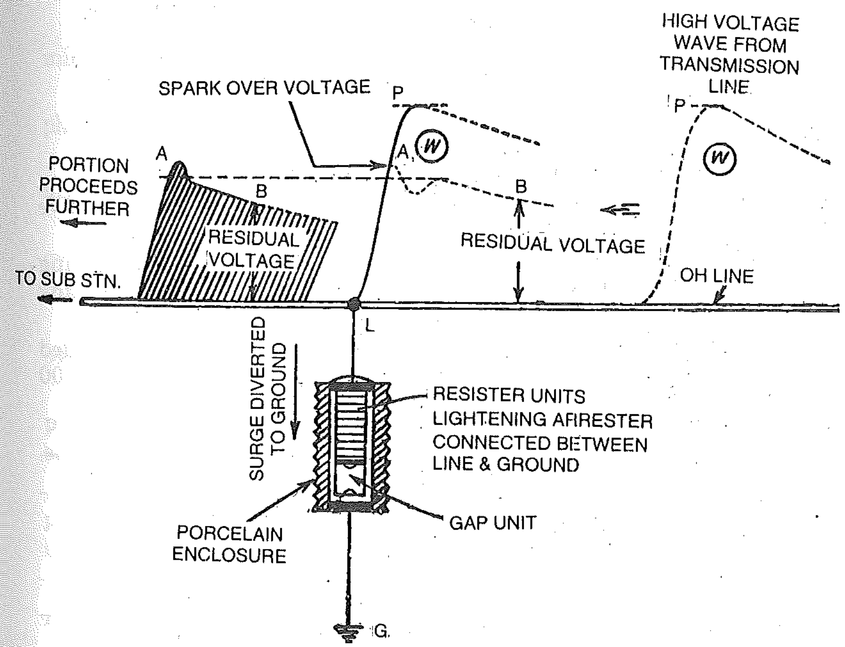
1. **Gapped Silicon-carbide Surge Arresters** called valve type or conventional Gapped Arresters. These consist of silicon-carbide discs in series with spark gap units.

2. **Zinc-Oxide Gapless Arresters** called ZnO Arresters or Metal-oxide Arresters. These are gapless and consist of zinc-oxide discs in series. ZnO arresters have superior V/I characteristic and higher energy absorption level. They are preferred for EHV and HVDC installations.

Gap Type SiC Arrester

Surge arrester is connected between phase and earth. It consists of silicon-carbide (SiC) resistor elements in series with gap elements. The resistor elements offer non-linear resistance such that for normal frequency power system voltage the resistance is high. For discharge currents the resistance is low. The gap unit consist of air gaps of appropriate length. During normal voltages the surge arrester does not conduct. When a surge-wave travelling along the line reaches the arrester, the gap breaks down. The resistance offered being low the surge is diverted to the earth. After a few μ seconds the surge vanishes and normal power frequency voltage is set up across the arrester. The resistance offered by resistors to this voltage is very high. Therefore, arc current in gap units reduces and voltage across the gap is no more sufficient to maintain the arc. Therefore, the current flowing to the earth is automatically interrupted and normal condition is restored. Thus, high voltage surge is discharged to earth. Hence the insulation of equipment connected to the line is protected.*

Fig. 18.6 illustrates the operation of a surge arrester. When a lightning surge or switching surge travelling along the transmission line reached the terminal of the surge arrester, at a particular



W Surge travelling along OH line
P Peak of impulse wave
A Voltage at which LA sparks over
B Average residual voltage.

Fig. 18A-6. Illustrates the operation of Surge Arrester.

* Refer Sec. 17.2 for Location of Surge Arresters.

voltage (instantaneous value) A, depending upon steepness of wave front, the SA sparks over. The voltage is called impulse sparkover voltage. Hence the surge is diverted to earth through the SA and insulation on sub-section side is not subjected to peak voltage *P*. After breakdown the voltage across LA does not drop to zero like in rod gaps because of the series resistors. The voltage across the gap remains at residual value *B* for a short time. *Hence line to earth voltage remains at residual value during discharge.* A portion of wave proceeds further but the peak and steepness of wave front are reduced.

After short time of the order of some microseconds, the wave is discharged and normal frequency voltages appear across the SA. The normal voltage is not enough to maintain the arc in the gap units and the arc extinguishers. The SA restores the original condition (Fig. 18.8).

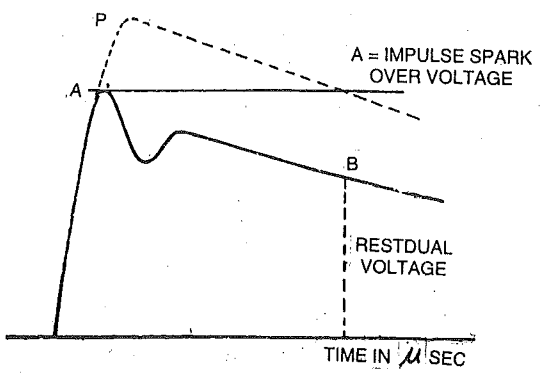


Fig. 18A-7. Voltage characteristic of surge arrester.

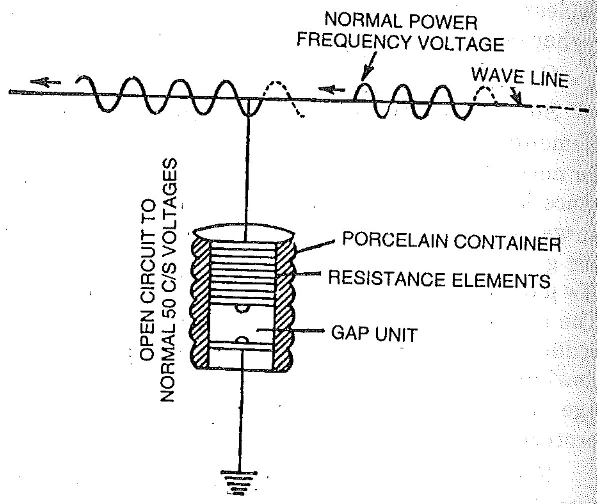


Fig. 18A-8. SA restores normal condition as the normal voltage is not enough to maintain the arc in the gap unit. The resistance offered to low currents by resistor elements is high — Gap is blown out by magnetic field.

Classification of Surge Arresters

The classification is based on voltage, current and energy capability. (Ref. Table 18.5).

(1) **Station Type SA.** This has highest capability for energy dissipation and lowest protective level.

(2) **Line Type Surge Arrester** (Intermediate type). These are generally used for protecting large transformers, intermediate sub-stations. These are smaller than station transformers. Rating upto 5000 A.

(3) **Distribution type and Rural or Secondary type surge arresters.** These are intended for pole mounting in distribution circuits for protection of distribution transformers. Rating : 2500 A and 1500 A. (Refer Table 18.2).

Table 18.5. Classification of Surge Arrester

	Station type	*Line type*	*Distribution type*
Standard normal discharge current (amperes) peak	10,000	5000	2500 : 1500
Voltage rating kV r.m.s.	3.3 — 245	3.3 — 123	Upto 3.3
Application (Ref. Sec. 18.6)	Large power-Station and Large Sub-station	Intermediate, Large Sub-station, Medium Power Station	Distribution system ; Rural Distribution

Refer Definitions in Sec. 18.11.

18.11. SURGE ARRESTER SPECIFICATIONS AND TERMS

1. **Surge arrester** is a device designed to protect electrical equipment from transient high voltage, to limit the duration and amplitude of the follow current.

2. **Non-linear resistor.** The part of the arrester which offers a low resistance to the flow of discharge currents thus limiting the voltage across the arrester terminals and high resistance to power frequency voltage, thus limiting the magnitude of follow current.

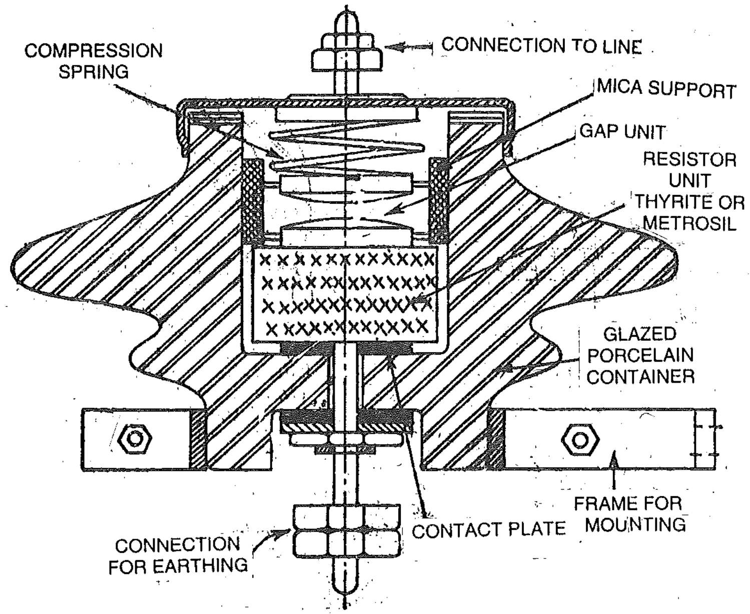


Fig. 18A-9. Distribution type surge arrester.

3. **Rated voltage of the arrester.** Maximum permissible RMS voltage between the line terminal and earth terminal of the arrester as designated by the manufacturer.

We have to note this term carefully. For all the other apparatus, the rated voltage is generally phase to phase. For Surge Arrester rated voltage is in terms of phase to ground. (Ref. Sec. 18.11).

4. **Follow current.** The current which flows from connected power source through lightning arrester following the passage of the discharge current.

5. **Normal Discharge Current.** Surge current which flows through the SA after the spark over, expressed in crest value (peak value) for a specified wave. This term is used in classifying the SA (station type, line type, distributor type).

6. **Discharge Current.** The surge current which flows through the arrester after the spark over.

7. **Power frequency spark-over voltage.** r.m.s value of power frequency 50 Hz voltage applied between the line and earth terminals of arrester and earth which causes sparkover of the series gap.

8. **Impulse spark-over voltage.** Highest value of voltage attained during an impulse of given polarity, of specified wave shape applied between the line terminal and earth terminal of an arrester before the flow of discharge current.

9. **Residual voltage (Discharge voltage).** The voltage that appears between the line terminals and earth, during the passage of the discharge current.

10. **Rated current.** Maximum impulse current at which the peak discharge residual voltage is determined.

11. **Coefficient of Earthing**

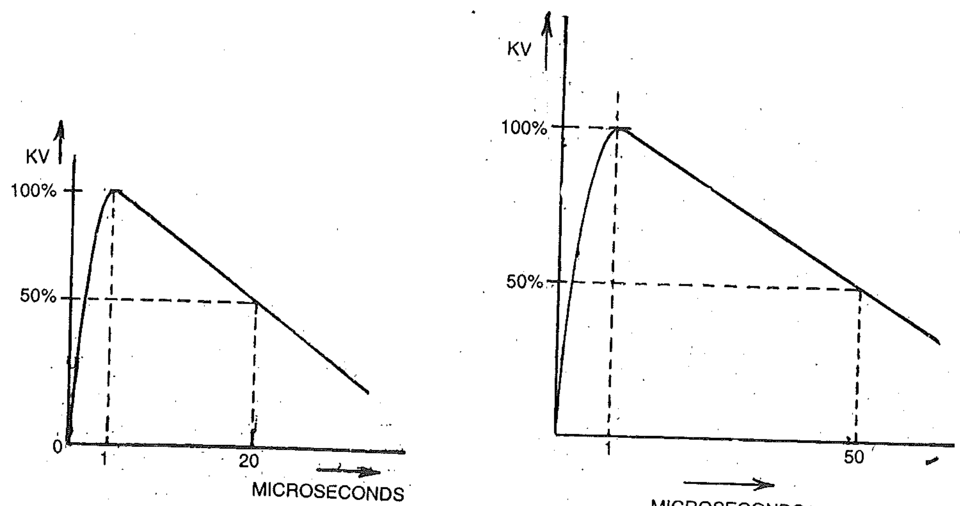
$$= \frac{\text{Highest r.m.s. voltage of healthy phase to earth}}{\text{Phase to phase normal r.m.s. voltage}} \times 100$$

(during earth fault on one phase).

18.12. TESTS ON SURGE ARRESTERS

The standard impulse test waves are shown in Fig. 18.10 (*a*) and (*b*). Tests performed on SA are the following :

1. 1/50 impulse sparkover test.
2. Wave front impulse sparkover test.
3. Peak discharge residual voltage at low current.
4. Peak discharge residual voltage at rated diverter current.
5. Impulse current withstand test.
6. Switching-impulse voltage test.
7. Discharge capability of durability.
8. Transmission line discharge test.
9. Low current long-duration test.
10. Power duty cycle test.
11. Pressure-relief test.



