High Voltage Engineering

Syllabus

Subject Code	:	10EE73	IA Marks	:	25
No. of Lecture Hrs./ Week	:	04	Exam Hours	:	03
Total No. of Lecture Hrs.	:	52	Exam Marks	:	100

PART - A

UNIT - 1

INTRODUCTION: Introduction to HV technology, advantages of transmitting electrical power at high voltages, need for generating high voltages in laboratory. Important applications of high voltage, Electrostatic precipitation, separation, painting and printing.

6 Hours

UNIT- 2 & 3

BREAKDOWN MECHANISM OF GASEOUS, LIQUID AND SOLID MATERIALS: Classification of HV insulating media. Properties of important HV insulating media under each category. Gaseous dielectrics: Ionizations: primary and secondary ionization processes. Criteria for gaseous insulation breakdown based on Townsend's theory. Limitations of Townsend's theory. Streamer's theory breakdown in non uniform fields. Corona discharges. Breakdown in electro negative gasses. Paschen's law and its significance. Time lags of Breakdown. Breakdown in solid dielectrics: Intrinsic Breakdown, avalanche breakdown, thermal breakdown, and electro mechanic breakdown. Breakdown of liquids dielectric dielectrics: Suspended particle theory, electronic Breakdown, cavity breakdown (bubble's theory), electro convection breakdown.

12 Hours

UNIT- 4

GENERATION OF HIGH DC AND AC VOLTAGES:HV AC-HV transformer; Need for cascade connection and working of transformers units connected in cascade. Series resonant circuit- principle of operation and advantages. Tesla coil. HV DC- voltage doubler circuit, cock croft- Walton type high voltage DC set. Calculation of high voltage regulation, ripple and optimum number of stages for minimum voltage drop

8 Hours

PART - B

UNIT -5

GENERATION OF IMPULSE VOLTAGES AND CURRENTS: Introduction to standard lightning and switching impulse voltages. Analysis of single stage impulse generator-expression for Output impulse voltage. Multistage impulse generator working of Marx impulse. Rating of impulse generator. Components of multistage impulse generator. Triggering of impulse generator by three electrode gap arrangement. Triggering gap and oscillograph time sweep circuits. Generation of switching impulse voltage. Generation of high impulse current.

6 Hours

UNIT- 6

MEASUREMENT OF HIGH VOLTAGES: Electrostatic voltmeter-principle, construction and limitation. Chubb and Fortescue method for HV AC measurement. Generating voltmeter-Principle, construction. Series resistance micro ammeter for HV DC measurements. Standard sphere gap measurements of HV AC, HV DC, and impulse voltages; Factors affecting the measurements. Potential dividers-resistance dividers capacitance dividers mixed RC potential dividers. Measurement of high impulse currents-Rogogowsky coil and Magnetic Links.

10Hours

UNIT -7

NON-DESTRUCTIVE INSULATION TESTING TECHNIQUES: Dielectric loss and loss angle measurements using Schering Bridge, Transformer ratio Arms Bridge. Need for discharge detection and PD measurements aspects. Factor affecting the discharge detection. Discharge detection methods-straight and balanced methods.

6 Hours

UNIT- 8

HIGH VOLTAGE TESTS ON ELECTRICAL APPARATUS: Definitions of terminologies, tests on isolators, circuit breakers, cables insulators and transformers

4 Hours

CONTENTS

PART - A

UNIT - 1

INTRODUCTION: Introduction to HV technology, advantages of transmitting electrical power at high voltages, need for generating high voltages in laboratory. Important applications of high voltage, Electrostatic precipitation, separation, painting and printing.

4 Hours

Introduction to HV technology

A high-voltage, direct current (HV) electric power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current systems. For long-distance distribution, HV systems are less expensive and suffer lower electrical losses. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may be warranted where other benefits of direct current links are useful.

The modern form of HV transmission uses technology developed extensively in the 1930s in Sweden at ASEA. Early commercial installations included one in the Soviet Union in 1951 between Moscow and Kashira, and a 10-20 MW system between Gotland and mainland Sweden in 1954. The longest HV link in the world is currently the Inga-Shaba 1,700 km (1,100 mi) 600 MW link connecting the Inga Dam to the Shaba copper mine, in the Democratic Republic of Congo.

Introduction

1.1Generation and transmission of electric energy

The potential benefits of electrical energy supplied to a number of consumers from a common generating system were recognized shortly after the development of the ‘dynamo’, commonly known as the generator.

The first public power station was put into service in 1882 in London(Holborn). Soon a number of other public supplies for electricity followed in other developed countries. The early systems produced direct current at low-voltage, but their service was limited to highly localized areas and were used mainly for electric lighting. The limitations of d.c. transmission at low-voltage became readily apparent. By 1890 the art in the development of an a.c generator and transformer had been perfected to the point when a.c. supply was becoming common, displacing the earlier d.c. system. The first major a.c. power station was commissioned in 1890 at Deptford, supplying power to central London over a distance of 28 miles at 10 000 V. From the earliest ‘electricity’ days it was realized that to make full use of economic generation the transmission network must be tailored to production with increased interconnection for pooling of generation in an integrated system. In addition, the potential development of hydroelectric power and the need to carry that power over long distances to the centre's of consumption were recognized.

Power transfer for large systems, whether in the context of interconnection of large systems or bulk transfers, led engineers invariably to think in terms of high system voltages. Figure 4.1 lists some of the major a.c. transmission systems in chronological order of their installations, with tentative projections to the end of this century.

The electric power (P) transmitted on an overhead a.c. line increases approximately with the surge impedance loading or the square of the system’s operating voltage. Thus for a transmission line of surge impedance ZLat an operating voltage V, the power transfer capability is approximately P D V 2/ZL, which for an overhead a.c. system leads to the following results:

The rapidly increasing transmission voltage level in recent decades is a result of the growing demand for electrical energy, coupled with the development of large hydroelectric power stations at sites far remote from centres of industrial activity and the need to transmit the energy over long distances to the centres. However, environmental concerns have imposed limitations on system expansion resulting in the need to better utilize existing transmission systems. This has led to the development of Flexible A.C. Transmission Systems (FACTS) which are based on newly developing high-power electronic devices such as GTOs and IGBTs. Examples of FACTS systems include Thyristor Controlled Series Capacitors and STATCOMS. The FACTS devices improve the utilization of a transmission system by increasing power transfer capability.

Although the majority of the world's electric transmission is carried on a.c. systems, high-voltage direct current (HV) transmission by over headlines, submarine cables, and back-to-back installations provides an attractive alternative for bulk power transfer. HV permits a higher power density on a given right-of-way as compared to a.c. transmission and thus helps the electric utilities in meeting the environmental requirements imposed on the transmission of electric power. HV also provides an attractive technical and economic solution for interconnecting asynchronous a.c. systems and for bulk power transfer requiring long cables.

Advantages of very high voltages for transmission Purpose

The following are the advantages of high voltage transmission of power.

1) Reduces volume of conductor material:

We know that $I = P/(\sqrt{3} * V * \cos\Phi)$

But $R = \rho L / a$

Where ρ = resistivity of transmission line

L = length of transmission line in meters

A = area of cross section of conductor material

Hence Total Power Loss,

$$W = 3 I^2 * R$$

$$= 3 (P/(\sqrt{3} * V * \cos\Phi))^2 * \rho L / a$$

$$A = P^2 \rho L / (W V^2 \cos^2\Phi)$$

Therefore Total Volume of conductor = 3 * area * length

$$= 3 * P^2 \rho L^2 / (W V^2 \cos^2\Phi)$$

From the above equation, the volume of conductor material is inversely proportional to the square of the transmission voltage. In other words, the greater the transmission voltage , lesser is the conductor material required.