(*a*) 1/20 Impulse current wave

(*b*) 1/50 Impulse wave (Voltage wave)

Fig. 18.10

18.13. RATED VOLTAGE OF SURGE ARRESTER

It is the maximum power frequency voltage between the terminals of the Surge Arrester at which the Surge Arrester is capable of performing its rated duty. For a Surge Arrester to be connected phase to earth, the minimum required voltage is calculated as follows.

U_n = Nominal system voltage r.m.s. phase to phase

U_m = Highest system voltage, phase to phase

U_a = Rated voltage of the Surge Arrester, kV rms (phase to ground)

C_e = Coefficient of earthing.

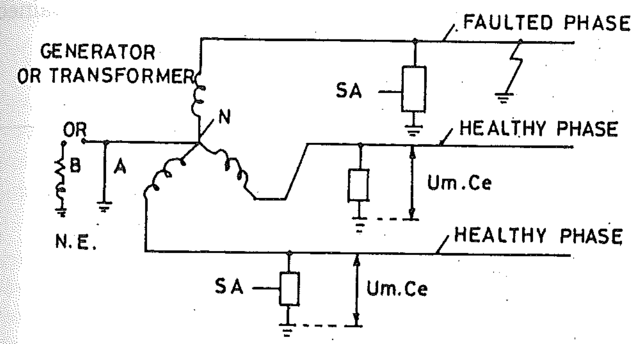
The surge arrester pole is connected between phase and ground. The rated voltage should be more than the phase to ground voltage on unfaulted phase during a single line to ground fault on any other phase. (Ref. Sec. 18.11.)

During a single phase to earth fault on one phase, the phase to ground voltage of other two healthy phases rises to $(U_m \cdot C_e)$. The Rated Voltage of surge arrester (U_a) should be more than $(U_m \cdot C_e)$ rms kV continuous across the terminals.

$$U_a > U_m \times C_e \text{ kV rms}$$

Note : U_a is across the terminals of the Surge Arrester Pole. Surge Arrester should be capable to perform its rated duties at rated rms voltage U_a across its terminals. The leakage currents through the surge arrester pole during normal system voltage and after diverting the surge should be only a few mA.

In a system without neutral-earth, the phase to earth voltage of phase *A* and phase *B* rises to 3 U_m during a single phase to earth fault (*F*) on phase *C*. In an neutral earthed system the voltage of healthy phases rises to $C_e \cdot U_m$.



SA-1— in unfaulted phase, during a single phase to earth fault *F*.
A — Solid or Effective Neutral Earthing : $C_e < 0.8$
B — Non-Effective Neutral Earthing : $0.8\, C_e < 1$
U_m — Highest phase to phase power system voltage
C_e — Coefficient of Earthing

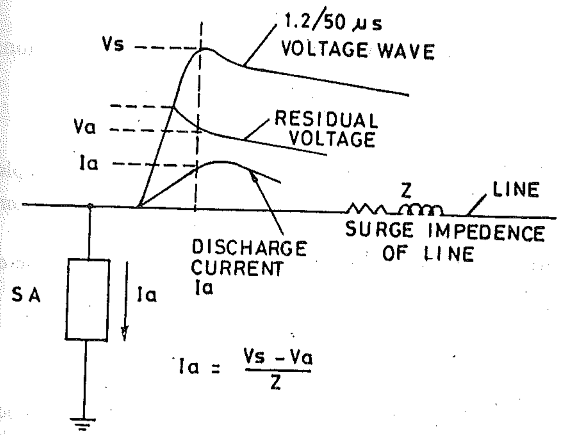
Fig. 18 A. 13. Explaining the voltage across the Surge Arrester

18.14. COEFFICIENT OF EARTHING (C_e) is the ratio :

$$C_e = \frac{\text{Highest phase to ground voltage of healthy phase}}{\text{Phase to phase voltage } U_m \text{ rms}} \times 100$$

measured during a single phase to ground fault.

For Non-Effectively Earthed System $C_e = 1$.



V_s = Surge Voltage, kV*
V_r = Residual Voltage of SA, kV*
Z = Surge Impedance of transmission line, on m
I_a = Discharge current through the SA, kA*
*Instantaneous values from waveform

Fig. 18.14. Explaining Surge Current Calculation.

C_e For Effectively Earthed System

For *effectively earthed* system, (solid neutral earthed system) Coefficient of earthing $C_e < 0.8$. Therefore, the Surge arrester rated voltage is

$$U_a > 0.8\ U_m \text{ rms}$$

Surge Voltage (V_s). *kV instantaneous* is taken as 2.5 times Critical Flashover Voltage (CFOV) of Line Insulation. Therefore Discharge Current I_a is given by :

$$I_a = \frac{2.5 \text{ CFOV of Line–Residual Voltage of Arrester}}{\text{Surge Impedance of Line}}$$

$$= \frac{2.5 \text{ CFOV} - V_r}{Z}$$

SUMMARY

Insulation Coordination : Coordination between Withstand Levels of Equipment, Protective Levels of protective devices, with adequate protective margin such that overall economy is obtained and least damage is caused to the electrical installation during overvoltage surges.

Table of Summary Type of Overvoltages ; Protections/Time, Withstand, Tests.

Temporary Power Frequency Overvoltage (ms or s)	Lightning Surge (μs)	Switching Surge (μs)
↓	↓	↓
Overvoltage Relay & CB < 70 ms	Surge Arrester app. < 1.2 μs	Surge Arrester app. < 100 μs
↓	↓	↓
Power Frequency Voltage Withstand Level kV rms	Lightning Surge Withstand Level kV peak	Switching Surge Withstand Level kV peak
↓	↓	↓
One minute P.F. Voltage Withstand Test	Lightning Impulse Test Withstand Test	Switching Impulse Withstand Test

Peak Value = Crest in kV instantaneous.

Basic Impulse Insulation Level (BIL) is reference level of the expressed in peak (crest) voltage value with standard 1.2/50 μs. Lightning impulse wave. Apparatus should be capable of withstanding test waves above BIL.

Other withstand levels get co-related with BIL as per applicable Standard Specifications (IEC/IS).

QUESTIONS

1. State the difference between the Nominal System Voltage and Highest System Voltage. Give example.
2. Which are the Voltage Withstand Values assigned to a High Voltage Equipment ? Which are the corresponding tests for proving these Withstand Capabilities.
3. Explain the Protective Characteristic of a Surge Arrester against the Withstand Characteristic of Equipment on a Voltage/Time Curve.
4. Define the terms :
   — Insulation Coordination
   — Rated Voltage of Surge arrester
5. A 132 kV Busbar needs a surge arrester protection. The system neutral is non-effectively earthed. The surge impedance of the incoming line is 400 ohm. The highest system voltage is 145 kV rms ph. to ph. Calculate : (A) Voltage Rating of the Surge arrester for the Busbar Surge Protection. (B) Discharge Current corresponding to surge voltage Vs= 300 kV instantaneous, residual voltage $V_r = 250$ kV instantaneous.

6. Define: "Coefficient of Earthing." What is the significance of the coefficient of earthing in the selection of voltage rating of Surge Arrester ?
7. State the various protective installations for intercepting Lightning Surges. Sketch a typical wave of Lightning Surge. Explain operation of a ZnO Surge Arrester.
8. Explain the basic difference between the construction, operation and characteristics of a SiC Gapped Surge Arrester and ZnO Surge Arrester.
9. State the following for a 400 kV High Voltage Equipment :
   Withstand Levels to be Specified :
   — Name of proving test :
   — Names of Protective equipment.
10. What is *Shielding Angle* of an overhead ground wire ? What are the values as per American and European Practices ?
11. Explain the origin of Switching Overvoltage Surges. What are the time duration of a Switching Surges ? Define Switching Overvoltage Factor.
    During no-load closing of a 400 kV transmission line, the peak of switching over voltage in one phase was 880 kV peak. Calculate the switching over voltage factor. The highest system voltage is 420 kV rms.
12. Explain the function of (A) Preinsersion Resistors (B) Opening Resistors ; with a 400 kV Circuit Breaker.
13. Explain the causes of overvoltages at Medium High Voltages (< 33 kV) and the principle of Surge Absorber Protection for a Rotating Machine.

18-B

Neutral Grounding (Neutral Earthing)

18.15. INTRODUCTION TO NEUTRAL GROUNDING

The three phase 50Hz AC power systems *with neutral grounding at every voltage level* are used for generation, transmission, distribution and utilization. The neutral points (star points) of star-connected 3 phase winding of power transformers, generators, motors, earthing transformers are connected to low resistance ground. (earth electrode/earth mat). Such a connection is called Neutral Grounding (Neutral Earthing).

Before 1950s the power systems were often without neutral grounding. Such systems were called *Ungrounded Systems.* Such systems experience repeated arcing grounds.* In ungrounded systems, insulation failures occur in several equipment, during single phase to ground faults elsewhere. The earth fault protection of ungrounded systems is difficult. Insulation failures may occur in several equipment and machines over entire voltage level during a single earth fault at remote location. The ungrounded systems must necessarily have equipment insulation withstand level corresponding to next higher system voltage to avoid cascade insulation failures. The ungrounded neutral system needs a costlier insulation system of next higher voltage level (*e.g.* 11 kV insulation for 6.6 kV Busbars and Motors, transformers, CTs, VTs, etc.).

Ungrounded Systems have *advantage* of negligible earth fault current but *disadvantage* of arcing grounds. Modern power systems are with grounded neutrals except some continuous process systems and essential protection/auxiliary supply systems where single phase to ground faults should not to trip entire bus supply.

Equipment Grounding is different from the Neutral Grounding. Equipment grounding is the connection between non-current carrying metallic parts in electrical installation to earth. By earthing the part, the voltage is within safe value even during earth fault. Equipment grounding is for Safety and for discharging earth fault currents effectively (till protection operates on earth fault and faulty part is disconnected).

18.16. TERMS AND DEFINITIONS

1. **Earthing or grounding.** Connecting to earth or ground.

2. **Neutral earthing or system neutral earthing (grounding).** Connecting to earth, the neutral point, *i.e.* the star point of generator, transformer, rotating machine, neutral point of a grounding transformer.

The calculations of third harmonic and zero sequence earth fault currents is covered in Ch. 23.

* Intermittent, repeating phase to ground arc through air insulation on overhead line/exposed conductor due to charging and discharging of phase to ground capacitance.

3. **Reactance earthing.** Connecting the neutral point to earth through a reactance.

4. **Resistance earthing.** Connecting the neutral point to earth through a resistance.

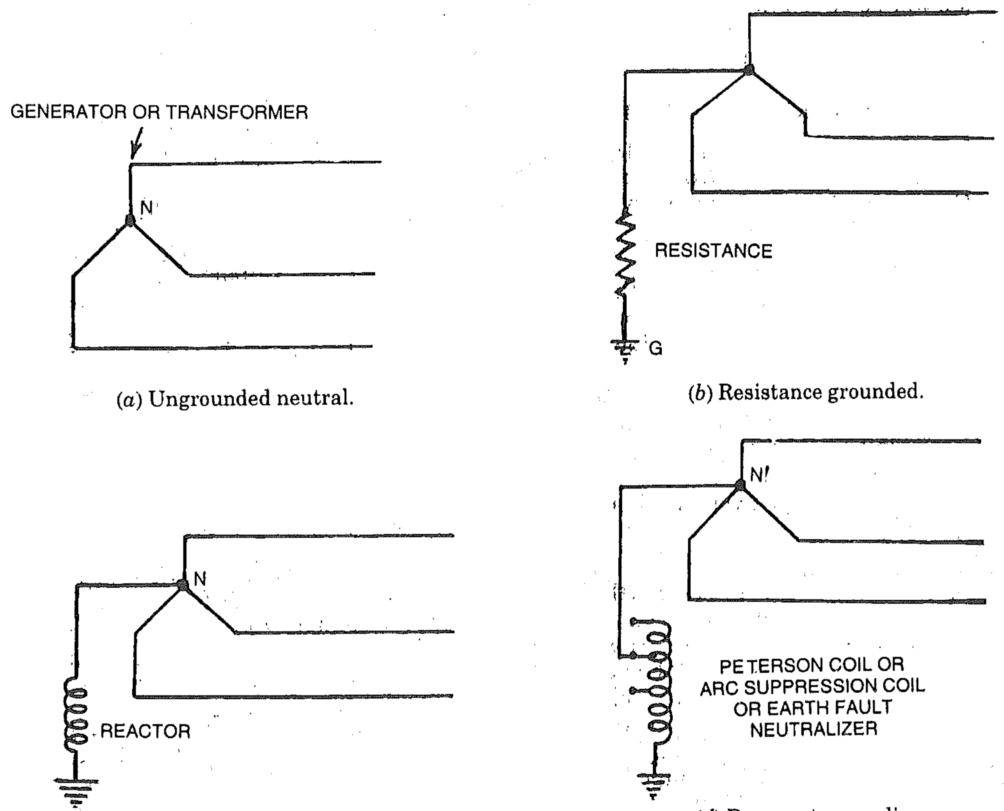
5. **Non-effective earthing.** When an intentional resistance or reactance is connected between neutral point and earth. Coefficient of earthing > 80%.