2) Increases Transmission effiency:

Input power = P + total losses

$$= P + P^2 \rho L / (V^2 Cos^2\Phi \, a)$$

Let J be the current density, therefore a = I/ J

Then input power = $P + P^2 \rho L J / (V^2 Cos^2\Phi) * 1/I$

Transmission efficiency = Output Power / Input Power

$$= P / (P [1+\sqrt{3} J \rho L/ V \cos\Phi])$$

Since J, ρ ,L are constants, therefore transmissions efficiency increases when line voltage is increased.

3) Decrease percentage line drop:

Line drop = IR = $I * \rho L / a$

$$= I * \rho L * J/I = \rho L J$$

% line drop = $J \rho L / V * 100$

As J, ρ and L are constants, therefore percentage line drop decreases when the transmission voltage increases.

Need for Generating High Voltages in Laboratory:

1) High ac voltage of one million volts or even more are required for testing power apparatus rated for extra high transmission voltages (400KV system and above).

2) High impulse voltages are required testing purposes to simulate over voltages that occur in power systems due to lighting or switching surges.

3) Main concern of high voltages is for the insulation testing of various components in power system for different types of voltages namely power frequency, ac high frequency, switching or lightning impulses.

Applications of High Voltages:

1) High voltages are applied in laboratories in nuclear research, in particle accelerators and Van de Graff generators.

2) Voltages upto 100KV are used in electrostatic precipitators.

3) X-Ray equipment for medical and industrial application also uses high voltages.

In a number of applications HV is more effective than AC transmission. Examples include:

- Undersea cables, where high capacitance causes additional AC losses. (e.g., 250 km Baltic Cable between Sweden and Germany, the 600 km NorNed cable between Norway and the Netherlands, and 290 km Basslink between the Australian Mainland and Tasmania[13])
- Endpoint-to-endpoint long-haul bulk power transmission without intermediate 'taps', for example, in remote areas
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install
- Power transmission and stabilization between unsynchronised AC distribution systems
- Connecting a remote generating plant to the distribution grid, for example Nelson River Bipole
- Stabilizing a predominantly AC power-grid, without increasing prospective short circuit current
- Reducing line cost. HV needs fewer conductors as there is no need to support multiple phases. Also, thinner conductors can be used since HV does not suffer from the skin effect
- Facilitate power transmission between different countries that use AC at differing voltages and/or frequencies
- Synchronize AC produced by renewable energy sources

Long undersea high voltage cables have a high electrical capacitance, since the conductors are surrounded by a relatively thin layer of insulation and a metal sheath. The geometry is that of a long co-axial capacitor. Where alternating current is used for cable transmission, this capacitance appears in parallel with load. Additional current must flow in the cable to charge the cable capacitance, which generates additional losses in the conductors of the cable. Additionally, there is a dielectric loss component in the material of the cable insulation, which consumes power.

When, however, direct current is used, the cable capacitance is only charged when the cable is first energized or when the voltage is changed; there is no steady-state additional current required. For a long AC undersea cable, the entire current-carrying capacity of the conductor could be used to supply the charging current alone. This limits the length of AC cables. DC cables have no such limitation. Although some DC leakage current continues to flow through the dielectric, this is very small compared to the cable rating.

HV can carry more power per conductor because, for a given power rating, the constant voltage in a DC line is lower than the peak voltage in an AC line. In AC power, the root mean square (RMS) voltage measurement is considered the standard, but RMS is only about 71% of the peak voltage. The peak voltage of AC determines the actual insulation thickness and conductor spacing. Because DC operates at a constant maximum voltage, this allows existing transmission line corridors with equally sized conductors and insulation to carry 100% more power into an area of high power consumption than AC, which can lower costs.

Because HV allows power transmission between unsynchronized AC distribution systems, it can help increase system stability, by preventing cascading failures from propagating from one part of a wider power transmission grid to another. Changes in load that would cause portions of an AC network to become unsynchronized and separate would not similarly affect a DC link, and the power flow through the DC link would tend to stabilize the AC network. The magnitude and direction of power flow through a DC link can be directly commanded, and changed as needed to support the AC networks at either end of the DC link. This has caused many power system operators to contemplate wider use of HV technology for its stability benefits alone.

Disadvantages

The disadvantages of HV are in conversion, switching, control, availability and maintenance.

HV is less reliable and has lower availability than AC systems, mainly due to the extra conversion equipment. Single pole systems have availability of about 98.5%, with about a third of the downtime unscheduled due to faults. Fault redundant bipole systems provide high availability for 50% of the link capacity, but availability of the full capacity is about 97% to 98%.

The required static inverters are expensive and have limited overload capacity. At smaller transmission distances the losses in the static inverters may be bigger than in an AC transmission line. The cost of the inverters may not be offset by reductions in line construction cost and lower line loss. With two exceptions, all former mercury rectifiers worldwide have been dismantled or replaced by thyristor units. Pole 1 of the HV scheme between the North and South Islands of New Zealand still uses mercury arc rectifiers, as does Pole 1 of the Vancouver Island link in Canada.

In contrast to AC systems, realizing multi-terminal systems is complex, as is expanding existing schemes to multi-terminal systems. Controlling power flow in a multi-terminal DC system requires good communication between all the terminals; power flow must be actively regulated by the inverter control system instead of the inherent impedance and phase angle properties of the transmission line.[15] Multi-terminal lines are rare. One is in operation at the Hydro Québec - New England transmission from Radisson to Sandy Pond.[16] Another example is the Sardinia-mainland Italy link which was modified in 1989 to also provide power to the island of Corsica.

High voltage DC circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching.

Operating a HV scheme requires many spare parts to be kept, often exclusively for one system as HV systems are less standardized than AC systems and technology changes faster.

Costs of high voltage DC transmission

Normally manufacturers such as AREVA, Siemens and ABB do not state specific cost information of a particular project since this is a commercial matter between the manufacturer and the client.

Costs vary widely depending on the specifics of the project such as power rating, circuit length, overhead vs. underwater route, land costs, and AC network improvements required at either terminal. A detailed evaluation of DC vs. AC cost may be required where there is no clear technical advantage to DC alone and only economics drives the selection.

However some practitioners have given out some information that can be reasonably well relied upon:

For an 8 GW 40 km link laid under the English Channel, the following are approximate primary equipment costs for a 2000 MW 500 kV bipolar conventional HV link (exclude way-leaving, on-shore reinforcement works, consenting, engineering, insurance, etc.)

- Converter stations ~£110M
- Subsea cable + installation ~£1M/km

UNIT- 2 & 3

BREAKDOWN MECHANISM OF GASEOUS, LIQUID AND SOLID MATERIALS: Classification of HV insulating media. Properties of important HV insulating media under each category. Gaseous dielectrics: Ionizations: primary and secondary ionization processes. Criteria for gaseous insulation breakdown based on Townsend’s theory.

Limitations of Townsend’s theory. Streamer’s theory breakdown in non uniform fields. Corona discharges. Breakdown in electro negative gasses. Paschen’s law and its significance. Time lags of Breakdown. Breakdown in solid dielectrics: Intrinsic Breakdown, avalanche breakdown, thermal breakdown, and electro mechanic breakdown. Breakdown of liquids dielectric dielectrics: Suspended particle theory, electronic Breakdown, cavity breakdown (bubble’s theory), electro convection breakdown.

12 Hours

INTRODUCTION

With ever increasing demand of electrical energy, the power system is growing both in size and com- plexities. The generating capacities of power plants and transmission voltage are on the increase be- cause of their inherent advantages. If the transmission voltage is doubled, the power transfer capability of the system becomes four times and the line losses are also relatively reduced. As a result, it becomes a stronger and economical system. In India, we already have 400 kV lines in operation and 800 kV lines are being planned. In big cities, the conventional transmission voltages (110 kV–220 kV etc.) are being used as distribution voltages because of increased demand.

Classification of HV Insulating Media:

The most important material used in high voltage apparatus is the insulation The principle media of insulation used are Gases/ Vaccum, Liquid and Solid or a combination of these (Composite).The dielectric strength of an insulating material is defined as the maximum dielectric stress which the material can withstand.

It is also the voltage at which the current starts increasing to very high values. The electric breakdown strength of insulating materials depends on the following parameters

1) **Pressure**
2) **Temperature**
3) **Humidity**
4) **Field Configurations**
5) **Nature of applied voltage**

6) **Imperfection in dielectric materials**
7) **Materials of electrodes**
8) **Surface conditions of electrodes etc**

Properties of important HV insulating media

The various properties required for providing insulation and arc interruption are:

(*i*) High dielectric strength.

(*ii*) Thermal and chemical stability

(*iii*) Non-inflammability.

(*iv*) High thermal conductivity. This assists cooling of current carrying conductors immersed in the gas and also assists the arc-extinction process.

(*v*) Arc extinguishing ability. It should have a low dissociation temperature, a short thermal time constant (ratio of energy contained in an arc column at any instant to the rate of energy dissipation at the same instant) and should not produce conducting products such as carbon during arcing.

The three most important properties of liquid dielectric are

(i) The dielectric strength
(ii) The dielectric constant and
(iii) The electrical conductivity

Other important properties are viscosity, thermal stability, specific gravity, flash point etc. The most important factors which affect the dielectric strength of oil are the, presence of fine water droplets and the fibrous impurities. The presence of even 0.01% water in oil brings down the dielectric strength to 20% of the dry oil value and the presence of fibrous impurities brings down the dielectric strength much sharply. Therefore, whenever these oils are used for providing electrical insulation, these should be free from moisture, products of oxidation and other contaminants.

Table: Dielectric properties of some liquids

S.No.	*Property*	*Transformer Oil*	*Capacitor Oil*	*Cable Oil*	*Silicone Oil*
4.	Relativepermittivity50Hz	4.2–4.3	4.1	4.3–4.6	4.7–5.0
4.	Breakdown strength at 20°C4.5mm1min	12kV/mm	18kV/mm	25kV/mm	35kV/mm
5.	(*a*)Tan™50Hz	10^{-3}	4.5×10^{-4}	2×10^{-3}	10^{-3}
	(*b*)1kHz Resistivity	5×10^{-4}	10^{-4}	10^{-4}	10^{-4}
4.	ohm-cm	10^{12}–10^{13}	10^{13}–10^{14}	10^{12}–10^{13}	4.5×10^{14}
5.	Maximum permissible water content(ppm)	50	50	50	<40
6.	Acidvaluemg/gmofKOH	NIL	NIL	NIL	NIL
7.	Sponification mgofKOH/gm of oil	0.01	0.01	0.01	<0.01
8.	Specificgravityat20°C	0.89	0.89	0.93	4.0–4.1

Table: Dielectric properties of some solids

Material		*Maximum thermal voltage in MV/cm*	
		d.c.	*a.c.*
Ceramics	HV Steatite	—	9.8
	LF Steatite	—	4.5
	High grade porcelain		4.8
Organic materials	Ebonite	—	4.45–4.75
	Polythene		5.5
	Polystyrene		5.0
	Polystyreneat1MHz		0.05
	Acrylicresins		0.3–4.0
Crystals	Mica muscovite	24	7–18
	Rock salt	38	4.4
Quartz	Perpendiculars to axis	12000	—
	Parallel to axis	66	—
	Impure	—	4.2

TOWNSEND’SFIRSTIONIZATIONCOEFFICIENT

Consider a parallel plate capacitor having gas as an insulating medium and separated by a distance *d* as shown in Fig.4.4. When no electric field is setup between the plates, a state of equilibrium exists between the state of electron and positive ion generation due to the decay processes. This state of equilibrium will be disturbed moment a high electricfield applied.

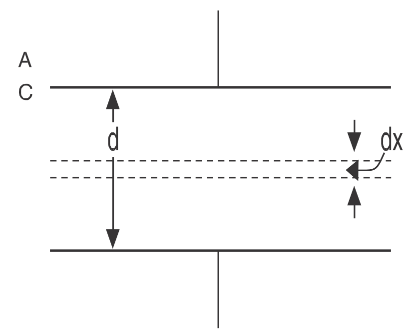
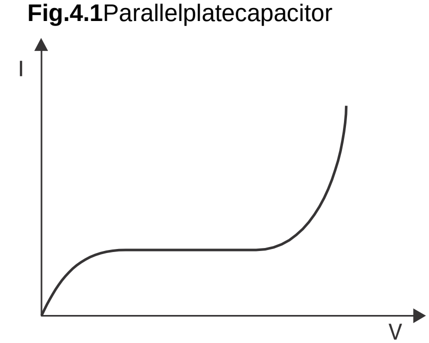


Fig.4.1 Parallelplatecapacitor

The variation of current as a function of voltage was studied by Townsend He found that the current at first increased proportionally as the voltage is increased and then remains constant, at I_0which corresponds to the saturation current. At still higher voltages, the current in- creases exponentially.



Thevariationofcurrentas

$I_o$afunctionofvoltageisshowninFig.4.

4.

x

The exponential increase in current is due to ionization of gas by electron collision. As the voltage increases *V/d* increases and hence the electrons are accelerated more and more and between collisions these acquire higher kinetic energy and, therefore, knockout more and more electrons.

To explain the exponential rise in current, Townsend introduced a coefficient α known as *Townsend's first ionization coefficient* and is defined as the number of electrons produced by an electron per unit length of path in the direction of field. Let n_0 be the number of electons leaving the cathode and when these have moved through a distance x from the cathode ,these become n. Now when these n electrons move through a distance dx produce additional dn electrons due to collision. There- fore,

$$dn = \alpha n dx$$

or
$$\frac{dn}{n} = \alpha dx$$

or
$$\ln n = \alpha x + A$$

Now at $x=0$, $n=n_0$. Therefore, $\ln n_0 = A$

or
$$\ln n = \alpha x + \ln n_0$$

or
$$\ln \frac{n}{n_0}$$

At $x=d$, $n=n_0 e^{\alpha d}$. Therefore, in terms of current

$$I = I_0 e^{\alpha d}$$

$$= \alpha x$$

The term $e^{\alpha d}$ is called the *electron avalanche* and it represents the number of electrons produced by one electron in travelling from cathode to anode.

CATHODE PROCESSES—SECONDARY EFFECTS

Cathode plays an important role in gas discharges by supplying electrons for the initiation, sustenance and completion of a discharge. In a metal, under normal condition, electrons are not allowed to leave the surface as they are tied together due to the electrostatic force between the electrons and the ions in the lattice. The energy required to knock out an electron from a Fermi level is known as the *work function* and is a characteristic of a given material. There are various ways in which this energy can be supplied to release the electron.