6. **Solid earth or effective earthing.** Connecting the neutral point to earth without intentional resistance or reactance, coefficient earthing < 80%.

7. **Resonant earthing.** Earthing through a reactance of such a value that power frequency current in the neutral or ground connection is almost equal opposite to power frequency capacitance current between unfaulted phases and earth. In this case the reactance between the neutral point and earth is selected to neutralise the power frequency capacitive current between line and earth. Resonant earthing is in fact a reactance earthing, with a selected value of reactance to match with line to ground capacitance.

8. **Coefficient of Earthing.** Refer Sec. 18.13

9. **Petersen coil, arc suppression coil, ground fault neutraliser.** All the three terms have the same meaning. The adjustable reactor (specially constructed) connected between neutral and earth, the reactance is such that power-frequency current between line and earth due to capacitance of healthy lines and earth is equal and opposite to the current in the earth connection. In other words, the reactor used in resonant earthing is called Peterson coil or arc suppression coil or earth fault neutralizer.



(*a*) Ungrounded neutral. (*b*) Resistance grounded.

(*c*) Reactance grounding. (*d*) Resonant grounding.

Fig. 18B-1. Types of neutral grounding.

10. **Ungrounded system.** The system whose neutral points are not earthed. The system is also called Isolated Neutral System.

11. Earth Fault Factor. It is calculated at the selected point of the system for a given system. It is a ratio :

$$\text{Earth fault factor} = \frac{V_1}{V_2}$$

when V_1 = Highest rms phase-to-phase power frequency voltage of healthy phases during earth fault on another phase.

V_2 = rms phase to earth power frequency voltage at the same location with fault on the faulty phase removed

Nature of the Problem

Consider a high voltage line connected to supply and without load. Even if no currents are drawn by the load, the conductors of the system continue to charge the system capacitance alternately to positive and negative polarity. The distributed capacitance between phases and earth draw charging currents from the source. The charge is given by

$$Q = CV$$

where Q = charge, coulombs

C = capacitance, farads

V = voltage, volts.

For high voltage systems, the capacitance and the charging currents are significant and the reactive power may be of the order of hundreds of kVAr. Therefore, the reactive kVAr influences the total kVA of the system. The reactive kVAr becomes very important and should be controlled. During ground faults, the reactive kVAr cause substantial flow of capacitance current flow with ground as a return path. Neutral grounding is a simple method of reducing such currents.

18.17. DISADVANTAGES OF UNGROUNDED SYSTEMS

In earlier years of the electrical power systems, the power systems were without neutral grounding. The following difficulties are encountered in ungrounded systems. Therefore, ungrounded systems are no more used.

1. **Arcing grounds.** The phenomena of arcing ground is commonly experienced with ungrounded systems. A temporary fault caused by falling on a branch, lightning surge, etc. creates an arc between phase conductor and ground. The arc extinguishes and restrikes in a repeated, regular manner. The phenomena is called "arcing ground". Arcing current is low due to high resistance of arc-path through air. But voltages of other two phases overshoot repeatedly.

Consider overhead line, R, Y, B connected to the system at normal voltage.

Each line has an inherent distributed capacitance with respect to earth. Consider an earth fault on phase B. The distributed capacitance discharges through the fault when the gap between F and ground breaks down. The capacitance, again gets charged and again discharged. Such repeated charging and discharging of line to ground

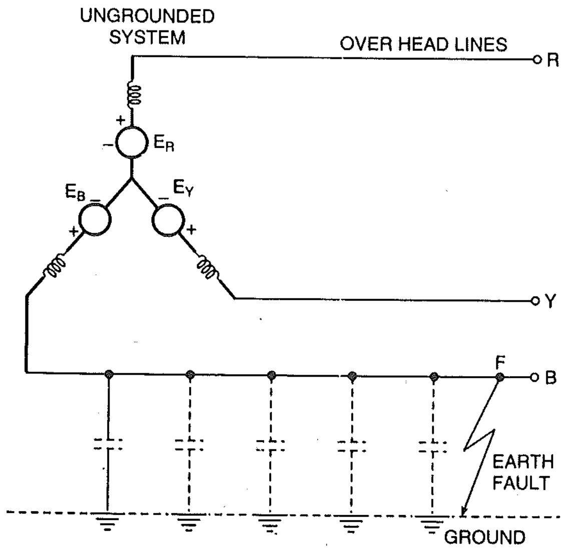


Fig. 18B-2. (a) Phenomena of Arcing Grounds. (The distributed capacitance gets changed and then discharged through the earth fault).

capacitance resulting in repeated arcs between line and ground is called Arcing Grounds. Arcing ground produce severe voltage oscillations reaching three to four times normal voltage. Secondly, a temporary fault grows into a permanent fault due to arcing grounds. The problem of arcing ground is solved by earthing the neutral through a coil called Petersen coil or Arc suppression coil or earthing reactor.

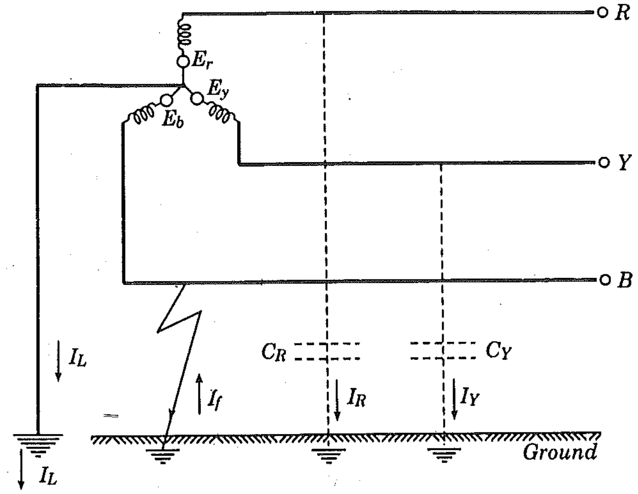


Fig. 18B-2. (b) Effect of Grounding.

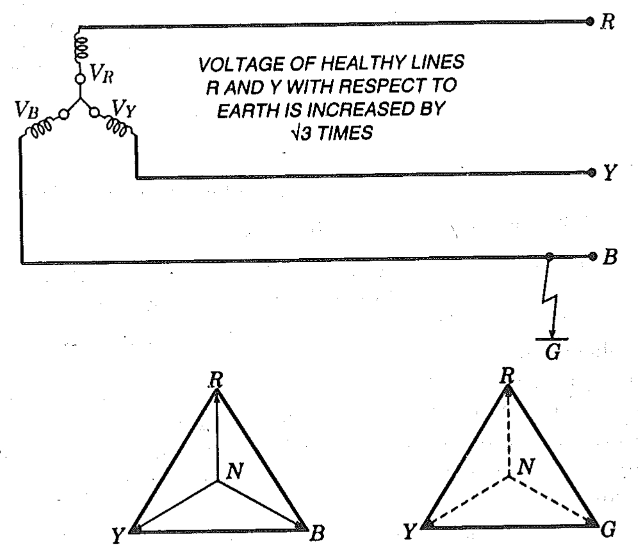
The charging currents, I_B, I_Y are neutralised by I_L, the current flowing through the neutral connections, *i.e.*

$$I_R + I_Y + I_L = 0$$

Thereby the arc in the phase to ground fault is extinguished.

2. In ungrounded systems, the voltage of healthy phases above earth is increased by $\sqrt{3}$ times when an earth fault occurs on a phase. This causes stress on the insulation of all the machines and equipment connected to the system. The voltage rise of the phase above earth is sustained and thereby insulation failure is likely to occur in connected machines, though fault current in arcing ground may be negligible.

Consider a system (Fig. 18B-3) in which one phase is faulted to ground. The potential of the phase becomes earth potential. Therefore, the voltage of healthy phases (R and Y above ground becomes equal to line voltage which is $\sqrt{3}$ times the phase voltage.



(a) BEFORE FAULT (b) AFTER FAULT

Fig. 18B-3. Effect of an earth fault on an ungrounded system.

Suppose a voltmeter is taken and the voltage of phases R, Y, B, is measured. During healthy state the voltages of phases R, Y, B above earth will be equal to phase voltage. The voltages between RY, YB, BR will be $\sqrt{3}$ time phase voltage. When an earth fault occurs on phase B, the voltage of B with respect to earth becomes zero. The voltage of health phases R and Y with respect to ground are increased to $\sqrt{3}$ times their normal value. The phase to phase voltage V_{RY}, R_{YB}, V_{BR} remains unchanged.

3. In ungrounded systems, earth faults cannot be easily sensed and the earth fault relaying becomes complicated. In grounded system, earth fault current is enough operate earth fault relay. Secondly, the current in neutral circuit can be used to operate earth fault relay (Refer Fig. 18.B-4)

4. The overvoltages due to induced static charges are not discharged to earth in ungrounded systems. The voltages due to lightning surges do not find path to earth.

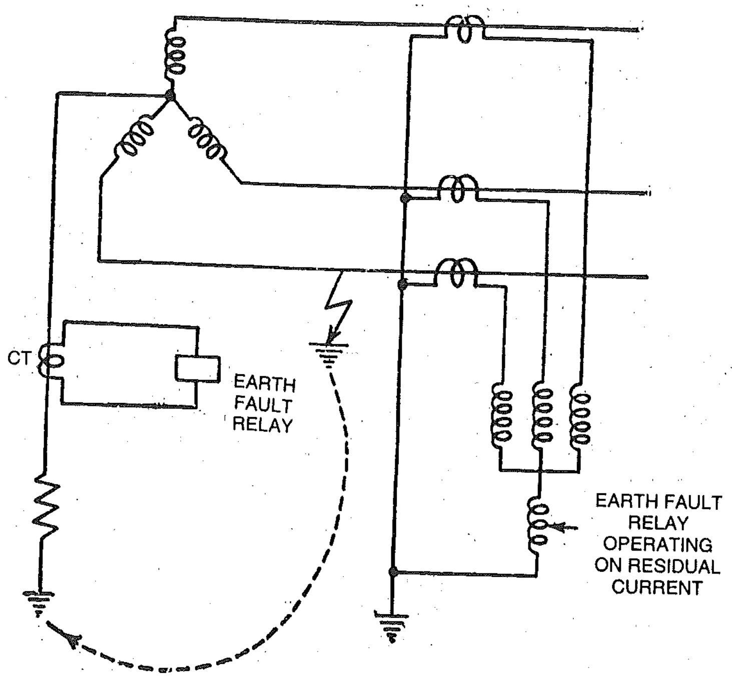


Fig. 18B.4. Neutral grounding is useful in earth fault relaying.

18.18. ADVANTAGES OF NEUTRAL GROUNDING

1. Arcing grounds are reduced or eliminated. The arcing ground current flowing through the neutral to ground connections is made almost equal and opposite to the capacitive current from healthy lines to ground. Thereby $I_L + I_R + I_Y = 0$ and arcing grounds are eliminated. The system is not subjected to overvoltage surge due to arcing grounds.

2. The voltages of healthy phases lines with respect to earth remain at normal value. They do not increase to $\sqrt{3}$ time normal value as in the case of ungrounded system.

3. The life of insulation is long due to prevention of voltage surges caused by arcing grounds. Thereby reduced maintenance, repairs, breakdowns. Improved continuity.

4. Stable neutral point.

5. The earth fault relaying is relatively simple. Useful amount of earth fault current is available to operate earth fault relay.

6. The over-voltages due to lightning are discharged to earth.

7. By employing resistance or reactance in earth-connection, the earth fault current can be controlled.

8. Improved service reliability due to limitation of arcing grounds and prevention of unnecessary tripping of circuit-breakers.

9. Greater safety to personnel and equipment due to operation of fuses or relays on earth fault and limitation of voltages.

10. Life of equipments, machines, installation is improved due to limitation of voltage. Hence overall economy.

18.19. TYPES OF GROUNDING

1. **Ungrounded system.** It is used no more. The neutral is not connected to earth. Also called insulated neutral system.