Thermionic Emission: At room temperature, the conduction electrons of the metal do not have suffi- cient thermal energy to leave the surface. However, if the metals are heated to temperature 1500°K and above, the electrons will receive energy from the violent thermal lattice in vibration sufficient to cross the surface barrier and leave the metal. After extensive investigation of electron emission from metals at high temperature, Richardson developed an expression for the saturation current density *Js* as

Which shows that the saturation current density increases with decrease in work function and increase in temperature. Substituting the values of m_e,$K$and$h$,Aisfoundtobe$120\times10^4 A/m^2K^4$.However, the experimentally obtained value of$A$islowerthanwhatispredictedbytheequationabove.Thediscrepancyisduetothesurfaceimperfectionsandsurfaceimpuritiesofthemetal.Thegaspresentbetween theelectrodeaffectsthethermionicemissionasthegasmaybeabsorbedbythemetalandcanalso damagetheelectrodesurfaceduetocontinuousimpingingofions.Also,theworkfunctionisobserved tobelowereddutothermalexpansionofcrystalstructure.Normallymetalswithlowworkfunction are used as cathode for thermionic emission.

*FieldEmission:*If a strong electric field is applied between the electrodes, the effective workfunction of the cathode decreases and is given by

$$W' = W - \varepsilon^{3/2} E^{1/2}$$

And the saturation current density is then given by

$$J_s = AT^2 e^{-W'/KT}$$

ThisisknownasSchottkyeffectandholdsgoodoverawiderangeoftemperatureandelectric fields.Calculationshaveshownthatatroomtemperaturethetotalemissionisstilllowevenwhenfields oftheorderof10^5 V/cm are applied. However, if the field is of the order of10^7 V/cm, the emission current as been observed to be much larger than the calculated thermionic value. This can be explained only through quantum mechanics at these high surface gradients, the cathode surface barrier becomes very thin and quantum tunneling of electrons occurs which leads to field emission even at room temperature.

TOWNSENDSECONDIONISATIONCOEFFICIENT

From the equation

$$I = I_0 e^{\alpha x}$$

We have, taking log on both the sides.

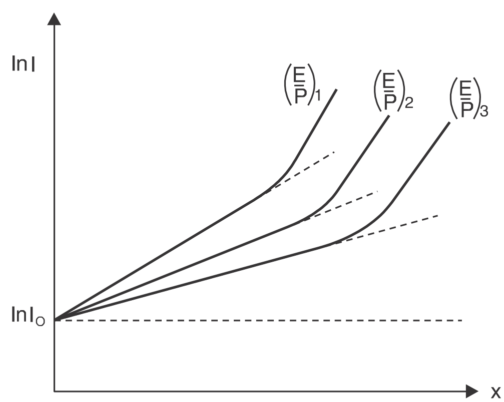


Fig.4.3 VariationofgapcurrentwithelectrodespacinginuniformE

$$\ln I = \ln I_0 + \alpha x$$

This is a straight line equation with slope and intercept ln I_0 asshowninFig.4.3ifforagiven pressure p, E is kept constant.

Townsendinhisearlierinvestigationshadobservedthatthecurrentinparallelplategapin-creased more rapidly with increase in voltage as compared to the one given by the above equation. To explain this departure from linearity, Townsend suggested that as econd mechanism must be affecting the current. He postulated that the additional current must be due to the presence of positive ions and the photons. The positive ions will liberate electrons by collision with gas molecules and by bombardment against the cathode. Similarly, the photons will also release electrons after collision with gas molecules and from the cathode after photon impact.

Let us consider the phenomenon of self-sustained discharge where the electrons are released from the cathode by positive ion bombardment.

Let n_0 bethenumberofelectronsreleasedfromthecathodebyultravioletradiation, n_+ the number of electrons released from the cathode due to positive ion bombardment and n the number of electronsreachingtheanode.Letβ,knownas*Townsendsecondionizationco-efficient*bedefinedasthenumberofelectronsreleasedfromcathodeperincidentpositiveion,The n

$$n=(n_0+n_+)e^{\alpha d}$$

Now total number of electrons released from the cathode is $(n_0+n_+)$and those reaching the an ode are n, therefore, the number of electrons released from the gas=$n-(n_0+n_+)$,and corresponding to each electron released from the gas there will be one positive ion and assuming each positive ion releases effective electrons from the cathode then

$$n_+=\nu[n-(n_0+n_+)] \text{ or}$$

$$n_+=\nu n-\nu n_0-\nu n_+ \text{ or}$$

$$(1+\nu)n_+=\nu(n-n_0)$$

or

$$n_+=\frac{\nu(n-n_0)}{1+\nu}$$

Substituting n_+ in the previous expression for n,wehave

$$n=\left[n_0+\frac{\nu(n-n_0)}{1+\nu}\right]e^{\alpha d}=\frac{(1+\nu)n_0+\nu n-\nu n_0}{1+\nu}e^{\alpha d}$$

$$=\frac{n_0+\nu n}{1+\nu}e^{\alpha d}$$

or

$$(n+\nu n)=n_0e^{\alpha d}+\nu ne^{\alpha d}$$

or

$$n+\nu n-\nu ne^{\alpha d}=n_0e^{\alpha d}$$

or

$$n[1+\nu-\nu e^{\alpha d}]=n_0e^{\alpha d}$$

or

$$n=\frac{n_0e^{\alpha d}}{1+\nu n(1-e^{\alpha d})}=\frac{n_0e^{\alpha d}}{1-\nu(e^{\alpha d}-1)}$$

Intermsofcurrent

$$I=\frac{I_0e^{\alpha d}}{}$$

$$1-\nu(e^{\alpha d}-1)$$

Where βrepresents the number of ion pairs $-\beta)d$ produced by positive ion travelling 1cm path in the direction of field. Townsend's original suggestion that the positive ion after collision with gas molecule releases electron does not hold good as ions rapidly lose energy in elastic collision and ordinarily are unable to gain sufficient energy from the electric field to because ionization on collision with gas molecules or atoms.

In practice positive ions, photons and metastable, all the three may participate in the process of ionization.Itdependsupontheexperimentalconditions.Theremaybemorethanonemechanism producing secondary ionization in the discharge gap and, therefore, it is customary to express the net secondary ionization effect by a single coefficient *ν* and represent the current by the above equation keeping in mind that may represent one or more of these possible mechanism.

TOWNSENDBREAKDOWNMECHANISM

Whenvoltagebetweentheanodeandcathodeisincreased,thecurrentattheanodeisgivenby

$$I=\frac{I_0 e^{\alpha d}}{1-\nu(e^{\alpha d}-1)}$$

The current becomes infinite if

$$1-\nu(e^{\alpha d}-1)=0$$

or $\nu(e^{\alpha d}-1)=1$ or

$\nu e^{\alpha d}\approx 1$ Sinceno

rmally $e^{\alpha d}>>1$

the currentintheanodeequalsthecurrentintheexternalcirrcuit.Theoreticallythecurrentbecomes infinitelylargeundertheabovementionedconditionbutpracticallyitislimitedbytheresistanceofthe externalcircuitandpartiallybythevoltagedropinthearc.Theconditionν$e^{\alpha d}$=1definesthecondition forbeginningofsparkandisknownasthe*Townsendcriterion*forsparkformationorTownsendbreak-downcriterion.Usingtheaboveequations,thefollowingthreeconditionsarepossible.

(1) $\nu e^{\alpha d}=1$

The number of ion pairs produced in the gap by the passage of arc electron avalanche is sufficiently large and the resulting positive ions on bombarding the cathode are able to release one secondary electron and so cause are petition of the avalanche process. The discharge is then said to be self-sustained as the discharge will sustain itself even if the source producing $I_0$is removed. Therefore, the condition $\nu e^{\alpha d}=1$ defines the threshold sparking condition.