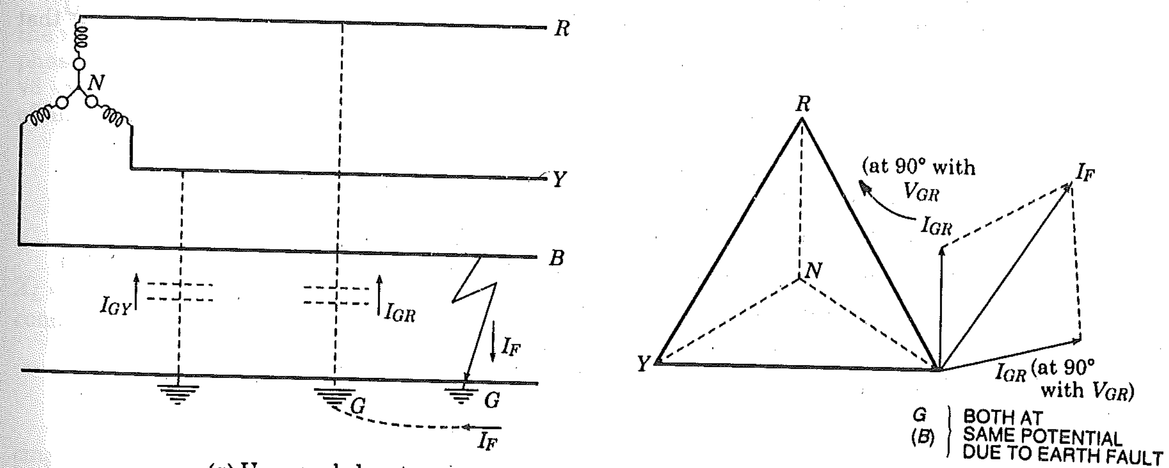
2. **Solid Grounding or Effective Grounding.** The neutral is directly connected to ground without any intentional impedance between neutral and ground. The coefficient of earthing is less than 80% for such systems.

3. **Reactance Grounding.** Reactance is connected between neutral and ground.

4. **Resonant Grounding.** An adjustable reactor of correctly selected value to compensate the capacitive earth currents is connected between neutral and earth. The coil is called Petersen coil or Arc suppression coil or Earth fault neutralizer.

Principles

(A) **Ungrounded System** (Fig. 18B.5). I_F is 90° is ahead of V_{GN} or V_{BN}. I_{GY} capacitive current from Y to earth is 90° ahead of V_{GY} and capacitive current I_{GY} from line R is 90° ahead of V_{GR}. Though the neutral is not grounded, earth fault is fed by the two capacitive currents I_{YG} and I_{GR} through earth connection. The earth fault current is very low.



(a) Ungrounded system. (b) Simplified explaination.

Fig. 18B-5. Ungrounded system, fault on phase B.

(B) **Solid of Effective Earthing.** The situation is dramatically changed if neutral is grounded (Fig. 18.B.7). Referring to Fig. 18B.5 a fault occurs between line B and ground. I_F the fault current lags behind V_{NB} by 90° since the circuit is predominantly inductive (due to transformer/machines and line inductances). The potential of neutral is held at earth potential due to grounding. That is N and G will be at the same potential neglecting impedance of link NG. Capacitance current I_{GY} leads voltage V_{GY} by 90°, and I_{GR} leads V_{GR} by 90°. Their vector, *i.e.* $I_{GY} + I_{GR} = I_G$, the net capacitance current. From the geometry of the vectors, we can see that I_F is in phase opposition with I_L. Hence I_F due to arcing grounds is eliminated or reduced by I_G.

Solid or Effective Earthing. By solid grounding, the earth fault current during arcing grounds is partially or completely eliminated by the capacitive ground current. Hence arcing grounds are substantially reduced. Secondly the potential of healthy phases above earth is held on at approximately constant value. However earth fault current is high.

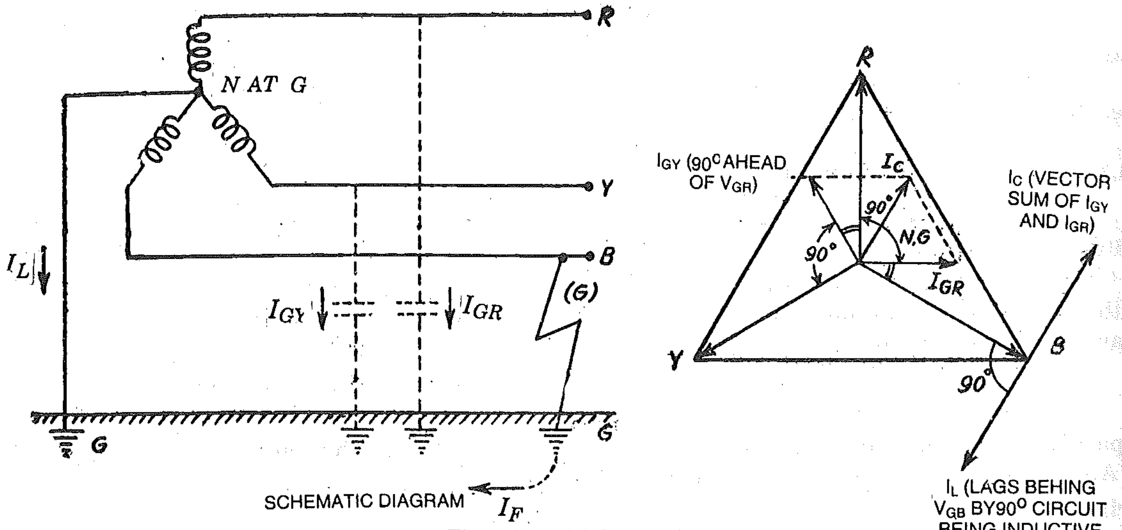


Fig. 18B.6. Solid grounding.

(C) **Resistance Earthing.** For circuit between 3.3 kV and 33 kV, the capacitive ground current (I_{GY}, I_{GB}) may not be large enough to demand reactance grounding. Secondly the ground fault current for solid grounding become excessive. Hence it is a practice to connect the neutral point of circuits of this voltage range (3.3 to 33 kV) through resistance. The resistance in the ground-neutral connection limits the fault current. From the theory of symmetrical components, we know that single line to ground fault current is :

$$I_F = \frac{3E}{Z_1 + Z_2 + Z_0}$$

$$Z_0 = Z_{g0} + 3Z_n$$

where E = Voltage per phase r.m.s.

Z_1 = Positive sequence impedance Thevenin's equivalent.

Z_2 = Negative sequence impedance Thevenin's equivalent.

Z_0 = Zero sequence impedance. [Ref. Fig. 23.1]

Z_{g0} = Thevenin's equivalent of zero sequence circuits.

Z_n = Impedance in neutral to ground connection.

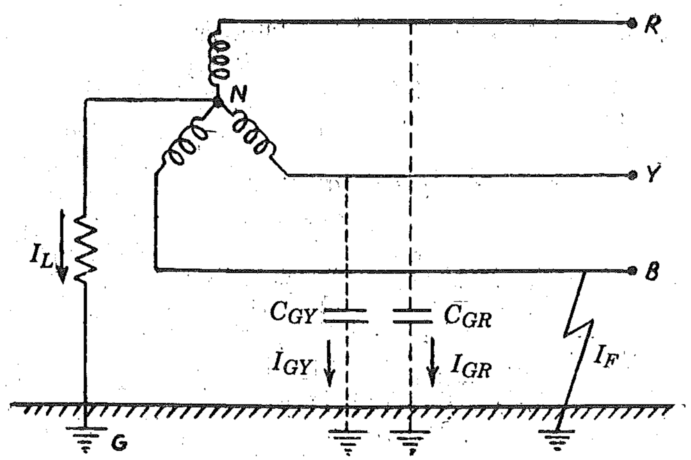


Fig. 18B.7 Resistance earthing.

[It is observed that the zero sequence components I_{RO}, I_{YO}, I_{BO} find the path through Z_n, hence the impedance Z_n is multiplied by 3 [Refer Chapter 23]. Therefore, by inserting a resistance in the circuit the fault current is limited.

For circuits below 3.3 kV, *i.e.* say 400 volts distribution networks, the external resistance in neutral circuit is unnecessary because the voltage available between phase and earth is only 230 volts. The earth resistance of earth plate, earthing connections etc. is of the order of 1.5 ohms. The earth current is limited to 230/1.5, *i.e.* 153 Amperes even if the grounding resistance is not used.

For circuits above 33, kV solid grounding is used. The capacitive ground current are enough to neutralize the reactive fault currents. Hence no resistance is necessary in neutral connection.

(D) **Reactance Earthing.** For circuits between 3.3 kV and 33 kV, the earth fault currents are likely to be excessive, if solid grounding is used. Either resistance or reactance is connected in neutral to ground connection. In Britain resistance grounding is a popular practice. In Europe, reactance grounding is favoured. The reactance connected between neutral and earth provides a lagging current which neutralizes the capacitive current (Fig. 18.B.8).

There is no rule as regards which grounding should be used-resistance or reactance. If resistance is used fault current is limited and system reactance provides the necessary phase opposition between capacitive ground current and fault current.

The reactance grounding provides additional reactance. Thereby the capacitive currents are neutralized. Hence for circuits where high charging currents are involved such as transmission lines, underground cables etc. Reactance grounding is preferred. For network where capacitance is relatively low, resistance grounding is preferred.

18.20. REACTANCE IN NEUTRAL CONNECTION

Ungrounded System. The charging current of phase to earth is, say, I. During earth fault the voltage across line to earth is increased by $\sqrt{3}$ times. Hence charging currents become $\sqrt{3}\,I$ per phase. The charging currents of phase R and Y are displaced by 120°. Hence their vector sum is $\sqrt{3} \cdot \sqrt{3}I$, *i.e.*, $3I$, where I is charging current of line to ground of one phase.

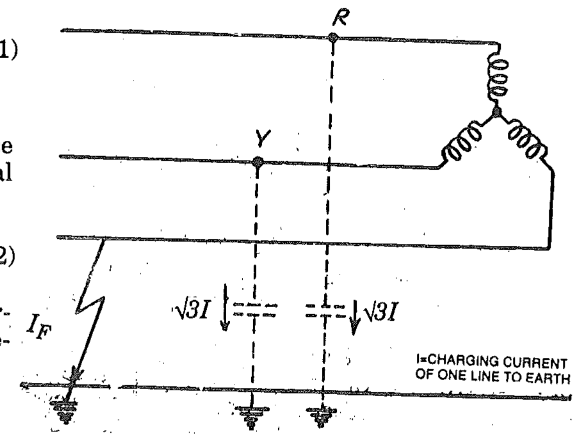


Fig. 18B.8. Current in arcing ground.

$$I = \frac{V_{ph}}{X_c} = \frac{V_{ph}}{1/\omega C} \quad ...(1)$$

$$I_c = 3I = 3V_{ph}\,\omega C$$

If the grounding is through a reactance $X_L = 2\pi f L$. Where L is reactance in neutral connection

$$I_L = \frac{V_{ph}}{X_L} = \frac{V_{ph}}{\omega L} \quad ...(2)$$

To obtain satisfactory cancellation of arcing grounds, the inductance L should be related to the capacitance, and

$$I_L = I_C$$

$$V_{ph}/\omega L = 3V_{ph} \times \omega C$$

$$L = \frac{1}{3\omega^2 C}$$

where L = inductance in neutral to ground connection in henry
or inductance of Petersen coil
or inductance of earth fault neutralizer

$\omega = 2\pi f$

C = capacitance per phase line to ground, farads,

f = frequency (50 Hz)

From this relation the inductance is calculated.

18.21. CONNECTION OF THE ARC SUPPRESSION COIL*

Arc suppression coil is provided with tappings. This permits selection of reactance of the coil depending upon the length of the transmission line and the capacitance to be neutralized. The arc suppression coil is connected between neutral and ground. The reactance of the coil can be calculated from expression.

$$L = \frac{1}{3\omega^2 C} \text{ Henries}$$

$\omega = 2\pi f$

C = capacitance line to ground per phase, farad

f = frequency, Hz

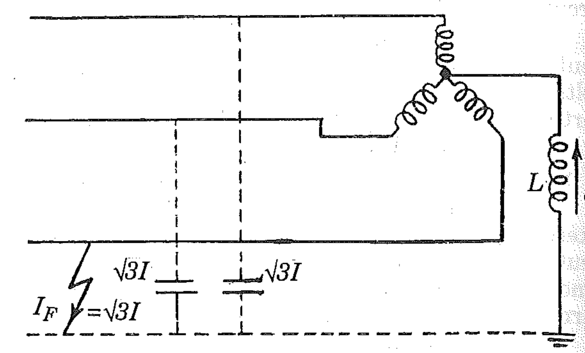


Fig. 18B.9. Reactance grounding current relations.