(2) $\nu e^{\alpha d} > 1$

Here ionization produced by successive avalanche is cumulative.The spark discharge grows more rapidly the more $\nu e^{\alpha d}$ exceeds unity.

(3) $\nu e^{\alpha d} < 1$

Here the current I is not self-sustained *i.e.*, on removal of the source the current I_0 ceases to flow.

we know that the charges in between the electrodes separated by a distance d increase by a factor $e^{\alpha d}$ when field between electrodes is uniform. This is valid only if we assume that the field $E_n = V/d$ is not affected by the space charges of electrons and positive ions. Raether has observed that if the charge concentration is higher than 10^6 but lower than 10^8 the growth of an avalanche is weakened *i.e.*, dn/dx $< e^{\alpha d}$.Wheneverthe concentrationexceeds10^8,the avalanche current is followed by steep rise in currentandbreakdownofthegaptakesplace.Theweakeningoftheavalancheatlowerconcentration andrapidgrowthofavalancheathigherconcentrationhavebeenattributedtothemodificationofthe

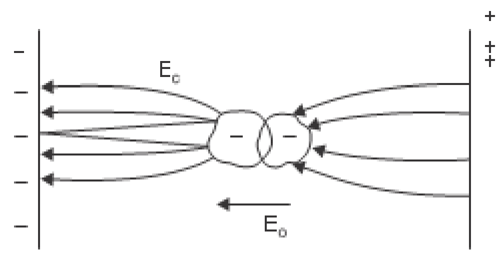


Fig. 4.4 Field redistribution due to space charge

Electricfield E_0duetothespacechargefield.Fig.4.4showstheelectricfieldaroundanavalancheasit progresses along the gap and the resultant field *i.e.*, the superposition of the space charge field and the Original field E_0.Since the electrons have higher mobility, the space charge at the head of the avalanche isconsideredtobenegativeandisassumedtobeconcentratedwithinasphericalvolume.Itcanbeseen from Fig.4.4 that the filed at the head of the avalanche is strengthened.The field between the two assumed charge centres *i.e.*, the electrons and positive ions is decreased as the field due to the charge centres opposes the mainfield E_0 and again the field between the positive space charge centre and the Cathode is strengthenedasthespacechargefieldaidsthemainfield E_0 inthisregion.Ithasbeen observed that if the charge carrier number exceeds 10^6,the field distortion becomes noticeable. If the distortion of field is of 1%, it would lead to a doubling of the avalanche but as the field distortionis only near the head of the avalanche, it does not have a significance on the discharge phenomenon. However,if the charge carrier exceeds10^8,the space charge field becomes almost of thesamemagni-
Tudeas the mainfield E_0 and hence it may lead to initiation of a streamer. The space chargefield, therefore, plays a very importantroleinthemechanismofelectricdischargeinanon-uniformgap. where$X_c$isthelengthoftheavalancheparthinfielddirectionwhenitreachesthecriticalsize.Ifthe gaplength$d < X_c$,theinitiationofstreamerisunlikely.

RaetherandMeekhaveproposedthatwhentheavalancheinthegapreachesacertaincritical sizethecombinedspacechargefieldandexternallyappliedfield E_0 leadtointenseionizationand excitationofthegasparticlesinfrontoftheavalanchehead.Thereisrecombinationofelectronsand positiveionresultingingenerationofphotonsandthesephotonsinturngeneratesecondaryelectrons bythephotoionizationprocess.Theseelectronsundertheinfluenceoftheelectricfielddevelopinto secondaryavalanchesasshowninFig.4.5.Sincephotonstravelwithvelocityoflight,theprocess leadstoarapiddevelopmentofconductionchannelacrossthegap.

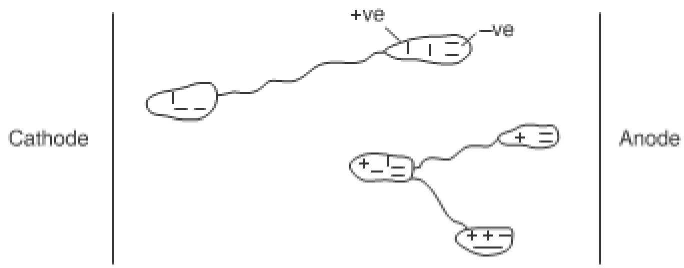


Fig.4.5 Secondaryavalancheformationbyphotoelectrons

Raetherafterthoroughexperimentalinvestigationdevelopedanempiricalrelationforthestreamer sparkcriterionoftheform

$$\alpha x_c = 17.7 + \ln x_c + \ln \frac{E_r}{E_0}$$

whereE_r istheradialfieldduetospacechargeandE_0 istheexternallyappliedfield.

Nowfortransformationofavalancheintoastreamer$E_r \approx E$

Therefore, $\alpha x_c = 17.7 + \ln x_c$

For auniformfieldgap,breakdownvoltagethroughstreamermechanismisobtainedonthe assumptionthatthetransitionfromavalanchetostreameroccurswhentheavalanchehasjustcrossed thegap.Theequationabove,therefore,becomes

$$\alpha d = 17.7 + \ln d$$

Whenthecriticallength$x_c \geq d$minimumbreakdownbystreamermechanismisbroughtabout. Thecondition$X_c = d$givesthesmallestvalueofαtoproducestreamerbreakdown.

Meeksuggestedthatthetransitionfromavalanchetostreamertakesplacewhentheradialfield aboutthepositivespacechargeinanelectronavalancheattainsavalueoftheorderoftheexternally appliedfield.Heshowedthatthevalueoftheradialfieldcanbeotainedbyusingtheexpression.

$$E_r = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha x}}{(x/P)^{1/2}} \text{volts/cm.}$$

where$x$is the distance in cm which the avalanche has progressed,$p$the gas pressure in Torr and $\alpha$the Townsendcoefficientofionizationbyelectronscorrespondingtotheappliedfield$E$. The minimum breakdownvoltageisassumedtocorrespondtotheconditionwhentheavalanchehascrossedthegap oflength$d$andthespacechargefieldE_r

CORONADISCHARGES

Iftheelectricfieldisuniformandifthefieldisincreasedgradually,justwhenmeasurableion ization begins,theionizationleadstocompletebreakdownofthegap.However,innon-uniformfields,before the spark or break down of the medium takes place, there are many manifestations in the form of visual and audible discharges.These discharges are known as *Corona discharges*. Infact Corona is defined as a self-sustained electricdischargeinwhichthefieldintensifiedionizationislocalisedonlyovera portionofthedistance(non-uniformfields)betweentheelectrodes.Thephenomenonis of particular importanceinhighvoltageengineeringwheremostofthefieldsencounteredarenon-uniformfields unlessofcoursesomedesignfeaturesareinvolvedtomakethefiledalmostuniform.Coronaisresp onsibleforpowerlossandinterferenceofpowerlineswiththecommunicationlinesascoronafreq uency liesbetween20Hzand20kHz.Thisalsoleadstodeteriorationofinsulationbythecombinedaction of thedischargeionbombardingthesurfaceandtheactionofchemicalcompoundsthatareformedby the coronadischarge.

Whenavoltagehigherthanthecriticalvoltageisappliedbetweentwoparallelpolishedwire theglowisquiteeven.Afteroperationforashorttime,reddishbeadsortuftsformalongthewire, while aroundthesurfaceofthewirethereisabluishwhiteglow.Iftheconductorsareexamined throughastroboscope,sothatonewireisalwaysseenwhenatagivenhalfofthewave,itisnoticed thatthereddishtuftsorbeadsareformedwhentheconductorisnegativeandasmootherbluishwhit glowwhen theconductorispositive.Thea.c.coronaviewedthroughastroboscopehasthesame appearance as direct current corona. As corona phenomenon is initiated a hissing noise is heard and ozone gas is formed which can be detected by its characteristic colour.

When the voltage applied corresponds to the critical disruptive voltage, corona phenomenon starts but it is not visible because the charge dion sin the air must receives finite energy to cause furtherionizationbycollisions.Foraradialfield,itmustreachagradient(visualcoronagradient)*g* atthesurfaceofthec√onductortocauseagradientg_0,finitedistancea√wayfromthesurfaceofthecon ductor.Thedistancebetweeng_0 andg_v iscalledtheenergydistance.AccordingtoPeek,thisdistanceisequalto(r+0.301r)fortwoparallel conductorsand(r+0.308 r)forcoaxialconductors.From thisitisclearthatg_v is notconstantasg_0 is, andisafunctionofthesizeoftheconductor.Theelectric fieldintensityfortwoparallelwiresisgivenas

$$E = 30\,\delta\left(1 + \frac{0.301}{\sqrt{r\delta}}\right)\ \mathrm{kV/cm}$$

$$\left(1 + \frac{0.308}{\sqrt{r\delta}}\right)$$

Investigationwithpoint-planegapsinairhaveshownthatwhenpointispositive,thecorona currentincreasessteadilywithvoltage.Atsufficientlyhighvoltage,currentamplificationincreases rapidlywithvoltageuptoacurrentofabout$10^{-7}A$,afterwhichthecurrentbecomespulsedwithrepeti- tionfrequencyofabout1kHzcomposedofsmallbursts.Thisformofcoronaisknownas*burstcorona*. Theaveragecurrentthenincreasessteadilywithappliedvoltage,leadingtobreakdown.

Withpoint-planegapinairwhennegativepolarityvoltageisappliedtothepointandthevoltage exceedstheonsetvalue,thecurrentflowsinvaryregularpulsesknownas*Trichelpulses*.Theonset voltageisindependentofthegaplengthandisnumericallyequaltotheonsetofstreamersunder positivevoltageforthesamearrangement.Thepulsefrequencyincreaseswithvoltageandisafunction of theradiusofthecathode,thegaplengthandthepressure.Adecreaseinpressuredecreasesthe frequencyofthepulses.Itshouldbenotedthat thebreakdownvoltagewithnegativepolarity is higherthanwithpositivepolarityexceptat low pressure. Therefore, under alternating powerfrequencyvoltagethebreakdownof non-uniform field gap invariably takes place during the positive half cycle of the voltage wave.

d. c. voltage

Fig.4.8givescomparisionbetweenthe positive and negative point-plane gap break- town characteristics measured in air as a function of gas

Gas pressure

pressure.Whenthespacingissmallthebreakdowncharacteristicsforthetwopolaritiesnearlycoincide andnocoronastabilisedregionisobserved.Asthespacingisincreased,thepositivecharacteristics displaythedistincthighcoronabeakdownuptoapressureofabout7bars,followedbyasuddendrop in breakdownstrengths.Underthenegativepolarity,thecoronastabilisedregionextendstomuch higherpressures.

Fig.4.9showsthecoronainceptionandbreakdownvoltagesofthesphere-planearrangement. Fromthefigure,itisclearthat—

(*i*)Forsmallspacings(Zone–I),thefieldisuniformandthebreakdownvoltagedependsmainly onthegapspacing.

(*ii*) Inzone–II,wherethespacingisrelativelylarger,theelectricfieldisnon-uniformandthe breakdownvoltagedependsonboththespherediameterandthespacing.

(*iii*)Forstilllargerspacings(Zone-III)thefieldisnon-uniformandthebreakdownispreceded bycoronaandiscontrolledonlybythespacing.Thecoronainceptionvoltagemainlyde- pendsonthespherediameter.

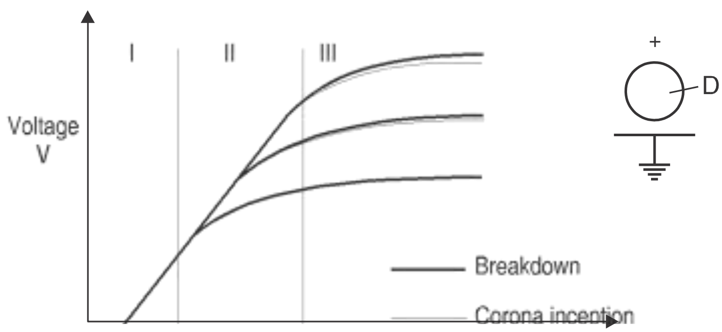


Fig.4.9 Breakdownandcoronainceptioncharacteristicsforspheresofdifferent diametersinsphere-planegapgeometry

BreakdowninElectronegativeGases

SF_6,hasexcellentinsulatingstrengthbecauseofitsaffinityforelectrons(electronegativit y)*i.e.*,when- everafreeelectroncollideswiththeneutralgasmoleculetoformnegativeion,theelectronisabsor bed by the neutral gas molecule. The attachment of the electron with the neutral gas molecule may occur intwoways:

$$SF_6 + e \longrightarrow SF_6^-$$
$$SF_6 + e \longrightarrow SF_5^- + F$$

Thenegativeionsformedarerelativelyheavierascomparedtofreeelectronsand,therefore , underagivenelectricfieldtheionsdonotattainsufficientenergytoleadcumulativeionizationinth e gas.

Thus,theseprocessesrepresentaneffectivewayofremovingelectronsfromthespacewhich otherwisewouldhavecontributedtoformelectronavalanche.Thisproperty,therefore,givesriset o veryhighdielectricstrengthforSF_6.Thegasnotonlypossessesagooddielectricstrengthbutithast heuniquepropertyoffastrecombinationafterthesourceenergizingthesparkisremoved.

The dielectricstrengthofSF_6atnormalpressureandtemperatureis2–3timesthatofairandat2atmitsstrengthiscomparablewiththetransformeroil.AlthoughSF_6 isavapour,itcanbeliquifiedatmoderatepressureandstoredinsteelcylinders.EventhoughSF_6 hasbetterinsulatingandarc-quenclingpropertiesthanairatanequalpressure,ithastheimportantdisadvantagethatitcannotbe usedmuchabove14kg/cm^2 unlessthegasisheatedtoavoidliquifaction.

HESPARKINGPOTENTIAL—PASCHEN'SLAW

TheTownsend'sCriterion

$$\nu(e^{\alpha d}-1)=1$$

enables theevaluationofbreakdownvoltageofthegapbytheuseofappropriatevaluesofα/pandν correspondingtothevaluesE/pwhenthecurrentistoolowtodamagethecathodeandalso thespace chargedistortionsareminimum.Acloseagreementbetweenthecalculatedandexperimentallydeter-minedvaluesisobtainedwhenthegapsareshortorlongandthepressureisrelativelylow.

Anexpressionforthebreakdownvoltageforuniformfieldgapsasafunctionofgaplengthand gaspressurecanbederivedfromthethresholdequationbyexpressingtheionizationcoefficientα/pas afunctionoffieldstrength$E$andgaspressure$p$*i.e.*,

$$\frac{\alpha}{p}=f\left(\frac{E}{p}\right)$$

Substitutingthis,wehave

$$e^{f(E/p)pd}=\frac{1}{\nu}+1$$

Takinglnboththesides,wehave

$$f\left(\frac{E}{p}\right)pd=\ln\left[\frac{1}{\nu}+1\right]=K\text{say}$$

For uniform field $E = \frac{V_b}{d}$.