The coil is rated at continuous rated current equal to maximum earth fault current. However, if a second earth fault develops or double phase to ground fault develops, more current is likely to flow in the coil. To avoid this condition, a circuit-breaker closes after a certain time lag and the earth fault current flows through the parallel circuit by-passing the arc suppression coil.

CB is normally open. It closes after the relay R closes the trip circuit thereby the arc suppression coil is by passed (Fig. 18B-10).

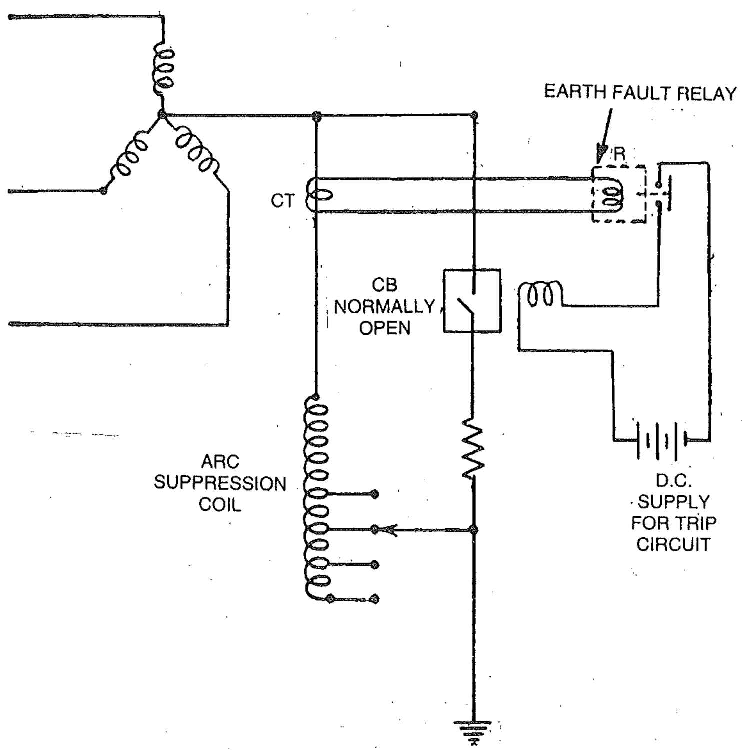


Fig. 18B.10. Connections of arc suppression coil.

* The three names : Arc suppression coil, Peterson coil, Ground fault neutralizer — have the same meaning. In such grounding the reactance of the coil is matched with the capacitance between phase and earth. The grounding is called Resonant Grounding.

18.22. NEUTRAL POINT EARTHING OF TRANSFORMER L.V. CIRCUITS.

$$Z_n = \frac{V^2}{n \times \text{kVA} \times 1000} \text{ ohms}$$

where Z_n = impedance in neutral circuit in ohms

V = Ph. to Ph. voltage LV side, volts

kVA = rating of transformer

n = neutral short circuit current in terms of full load line current.

Example 18.1. *Calculate the ohmic value of impedance to be connected in the neutral to ground circuit of a 2000 kVA transformer with earth fault relay set to 40%, with respect to 400 V side.*

Solution. $$Z_n = \frac{(400)^2}{0.4 \times 2000 \times 1000} = 0.2 \text{ ohm.}$$

Example 18.2. Peterson Coil. *Determine the value of reactance to be connected in the neutral connection to neutralize the capacitance current, of a overhead line to ground capacitance of each line equal to 0.015 μF. Frequency = 50 Hz.*

Solution. $$L = \frac{1}{3\omega^2 C} \text{ Henries}$$

where L = inductance of coil connected in neutral to ground circuit (Henries)

$Z = 2\pi f$, f = frequency Hz

C = capacitance to earth of each phase, f

Here, we have to determine L,

$$L = \frac{1}{3 \times (314)^2 \times 0.015 \times 10^{-6}} = \frac{1}{98596 \times 0.045 \times 10^{-6}}$$

$$= \frac{10^6}{4437} = 22.6 \text{ Henries.}$$

Example 18.3. *In a 50 Hz. overhead line the capacitance of one line to earth was 1.5 μF. It was decided to use an earth fault neutralizer. Calculate the reactance neutralize the capacitance of :*

(a) 100% of the length of line. *(b) 90% of the length of line.*

(c) 95% of the length of line.

Solution. (*a*)

$$C = 1.5 \times 10^{-6} \text{ F}$$

$$\omega = 2\pi f = 2 \times \pi\, 50 = 314$$

$$ZL = \frac{1}{3 \times 1.5 \times 314}$$

$$L = \frac{704}{304} = \mathbf{2.25\ H.}$$

To neutralize capacitance of 100% of the line reactance required 2.15 H.

(*b*) C of 90% length of line = 1.5 × 0.9 = 1.35

$$L = \frac{1}{3 \times \omega^2 \times C} = \frac{1}{3 \times (314)^2 \times 1.35 \times 10^{-6}} = \mathbf{2.5\ H}$$

or

$$L = 2.25 \times \frac{1}{0.9} = \mathbf{2.5\ H}$$

(C)

$$L = 2.25 \times \frac{1}{0.95} = \mathbf{2.37\ H.}$$

Example 18.4. *A 33 kV, 3 phase, 50 Hz, OH line 50 km long has a capacitance to earth line equal to 0.019 μF per km. Determine the inductance and kVA rating of the arc suppression coil.*

Solution. $$L = \frac{1}{3\omega^2 C} = \frac{1}{3 \times (314)^2 \times 0.01 \times 50 \times 10^{-6}} = 6.75 \text{ H}$$

$$\omega L = 2\pi f L = 314 \times 6.75 = 2120.$$

For ground fault, the current in neutral is given by

$$I_N = \frac{V_{ph}}{\omega L} = \frac{33 \times 1000}{\sqrt{3} \times 2120} = 8.99 \text{ A}$$

The voltage across the neutral phase voltage.

$$\text{kVA rating} = V_{ph} \times I_N = 8.99 \times \frac{33}{\sqrt{3}} = 169.3 \text{ kVA}$$

$$\left.\begin{array}{r} L = \mathbf{6.75\ H} \\ \text{kVA rating } = \mathbf{169.3} \end{array}\right\} \quad \textbf{Ans.}$$

18.23. NEUTRAL GROUNDING PRACTICE

1. Generally one-neutral ground is provided at each voltage level. Between generator voltage level and distribution voltage level there are several voltage levels. One ground is provided at each voltage level (Fig. 18B.11).

2. The grounding is provided at source end and not at load end (Fig. 18B.11).

3. Each major bus section is grounded.

4. **Generator Neutral Grounding**

There are several alternatives of generator neutral grounding methods depending upon :

— method of generator connection with bus bars, *i.e.*, whether connected to bus bars or to unit transformers.
— method of ground fault protection
— fault currents
— insulation levels.
— number of generators in parallel, etc.

Neutral Grounding for Classical Generator Connection

For Generators connected to busbars without unit transformers in-between :

(Refer Sec. 17.6.1*a*, Fig. 17.3).

— When several generators are operating in parallel only one generator neutral is grounded. If more neutrals are grounded, the zero sequence components of circulating currents create disturbance.
— In generating station there is provision to earth neutral of at least two generators. Though only one is grounded at a time. The other generator neutral is grounded when the first generator is out of service. Under any circumstances one generator neutral must be grounded.
— When there are one or two power sources, no switching equipment is used in the grounding circuit.
— A neutral bus is provided in case there are several generators. The neutral bus is connected to earth directly or through reactance. The neutral point of one generator is connected to neutral bus through circuit-breaker.

Neutral Grounding in Unit System of Generator Connection

Refer Sec. 17.6.2, Fig. 17.14 describing unit system, of generator connection in which each generator, associated unit transformer, unit a auxiliary transformer form a 'unit'.

The earth fault protection of generator requires neutral grounding of each generator (Refer Sec. 33.6 *a*, Fig. 33.11).

The generator winding is star connected and generator terminal are connected to step-up transformer low voltage delta connected winding. High voltage winding is star connected and taken to bus bars for transmission. Because of delta connection of low voltage side of transformers, the generators operating in parallel are, isolated from each other and also from high voltage bus so far as ground fault currents are concerned. Therefore, generator neutral of each unit is earthed.

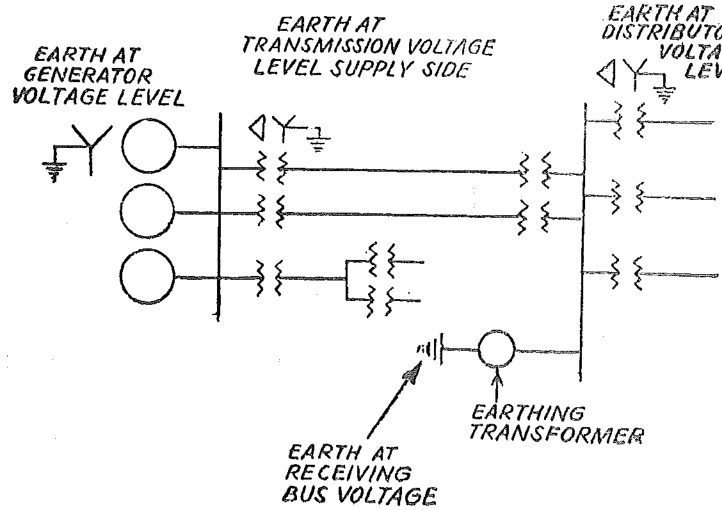


Fig. 18B.11. Earth at every voltage level at source-end.

The generator neutral grounding is through resistor or reactor or a voltage transformer (Refer Fig. 23.11). The grounding practice in unit system of generator connection is as follows :

Main generator neutral. Grounded through resistor or reactor or a VT.

Step up transformer. Neutral on star connected HV side is earthed through neutral grounding resistor.

Unit auxiliary transformer. It is delta connected on generator side and star connected as auxiliary bus side. The star connected LV side neutral is earthed directly. In this case also the delta connected LV of unit auxiliary transformer isolates the auxiliary system from generator as far as earth fault currents are concerned.

5. **Grounding of Neutral of Power Transformer.** For protection purpose, the neutral point of star side is usually earthed (Fig. 32.16).

6. **Grounding of Protective CTs, VTs.** The star connected secondary sides of protective CTs and VTs are earthed at one point [Fig. 32.16, Fig. 32.10 (*b*)]. This ensures stable neutral, proper measurement of voltages and currents, kWh and kVA on secondary side measuring instruments and controls.

The control circuits and battery circuits should also have a single earth point.

18.24. EARTHING TRANSFORMER

The neutral point (star point) is usually available at every voltage level from generator or transformer neutral. However if no such point is available due to delta connections or if neutral point is desired on bus-bars, the most common method is using a zig-zag transformer. Such a transformer has no secondary. Each phase of primary has two equal parts. There are three limbs and each limb has two windings providing opposite flux during normal condition. The two stars (1) and (2) are connected together as shown in Fig. 18B-14. Since the fluxes oppose, the transformer takes very small magnetising currents during normal condition. During earth faults on the circuit in primary side, the zero sequence currents which have the same phase for three components I_{RO}, I_{YO}, I_{ZO} flow in the transformer winding through earth connection. The earth fault current finds little impedance.

The grounding transformers are of short time ratings (10 seconds to 1 minute). Therefore, their size is small as compared to the power transformer of same ratings, almost one-tenth.

If grounding transformer is not available, a star-delta transformer can be used without loading the delta side (Fig. 18B.12)

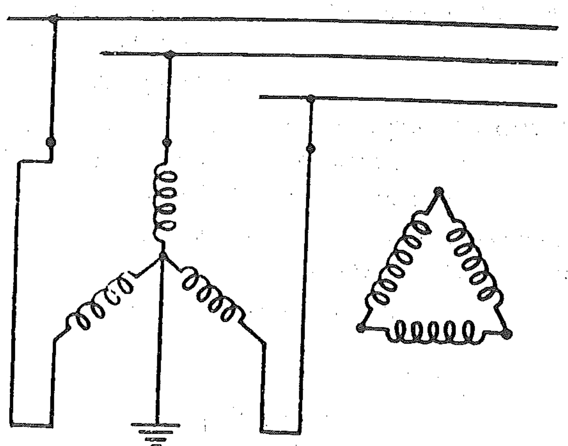


Fig. 18B.12. Use of star-delta transformer for grounding.

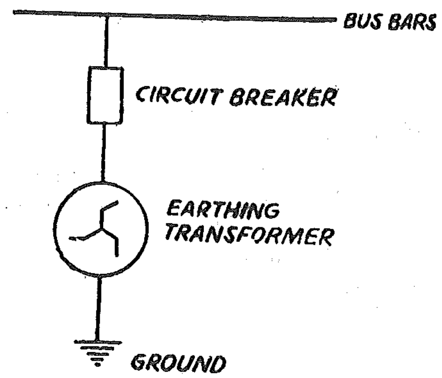


Fig. 18-B.13. Connection of earthing transformer. Current transformer not shown.

18.25. RATINGS OF NEUTRAL DEVICES

The ratings of equipment is neutral connection such as resistors, reactors, circuit-breaker etc. is usually 10 seconds or extended time.

On unit system grounding 10 seconds rating is used.

For feeders at generator voltage, 1 minute rating is used.

For distribution schemes, extended time ratings are used.

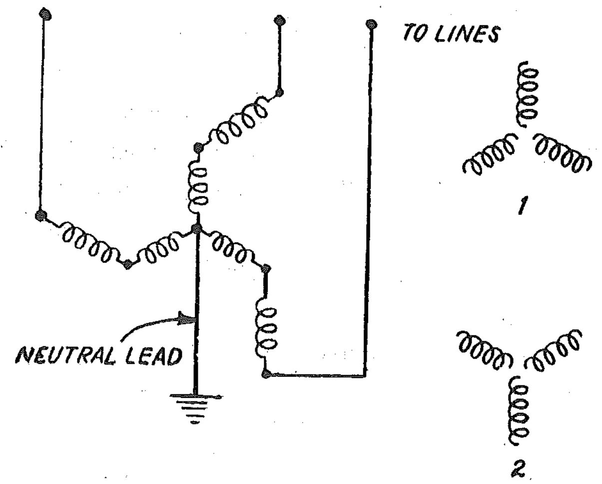


Fig. 18B.14. Winding of zig-zag transformer.

SUMMARY

The *neutral points* of three phase AC System are usually earthed at each voltage level for :

— Eliminating arcing grounds (frequent charging and discharging of phase to ground capacitance through the temporary arcing fault).

— Holding phase to ground voltages of two unfaulted phases at nearly original level during earth fault on third phase.

— Facility for Earth fault protection.

— Reducing Coefficient of earthing to < 0.8.

— Flow of 3rd Harmonic current through the earth (Ref. Ch. 23 Fig. 23.1). Reactance Grounding is preferred for compensating capacitive earth fault currents. Resistance grounding is preferred for reducing earth fault currents. Solid grounding is preferred for sensitive earth fault protection.

QUESTIONS

1. State the difference between Equipment Earthing and Neutral Earthing.
2. What are the merits and demerits of Reactance Earthing compared to Solid Earthing ?
3. Explain the phenomena of "Arcing Grounds" on overhead transmission lines. How does Neutral Earthing oppose arcing ground currents ?
4. Though Neutral Earthing results in higher ground fault currents, it is a *universal practice* to earth power system neutrals. Explain the merits of Neutral Earthing.
5. Explain by means of a diagrams :

   (*a*) The phase to earth voltage rise in unfaulted lines during a single phase to earth fault in a 3 phase system without (*a*) neutral earthing (*b*). The situation with neutral earthing.
6. A 36 kV, 3 phase distribution line is to be provided with Surge Arresters at the receiving substation. The transformer neutral is effectively earthed. Coefficient of earthing is 0.8. What would be the phase-to ground voltage of Unfaulted phases during a single phase to ground fault on one of the phases ?

   State the rated voltage of surge arrester. The Surge of 185 kV peak is discharged by the surge arrester with residual voltage of 130 kV, the surge impedance of line is 500 ohm. Calculate the Discharge current through the surge arrester.
7. A 132 kV, 3 phase 50 Hz overhead distribution line has phase to ground shunt capacitance of 0.0157 μF per km. Determine the inductance and kVA rating of arc supression coil to be connected between neutral and earth.

   [**Ans.** 4.3 H and 4300 kVA, single coil]
8. An 50 Hz, 3 phase overhead line has phase ground shunt capacitance of 0.08 μF. Determine the inductance required in neutral to ground circuit to eliminate an arcing-ground at (*a*) the other end of line (*b*) at 70% length of line from the neutral earthing end.

18-C

Substation Earthing System and Equipment Earthing

Introduction — Equipment Earthing — Parts to be Earthed — Station Earthing System — Earth Mat — Touch Potential — Step Potential — Earth Resistance Measurement by Low Current Method and High Current Method — Earth Resistance Values — Summary.

18.26. EQUIPMENT EARTHING (GROUNDING)

The non current carrying metallic parts in every electrical installation are connected to the underground earthing mesh at earth potential for safety of personnel and for discharging fault currents. The connecting of non current carrying metallic parts to underground earthing system is called *Equipment Earthing (grounding)*.

The equipment grounding also helps in the earth fault protection. The earth fault current from the equipment flows through the earthing system to the earth and is sensed by protection system and circuit breakers are opened. The faulty equipment is then repaired and recommissioned. The earthed parts remain at approximately earth potential even during flow of fault current. The equipment earthing ensures safety to personnel.

The core of the real earth has hot, liquid malma with low electrical resistivity. Earth is a good conductor except in the dry and rocky upper layers near the surface. The surface-soil and internal geological layers are with different resistivities.

The *Station Earthing System* should have *low earth resistance ; low touch potential and low step potential.* Modern Station Earthing System has burried horizontal mesh of steel rods and vertical electrodes (spikes) welded to the mesh. Further, the vertical risers and the galvanised steel earthing strips/copper bars etc. are connected between the earthing mesh and the points to be earthed.

The Earthing is of two principal types :

1. Neutral Earthing. (Chapter 18-B)
2. Equipment Body Earthing

The earthing system is also required for :

— Reference earthing
— Discharge earthing
— Overhead Shielding.

Table 18-C.1

Type of Earthing	*Points Earthed*	*Purpose*
Neutral Earthing	— Transformer Neutral	— Holding neutral at ground potential
	— Generator Neutral — Star point of load	— Prevent Arcing grounds on OH lines.
	— Neutral of circuit	— Discharge of voltage surges
	— Star point of CT/PT secondary	— Path for out-of-balance currents,
		— Simpler earth Fault Protection
Equipment Earthing (body earthing)	— Metallic noncurrent-carrying parts	— Holding the metallic parts at earth potential even on earth fault
		— Safety
Reference Earthing	— The floating point in the circuit	— Holding the point and the conductor at zero potential
Discharge Earthing	Earthing-terminal of,	— To discharge the surge voltages, capacitor charge, currents to earth
	— Earthing Switch, and currents	
	— Surge Arresters,	
	— Capacitor/Filter Bank,	

Note : Neutral Points and Equipment Earthing Parts are connected to the common Underground Earth mat *via* separate earthing conductors.

18.27. FUNCTIONS OF SUBSTATION EARTHING SYSTEM

1. **Safety of Operation and Maintenance Personnel.** The earthing system ensures safety against shocks to Operation and Maintenance Staff working in Substation. The earthed part are safer than unearthed parts. Deaths by shocks can be avoided completely by proper equipment earthing. Before commissioning, the earthing system should be checked and certified. Before carrying it any maintenance work, the equipment is isolated and earthed from both ends. Hence equipment earthing is also called as "Safety Earthing".

The earthed parts are held at near ground potential and safety is ensured.

2. **Discharge of Electrical Charges to Earth.** The earthing system provides return path for discharging fault currents and discharge currents/voltages from the earthed points of lightning masts, lightning conductors, earthing switches, surge arrester, etc. These parts are connected to the underground earthing system by solid or flexible earthing conductors of adequate short-time current carrying capability and low resistance.

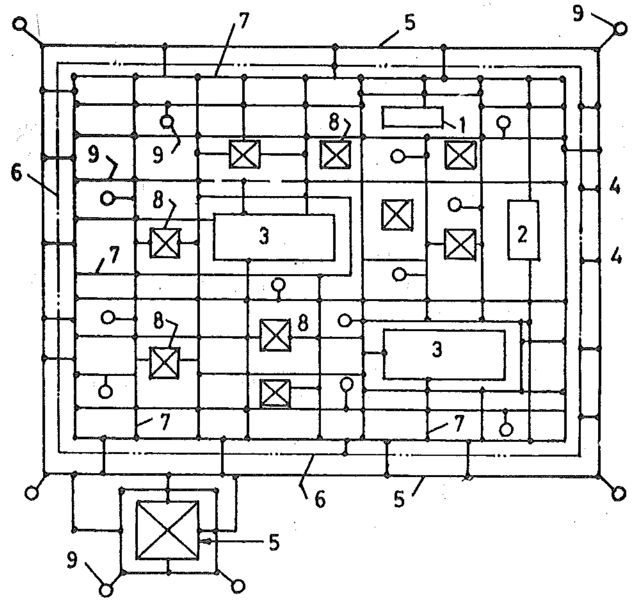
3. **Earthing of Overhead Shielding Wires.** The overhead shielding wires and earthed-flanges of insulators and bushings are held at earth potential by connection with the earthing system. Thereby the protection zone against lightning strokes is obtained for the outdoor, exposed conductors and equipment.

4. **Electro Magnetic Interference.** The earthing system ensues freedom from Electromagnetic interference in communication and data processing equipment in the substation. Earthing of chassis of instruments, earthed screening of control room, computer room ensures freedom from electro magnetic disturbances on operation of isolators, thyristors in main power circuits. The control rooms are provided with earthed screen in the walls and windows to ensure freedom from electromagnetic disturbances.

18.28. CONNECTION OF ELECTRICAL EQUIPMENT TO STATION-EARTHING SYSTEM

Table 18-C.2. Connection of Electrical Equipment to Station-Earthing System.

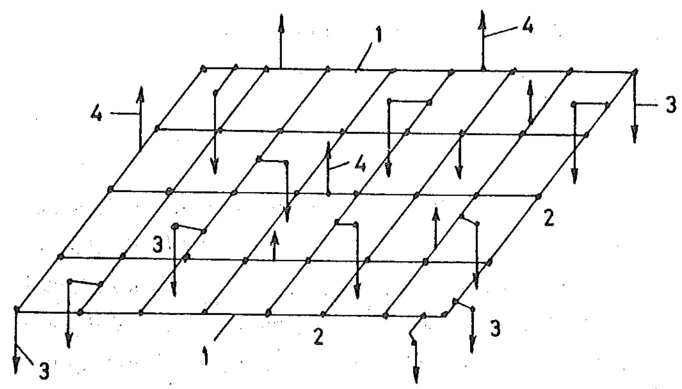
Apparatus	*Parts to be earthed*	*Method of connection*
Support of bushing insulators, lightning arrester, fuse, etc.	Device flange or base plate	1. Connect the earthing bolt of the device to station earthing system. In the absence of earthing bolt or in case of connection to non-conducting structures, connect fastening bolt to earth.
	Earth terminal of each pole of 3 phase. Surge Arrester	2. When the device is mounted on a steel structure, weld the structure, mounting the device flange; each supporting structure of apparatus to earthing mesh *via* separate conductor.
Cabinets of control and relay panels	Frameworks of switchgear and cabinets	Weld the framework of each separately mounted board and cabinet minimum at two points to the earth conductor of earthing system.
High-voltage circuit breakers	Operating mechanism, frame provided with earth-bus	Connect the earthing bus on the frame and operating mechanism of c.b. to earthing system.
Isolator	Isolator base (frame), operating mechanism bedplate.	Weld the isolator base frame, connect it to the bolt on operating mechanism base plate and station earth.
Earthing Switch	Lower pad/terminal	For discharging capacitance after opening of Isolator
Steel Doors, Fence, Screens	Each panel	Connected by flexible conductor to earth mat
Lightning Masts	Earthed member	Connected by earthing strip to Earth Mat
Foundation frames, Support Structures	Earthed member	Connected by earthing strip to Earth Mat
Overhead Shielding Conductors	Earthed point	Connected by Flexible conductor along each Tower or Structure to Earth Mat
Neutral Points	Earthed point	Connected to earth mat by Strips/Cable/ Flexible conductor.
Surge Arrester	Lower earth point of each pole	To be directly connected to the earth mat.
Potential transformer	Potential transformer tank, LV neutral, LV winding phase lead (if stipulated by the designers) Structure.	1. Connect the transformer earthing bolt to earthing system. 2. Connect LV neutral of phase lead to case with flexible copper conductor.
Current transformer	Neutral points of secondary, structure.	Connect secondary winding to earthing bolt on transformer case with a flexible copper conductor, the case being earthed in the same way as support insulators.
Power transformer	Transformer tank, Neutral point.	Connect the earthing bolt on transformer tank to station earth. Connect the Neutral to Earthing system.