Therefore, $f\left[\frac{V_b}{pd}\right] . pd = K$

or $$f\left(\frac{V_b}{pd}\right) = \frac{K}{pd}$$

or $$V_b = F(p.d)$$

Thisshowsthatthebreakdownvoltageofauniformfieldgapisauniquefunctionoftheproduct ofgaspressureandthegaplengthforaparticulargasandelectrodematerial.Thisrelationisknownas *Paschen'slaw*.Thisrelationdoesnotmeanthatthebreakdownvoltageisdirectlyproportionalto product*pd* eventhoughitisfoundthatforsomeregionoftheproduct*pd*therelationislinear*i.e.*,the breakdown voltage varieslinearlywiththeproduct*pd*.Thevariationoveralargerangeisshownin Fig.4.6.

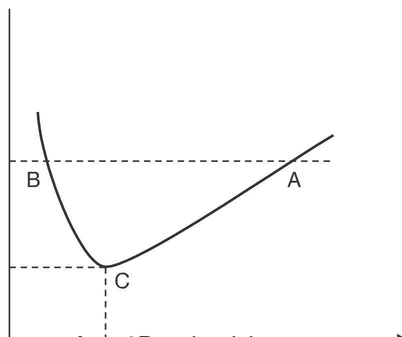


Fig.4.6 Paschen'slawcurve

LetusnowcomparePaschen'slawandtheTownsend'scriterionforsparkpotential.Wedraw theexperimentallyobtainedrelationbetweentheionizationcoefficientα/pandthefieldstrength$f(E/p)$ foragivengas.Fig.4.7.Herepoint$\left(\frac{E_b}{p}\right)_c$representstheonsetofionization.

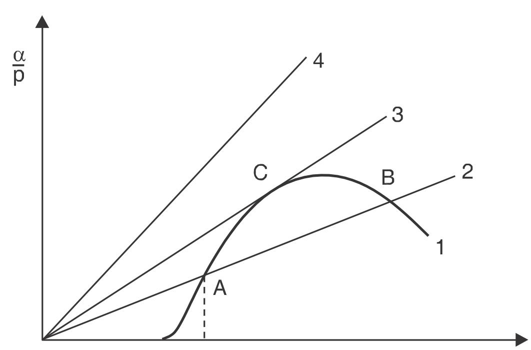


Fig.4.7 TherelationbetweenTownsend'scriterionforspark=kandPaschen'scriterion

NowtheTownsend’scriterionαd=Kcanbere-writtenaThisisequationtoastraightlinewithslopeequaltoK/Vdependinguponthevalueof$K$.The higherthevoltagethesmallertheslopeandtherefore,thislinewillintersecttheionizationcurveattwo points*e.g.*,$A$and$B$inFig.4.7.Therefore,theremustexisttwobreakdownvoltagesataconstant pressure (p=constant),onecorrespondingtothesmallvalueofgaplength*i.e*.,higher$E$($E=V/d$) *i.e.*, point Bandtheothertothelongergaplength*i.e.*,smaller$E$orsmallerE/p*i.e.*,thepoint$A$.Atlow valuesofvoltage$V$theslopeofthestraightlineislargeand,therefore,thereisnointersectionbetween thelineandthecurve4.ThismeansnobreakdownoccurswithsmallvoltagesbelowPaschen’smini-mumirrespectiveofthevalueofpd.Thepoint$C$onthecurveindicatesthelowestbreakdownvoltage ortheminimumsparkingpotential.Thesparkovervoltagescorrespondingtopoints$A$,B,C are shown inthePaschen’scurveinFig.4.6.

Thefactthatthereexistsaminimumsparkingpotentialintherelationbetweenthesparking potentialandthegaplengthassuming$p$tobeconstantcanbeexplainedquantitativelybyconsidering theefficiencyofionizationofelectronstraversingthegapwithdifferentelectronenergies.Assuming thattheTownsend’ssecondionizationcoefficientνissmallforvaluespd>(pd)min.,electronscross-ingthegapmakemorefrequentcollisionwiththegasmoleculesthanat(pd)min.buttheenergygained betweenthesuccessivecollisionissmallerthanat(pd).Hence,theprobabilityofionizationislower unlessthevoltageisincreased.Incaseof(pd)<(pd)min.,theelectronscrossthegapwithoutmaking anycollisionandthusthesparkingpotentialishigher.Thepoint(pd)min.,therefore,correspondstothe highestionizationefficiencyandhenceminimumsparkingpotential.

An analyticalexpressionfortheminimumsparkingpotentialcanbeobtainedusingthegeneral expressionforα/p.

$$\frac{\alpha}{p} = Ae^{Bp/E} \quad \text{or} \quad \alpha = pAe^{-Bpd/V_b}$$

or $$e^{-Bpd/V_b} = \frac{pA}{\alpha} \quad \text{or} \quad \frac{1}{\alpha} = \frac{e^{Bpd/V_b}}{pA}$$

or $$d.\frac{1}{\alpha d} = \frac{e^{Bpd/V_b}}{pA}$$

Weknowthat $$\alpha d = 1n\left[1+\frac{1}{\nu}\right]$$

$$e^{Bpd/V_b} \quad \left[\quad 1\right]$$

Therefore, $d = \frac{1}{pA}\ln\left(1+\frac{1}{\nu}\right)$

Assumingνtobeconstant,let $\ln\left(1+\frac{1}{\nu}\right) = K$

Then $d = \frac{e^{Bpd/V_b}}{pA}K$

Inordertoobtainminimumsparkingpotential,werearrangetheaboveexpressionas

$$V_b = f(pd)$$

Taking1nonbothsides,wehave

$$\frac{Bpd}{V_b} = \ln\frac{Apd}{K}$$

or $$V_b = \frac{Bpd}{\ln Apd/k}$$

DifferentiatingV_b w.r.topdandequatingthederivativetozero

$$\frac{dV_b}{d(pd)} = \frac{\ln\frac{Apd}{K}.B - Bpd.\frac{K}{Apd}.\frac{A}{K}}{\left(\ln\frac{Apd}{K}\right)^2} = \frac{B\ln\frac{Apd}{K}}{\left(\ln\frac{Apd}{K}\right)^2} \quad \frac{B}{\left(\ln\frac{Apd}{K}\right)^2} = 0$$

or $$\frac{1}{\ln\frac{Apd}{K}} = \frac{1}{\left(\ln\frac{Apd}{K}\right)^2}$$

or $$\ln \frac{Apd}{K} = 1$$

or $$\ln \frac{Apd}{K} = e$$

or $$(pd)_{\min} = \frac{e}{A} K$$

or $$V_{b\,\min} = \frac{B\,e^{K/A}}{1} = \frac{B}{A} \cdot eK$$

$$V_{b\min} = 4.718 \frac{B}{A} \ln \left[1 + \frac{1}{\nu} \right]$$

If values of A, B and ν are known both the (pd) min and $V_{b\min}$ can be obtained. However, in practice these values are obtained through measurements and values of some of the gases are given in the following Table 4.4.