1. Metal Tank
2. Transformer Foundation
3. Building
4. Welded joints+
5. Tower
6. Fence
7. Earthing rods of mesh+
8. Structures in substation
9. Earthing spikes/electrodes+

+Below ground level.

Fig. 18-C. 1 A. Substation Earthing System.



1. Horizontal earthing rods+
2. Welded joint
3. Vertical electrodes/spikes+
4. Vertical risers

+Below ground level.

Fig. 18-C. 2. Three-dimensional view of the Earthing System.

18.29. SUBSTATION EARTHING SYSTEM

Before 1960s the design criterion of substation earthing system was "low earth resistance." (ER < 0.5 ohms for High Voltage installations). During 1960s, the new criteria for the design and evaluation of Substation Earthing System were evolved particularly for EHV AC and HVDC Substations. The new criteria are :

1. Low Step Potential 2. Low Touch Potential 3. Low Earth Resistance.

The conventional "Low earth resistance criterion" and Low Current Earth Resistance Measurement continues to be in practice for Substations and Power Station upto and including 220 kV.

The parts of the Earthing System include the entire solid metallic conductor system between various earthed points and the underground earth mat. The earthed points are held near-earth potential by low resistance conductor connections with earthmat.

— *An Underground Horizontal Earth Mesh (Mat/Grid)*

The mesh is formed by placing mild steel bars placed in X and Y directions in mesh formation in the soil at a depth of about 0.5 m below the surface of substation floor in the entire substation area except the foundations. The crossings of the horizontal bars in X and Y directions are *welded*. The earthing rods are also placed the border of the fence, surrounding building foundations, surrounding the transformer foundations, inside fenced areas etc. The mesh ensures uniform and zero potential distribution on horizontal surface of the floor of the substation hence low "step potential" in the event of flow of earth fault current.

— *Earthing Electrodes (earthing Spikes)*. Several identical earth electrode are driven vertically into the soil and are welded to the earthing rods of the underground Mesh. Larger number of earth electrodes gives lower earth resistance.

(A) The number of Earth-Electrodes (Spikes) N_s for soil resistivity 500 ohm meter and earth fault current I_s is :

$$N_s = \frac{I_s \text{ Amperes}}{250}$$

i.e., approximately 250 Amp per spike, for soil resistivity of 500 ohm-meter.

(B) The number of Earth-Electrodes (Spikes) N_s for soil resistivity 5000 ohm meter is

$$N_s = \frac{I_s \text{ Amperes}}{500}$$

i.e., approximately 500 Amp per spike, for soil resistivity of < 5000 ohm-meter.

I_s = Short Circuit level of the substation, A

e.g. 33 kV sub stations : 25000 to 31000 A
400 kV Substations : 40000 A

— *Earthing Risers*. These are generally mild steel rods bent in vertical and horizontal shapes and welded to the earthing mesh at one end and brought directly upto equipment / structure foundation.

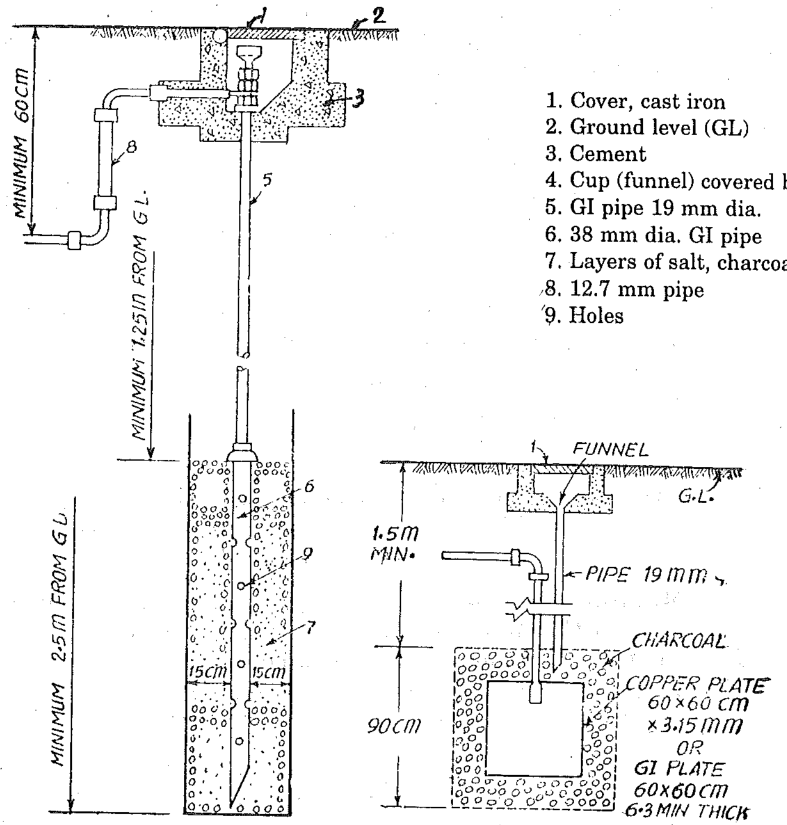
— *Earthing Connections*. (Galvanised Steel Strips or Electrolytic Copper Flats or Strips/Stranded Wires (Cables)/Flexibles. These are used for final connection (bolted/welded/clamped) between the Earthing Riser and the points to be earthed. For Transformer Neutral/High Current Discharge paths copper strips/stranded wires are preferred, Galvanised Iron Strips/stranded wires are more common for all other earthing connections. The earthing strips are finally welded or bolted or clamped to the *Earthed Point*.

18.30. EARTH ELECTRODES

Several vertical galvanised-steel pipes are inserted in the earth and their heads are connected solidly to the Earthing Mat by means of horizontal earthing rods/earthing strips.

Fig. 18-C.3 illustrates the typical Earth electrode. For low voltage, low current installations, plate electrodes may be preferred. Use of salt, charcoal, chalk powder in the earth pits surrounding the electrodes and irrigation of the soil gives lower earth resistance.

The size of conductor is based on temperature rise permissible to avoid fusing at the joints.



1. Cover, cast iron
2. Ground level (GL)
3. Cement
4. Cup (funnel) covered by sieve
5. GI pipe 19 mm dia.
6. 38 mm dia. GI pipe
7. Layers of salt, charcoal, coke
8. 12.7 mm pipe
9. Holes

(*a*) Pipe Earth Electrode. (*b*) Plate Earth Electrode.

Fig. 18-C.3. Typical Earth Electrodes.

Table 18C-2. Description of an Earthing System

1.	**Earthing Mat**
	40 mm dia, 2 to 3 m length per piece mild steel rods welded to get straight lengths and are placed in horizontal X-Y formation with mesh spacing 2 m to 3 m at 0.6 m depth in soil. Joints between X and Y rods are arc-welded.
2.	**Earthing Electrodes (Spikes)**
	30 to 40 mm dia GI pipes, 3m long, are driven in soil vertically (Z direction) and welded to X-Y rods of earth mesh via horizontal earthing rods. Surrounding Earth pits filled with salt, charcoal, chalk and irrigated periodically.
3.	**Riser**
	40 mm dia vertical rods welded to Earthing Mat brought upto the structures to be earthed.
	— Alternatively, 75 × 10 mm or 45 × 8 mm GI Flats welded to the earth mat and taken up vertically for bolting/welding with the point to be earthed.
4.	**Earthing Strips or Flexible stranded wires**
	75 × 10 mm Galvanised Iron Flats/or Copper Flats Welded/Bolted to the nearest riser and Welded/Bolted to the point to be earthed.
	Flexible stranded ACSR cables are connected between the overhead shielding wires and tower footing. Tower footing is connected to the earthing system.
	Welded joints covered by bituminous paint to prevent rusting.

Earthing System for Installations Within a Buildings. The Earthing System is planned as a part of civil design and construction. The earthing rods are placed in mesh formation in the floor and in the area surrounding the building Risers are placed in walls. Earth connections are by galvanised iron strips or copper strips/ stranded wires provided between the individual body/neutral point and the Risers. Earthing strips are placed in the floor and walls and are connected to that several places to the Earthing Mesh.

Sensitive Measuring Instruments, Communication Equipment, Computer Facility etc. need proper low resistance earthing system spread in the various rooms of the building. *Electro-Magnetic Disturbances are eliminated by proper Earthing.*

The thin wire mesh earthed screen is provided in the glass windows, portable single phase devices are provided with 3-pin plugs :

The three pins are for : Phase, Neutral and Earth (green).

The earth wire/strip is provided with the wiring of all the rooms. The earthing is via the earthing strips/earthing wire.

Current leakage through wet walls, floors and worn out old insulation; earth fault through pipe or reinforcement, minor occasional sparking are some causes of electric shocks within residential/commercial buildings.

Earthing System for Metallic Enclosure of Switchgear. Earthing Strip is provided along the entire length or periphery of the Metallic Enclosure. The Earthing Bus in the metallic enclosures is connected to the Station Earthing system at two or more points by Earthing Conductors. The individual neutral points, reference points and equipment bodies, doors etc. within the Metallic enclosure are connected to the Earthing Bus.

Earthing with Withdrawable Earthing Truck. With Drawout type Switchgear, there should be provision for busbar earthing after isolation from supply feeders. Earthing trucks consisting of a breaker with shorted terminals on one side and mounted on withdrawable truck. Before doing maintenance/repair work on the switchgear, the busbars are earthed by means of earthing truck.

Earthing Devices. Before doing any maintenance work, the overhead bus bars/other equipment in substations are disconnected, and then earthed by means of earthing device consisting of an insulating rod with a earthing hooks connected with insulated wires, the other end of the wire is connected to the earthing system.

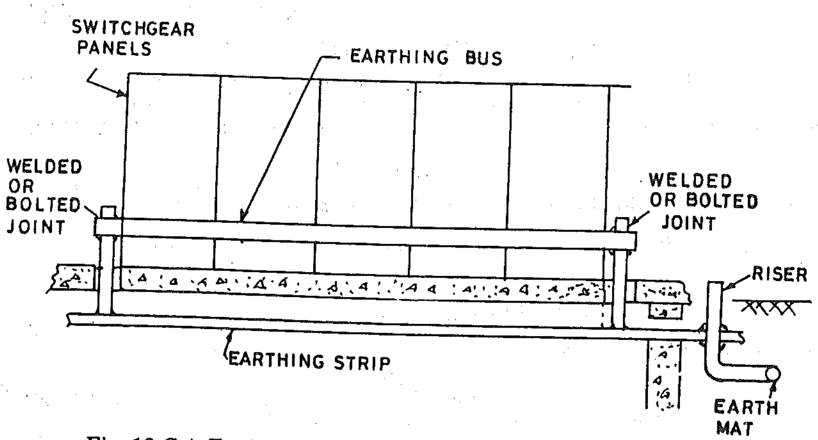


Fig. 18-C.4. Equipment Earthing Facility in Metal Clad-Switchgear.

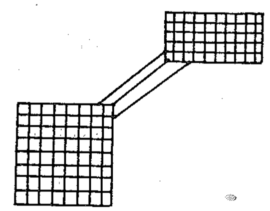
18.31. INTEGRATED EARTHING SYSTEMS FOR TWO OR MORE INSTALLATIONS

The Earthing Systems of two or more Substations/Generating Stations/Industrial/Commercial Installations may connected by a few earthing rods as shown in Fig. 18-C.5 between individual earthing meshes of these installations. The Individual Earthing Systems are thereby connected in parallel ensuring very low earth resistance (E_{Rc}) of the integrated Earthing Systems

$$\frac{1}{E_{Rc}} = \frac{1}{E_{R1}} + \frac{1}{E_{R2}} + \frac{1}{E_{R3}} + \ldots\ldots$$

E_{Rc} = Resistance of Combined Earthing Systems

E_{R1}, E_{R2} = Resistance of Individual Earthing Systems



1, 2, 3 ... Individual Station Earthing Systems
U_{RC} = Underground Earthing rod connections

Fig. 18-C.5. Concept of Integrated Earthing System.

18.32. STEP POTENTIAL AND TOUCH POTENTIAL

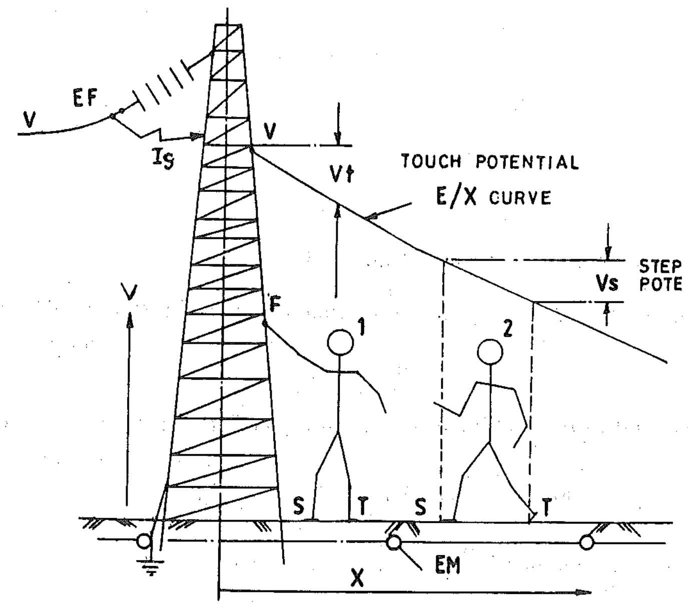
A person touching a faulted structure should not get a shock during flow of fault current through the structure.

A person walking on substation floor should not get a shock during flow of fault current through the earth mat. These conditions are ensured by low Touch Potential and low Step Potential.

Step Potential is the voltage between the feet of a person standing on the floor of the substation, with 0.5 m spacing between two feet (one step), during the flow of earth fault current I_s through the earthing system.

Touch Potential. The voltage between the fingers of raised hand touching the faulted structure and the feet of the person standing on substation floor. The person should not get a shock even if the earthed structure is carrying fault current. In other words the touch potential should be low.

Refer the curve V/X in Fig. 18-C.6. The point F is at potential V of faulted structure. The feet ST of Man 1 are on ground. The potential difference between F and ST is the Touch Potential (V_t) for Man 1. The potential between S and T of man 2 is Step potential V_t.



V_s = Step Potential between point S and P during flow of I_s.
V_t = Touch Potential
E_F = Earth fault
F = Raised finger
S, T = Steps of a person
I_s = Short-circuit current.

Fig. 18-C.6. Step Potential (V_s) and Touch Potential V_t

18.33. EARTH-RESISTANCE OF EARTHING SYSTEM

"Earth Resistance ER" is the resistance of the earthing electrode/earthing mat to the real earth and is expressed in ohms. ER is the ratio of V/I, where V is measured voltage between the electrode and the voltage spike and I is injected current during the earth resistance measurement through the electrode. The desirable values of earth resistance measurement (average of 12 monthly readings) are :

Table 18C.3.

EHV AC Installations*	< 0.01 ohm
High Voltage Installations above 33 kV	< 0.5 ohm
Medium Voltage Installation 1kV to 33 kV	< 0.5 ohms
Low Voltage Installations up to 1 kV	< 1 to 2 ohm
Residential buildings	< 2 ohm

*Measured by High Current Method.

— For installations rated below 1000 V and earth fault current (I_s) less than 500 A, the earth resistance shall be less than $125/I_s$

— For installations rated less than 2000 kVA and 1000 V, (Residential Loads), the earth resistance should not exceed 2 ohms.

Earth resistance value obtained would depend on :

— Whether the soil is dry or wet. During the rainy season lower values are obtained and during summers, higher values are obtained. It is a good practice to irrigate the earth electrodes regularly during summers and winters.

— The resistivity of soil varies widely between 1 ohm m to 10000 ohm m (Table 18-C.3) depending on the type of soil.

— The design of station earthing system.

— Method of measurement.

Table 18-C.4. Soil Resistivity

Type of Soil	*Resistivity ohm m*
Marshy	1 — 5
Clay	3 — 150
Clay and Gravel mixture	10 — 1250
Chalk	60 — 500
Sand	90 — 1000
Sand and gravel mixture	500 — 5000
Slate	100 — 500
Crystaline Rock	500 — 10,000

Let ER be earth resistance for one electrode in ohm.

$$\text{Resistivity of Soil (ohm m)} = \frac{\text{Earth-resistance } ER \text{ in ohm}}{0.003}$$

e.g. With $ER = 0.3$ ohm, soil resistivity $= \dfrac{0.3}{0.003} = 100$ ohm metre

With $ER = 12$ ohm, soil resistivity $= \dfrac{12}{0.003} = 4000$ ohm m

18.34. EARTH RESISTANCE MEASUREMENT

The measurement involves the Electrode under test, a current spike and a voltage spike. Current is injected into earth through the electrode under test and returned from the current spike. Voltage between the voltage spike and the electrode is measured.

$$ER = \frac{V_{dc}}{I_{dc}} \text{ ohms}$$

where,

V_{dc} = Voltage between voltage spike and earth electrode under test, volts

I_{dc} = Current injected through the Earth Electrode into earth and returned through the Current spike, ohms

The two different methods of Earth Resistance Measurement are :

1. *Low Current Method (Conventional Method)* used mostly for installations upto 400 kV.

The test current is 10 mA to 100 mA.

2. *High Current Method* for 400 kV and 500 kV Substations. This method gives more realistic measurement for earth mats of more than 300 m diameter/length.

The test current is 10 A to 100 A.

Description

1. **Low, Current Method (Conventional Method),** Measurement is by means of standard *Earth Resistance Tester,* with standard accessories like Current Spike and Voltage Spike. (Fig. 18-C.7) The test is conducted as per applicable Standard Specification.

The Earth Resistance Tester has a built-in ohm meter and a hand driven DC Generator. The DC generator supplies current (I) via the Earth Electrode under test and the Current Spike (CS). The voltage (V) develops between the Earthing System under test and the Voltage Spike. The Ohm Meter in the Earth Resistance Tester measures the ratio V/I. Several readings of $V/I = R$ are taken for different positions of the Voltage Spike. The graph of distance X versus R is plotted. The flat portion of the curve or R is considered to be the Earth Resistance of the Earth Point under measurement. The resistance value can be between a fraction of ohm to a few hundred ohms depending upon the soil resisting and depth of electrode. Electrode design may be suitably modified in case of hard rock.

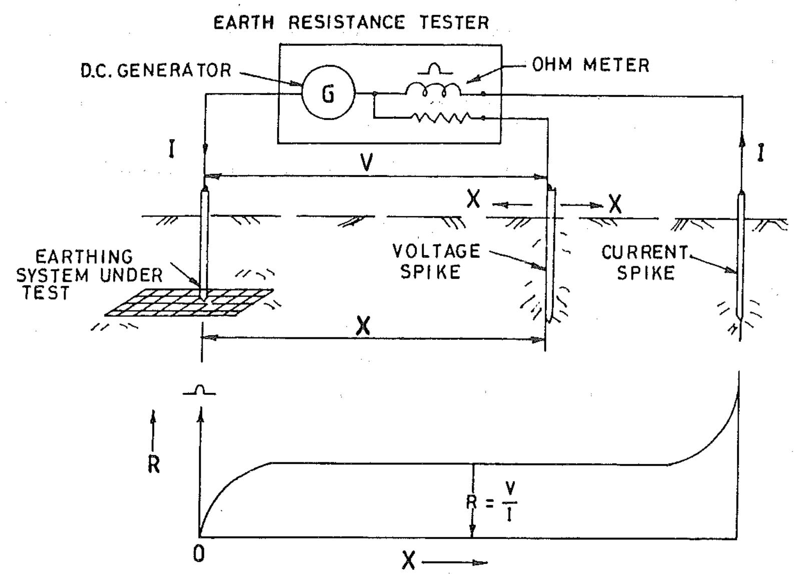


Fig. 18-C.7. Measurement of Earth Resistance by Low-Current method.

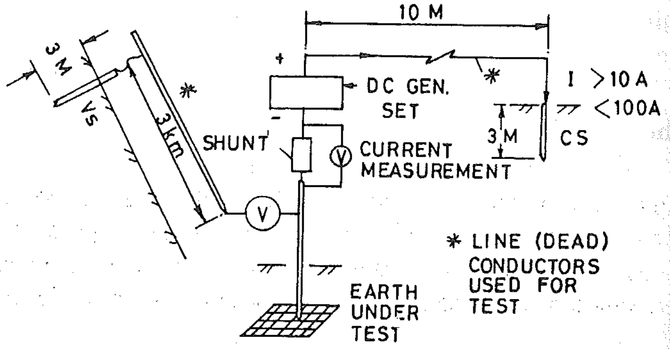
[The voltage spike is placed at various points (X) and measurements of R are taken for each point of X. The graph X versus R is plotted. The uniform value of 'R' is called earth Resistance of the Earthing System Under Test.]

2. **High Current Method of Earth Resistance Measurement.** The low current method does not reflect the true earth resistance for large earth mats designed for high short circuit currents. High Current Method gives more realistic value of earth resistance of Large Earthing Mats of 400 kV Substations and HVDC Substations in which fault levels are more than 30 kA. Fig. 18-C.8 gives the schematic.

In High Current method of Earth Resistance Test,

— The Current Spike (CS) should be at least 3 m long and should be located at least 10 km away from the Earth Mat under test. The location should be marshy/wet place.

— The Voltage Spike (VS) should be at least 5 km away from the Earth Mat under test.



V_s = Voltage Spike, 3 m deep
CS = Current Spike, 3 m deep
Fig. 18-C.8. Earth Resistance Measurement by High Current Method.

— The Voltage Spike should be separated from Current Spike by at least 500 m. The location should be marshy/wet place.

— The angle between voltage conductor and current conductor (marked *) should be greater than 90°, preferably 180°.

The line Conductors outgoing from the substation are temporarily disconnected (dead) and used as Voltage Conductor and Current Conductor. *Sufficient precautions should be taken to avoid shocks due to induced currents/live conductors,* by discharging the charges and avoiding induced voltages.

— The current Source can be a D.C. generator. (Welding Generator). The current flowing through the earth mat $= I_e = V/r$

— The Measurement is by DC Voltmeter with a Shunt and an Ammeter.

$$\text{Earth Resistance ER of Earth Mat} = \frac{V_v}{I_c}, \text{ ohm}$$

where,

V_v = D.C. Voltage between the Voltage Spike and the earth mat

V = Voltage across shunt 'r' ohms.

I_e = DC current flowing through the Current Spike and the earth and returning through the earth mat. Current is measured by means of a shunt as shown in Fig. 18-C.8. (V/r)

Table 18-C.5 Results of High Current Method of Earth Resistance Measurement in a 400 kV/500 kV HVDC Substation

Current I_c = 36 A DC
Voltage V_v = 0.103 V DC
Earth Resistance $ER = V_v/I_c$ = 0.00516, ohms
Size of Earth mat = 500 m × 30 m
Number of Earth electrodes = 167

18.35. EARTHED SCREENS

When equipment are not supported on earthed structures of 2.5 height (minimum), earthed screens are provided on ground for preventing persons entering unsafe safety zone.

SUMMARY

Station Earthing System is an underground horizontal mesh of metallic rods with vertical earthing spikes to which various neutral points, equipment bodies to be earthed are solidly connected such that the resistance to earth is low.

Equipment bodies, fences, doors, support structure, are connected to station earthing system.

The essential components of the earthing system are :

— Underground earth mat and earthing electrodes.

— Risers and Earthing Strips.

The Touch Potential, the Step Potential, Earth Resistance should be low for safety of personnel against electric shocks.

Equipment Earthing is for safety and Electrical Inspectors shall not permit charging of installation unless the earthing is properly done. The Earth Resistance is given by $ER = V/I$, and is measured by : (1) Low Current Method (< 1 A) for medium and low voltage installations and (2) High Current Methods for 400 kV installations. Earthing System is common for equipment Earthing and Neutral Point Earthing. Earth resistance shall be less than 0.5 ohm for medium/high voltage installations rated upto 200 kV and less than 0.01 ohms (as measured by high current method) for 400 kV installations.

QUESTIONS

1. Define : Neutral Earthing and Equipment Earthing.
2. Explain in brief, the four essential functions of Station Earthing System.
3. State which points in an electrical installation are connected to station earthing system.
4. State the modern criteria for the design of earthing system. How does it differ from the earlier criterion ?
5. Explain clearly the terms Touch Potential and Step Potential.
6. Describe a typical Station Earthing System and state the values of Earth Resistance to be achieved.
7. Describe High Current Method of Earth Resistance Measurement. Explain how the Earth Resistance can be minimised by integrated earthing system.
8. Describe the Low Current Method of Earth Resistance Measurement.
9. Design an earthing system for a 33 kV outdoor substation having area within fence of 200 m × 100 m.

   The soil resistivity is 1000 ohm m. Short circuit level of the substation is 25 kA rms.

   Give a Sketch and final specifications of your design.
10. Describe the Equipment Earthing Facility for a Metal Clad Switchgear and its Draw-out unit.