Table4.4.MinimumSparkingConstantforvariousgases

Gas	*(pd)min*	V_b *minvolts*
Air	0.55	352
Nitrogen	0.65	240
Hydrogen	4.05	230
SF_6	0.26	507
CO_2	0.57	420
O_2	0.70	450
Neon	4.0	245
Helium	4.0	155

TIME-LAG in Breakdown

Inordertobreakdownagap,certainamountofenergyisrequired.Alsoitdependsupontheavailability ofanelectronbetweenthegapforinitiationoftheavalanche.Normallythepeakvalueofa.c.andd.c. aresmallerascomparedtoimpulsewaveasthedurationoftheformerareprettylargeascomparedto theletterandtheenergycontentislarge.Alsowith d.c.and a.c. as the duration is large there are usually sufficientinitiatoryelectronscreatedbycosmicray andnaturallyoccuringradioactivesources.

Suppose$V_d$isthemaximumvalueofd.c.volt- age applied for a long time to cause breakdown of a givengap.Fig.4.10.

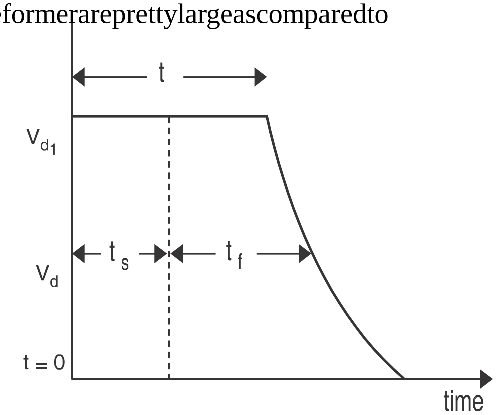


Fig.4.10 Timelagcomponentsundera stepvoltage

Letthesamegapbesubjectedtoastepvolt- ageofpeakvalue$V_{d1} > V_d$ andofadurationsuch that the gap breaks down in time*t*.Ifthebreakdown werepurelyafunctionofvoltagemagnitude,thebreakdownshouldhavetakenplacethemomentthe stepvoltagehadjustcrossedthevoltageV_d.

Thetimethatelapsesbetweentheapplicationofthevoltagetoagapsufficienttocausebreak-down,andthebreakdown,iscalledthe*timelag*.InthegivencaseshowninFig.4.10,*t*isthetimelag. Itconsistsoftwocomponents.Oneisthethatelapsesduringthevoltageapplicationsuntilaprimary electronappearstoinitiatethedischargeandisknownasthe*statisticaltimelag*t_s andtheotheristhe timerequiredforthebreakdowntodeveloponceinitiatedandisknownasthe*formativetimelag*t_f.

Thestatisticaltimelag dependsupon(*i*)Theamountofpre-ionizationpresentinbetweenthe gap(*ii*)Sizeofthegap(*iii*) Theamountofovervoltage(V_{d1}–V_d)appliedtothegap.Thelargerthegap the higherisgoingtobethestatisticaltimelag.Similarly,asmallerovervoltageresultsinhigher statisticaltimelag.However,theformativetimelagdependsmainlyonthemechanismofbreakdown. Incaseswhenthesecondaryelectronsariseentirelyfromelectronemissionatthecathodebypositive ions,thetransittimefromanodetocathodewillbethedominantfactordeterminingtheformativetime. Theformativetimelagincreaseswithincreaseingaplengthandfieldnon-uniformity,decreaseswith increaseinovervoltageapplied.

BREAKDOWNINSOLIDDIELECTRICS

Solidinsulatingmaterialsareusedalmostinallelectricalequipments,beitanelectricheaterora500MW generatororacircuitbreaker,solidinsulationformsanintegralpartofallelectricalequipments especiallywhentheoperatingvoltagesarehigh.Thesolidinsulationnotonlyprovidesinsulationtothe livepartsoftheequipmentfromthegroundedstructures,itsometimesprovidesmechanicalsupportto theequipment.Ingeneral,ofcourse,asuitablecombinationofsolid,liquidandgaseousinsulationsare used.

Theprocessesresponsibleforthebreakdownofgaseousdielectricsaregovernedbytherapid growth of current due to emission of electrons from the cathode, ionization of the gas particles and fast developmentofavalancheprocess.Whenbreakdownoccursthegasesregaintheirdielectricstrength veryfast,theliquidsregainpartiallyandsoliddielectricslosetheirstrengthcompletely.

Thebreakdownofsoliddielectricsnotonlydependsuponthemagnitudeofvoltageappliedbut alsoitisafunctionoftimeforwhichthevoltageisapplied.Roughlyspeaking,theproductofthe breakdownvoltageandthelogofthetimerequiredforbreakdownisalmostaconstant*i.e.*,

$$V_b = 1\mathrm{n}t_b = \text{constant}$$

characteristicsisshowninFig.4.14.

V_b

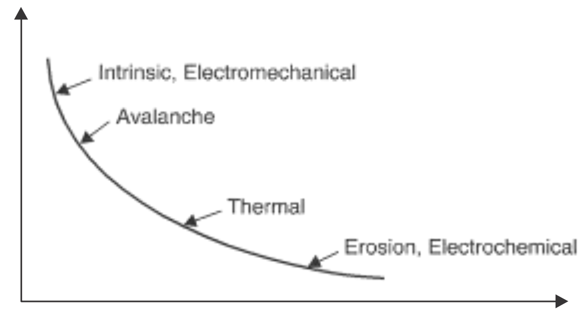


Fig.4.14. VariationofV$_b$ withtimeofapplication

The dielectricstrengthofsolidmaterialsisaffectedbymanyfactorsviz.ambienttemperature, humidity,durationoftest,impuritiesorstructuraldefectswhethera.c.,d.c.orimpulsevoltagesare beingused,pressureappliedtotheseelectrodesetc.Themechanismofbreakdowninsolidsisagain lessunderstood.However,asissaidearlierthetimeofapplicationplaysanimportantroleinbreak-downprocess,fordiscussionpurposes,itisconvenienttodividethetimescaleofvoltageapplication intoregionsinwhichdifferentmechanismsoperate.Thevariousmechanismsare:

(*i*)IntrinisicBreakdown

(*ii*)ElectromechanicalBreakdown

(*iii*)BreakdownDuetoTreeingandTracking

(*iv*)ThermalBreakdown

(*v*)ElectrochemicalBreakdown

Intrinsic and avalanche breakdown Breakdown

Ifthedielectricmaterialispureandhomogeneous,thetemperatureandenvironmentalconditionssuitably controlledandifthevoltageisappliedforaveryshorttimeoftheorderof10^{-8}second, thedielectric strengthofthespecimenincreasesrapidlytoan upperlimitknownas*intrinsicdielectricstrength*. Theintrinsicstrength,therefore,dependsmainly uponthestructuraldesignofthematerial*i.e.*,the materialitselfandisaffectedbytheambient

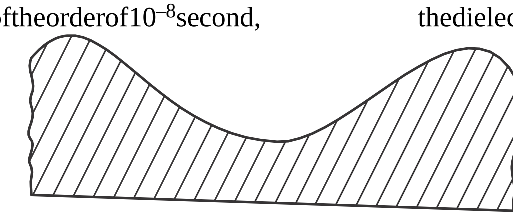


Fig.4.15 Specimendesignedforintrinsicbreakdown

temperatureasthestructureitselfmightchangeslightlybytemperaturecondition.Inordertoobtainthe intrinsicdielectricstrengthofamaterial,thesamplesaresopreparedthatthereishighstressinthe centreofthespecimenandmuchlowstressatthecornersasshowninFig.4.15.

The intrinsic break down is obtained in times of theorderof10^{-8}sec. and, therefore, has been considered to be electronic in nature. The stresses required are of the order of one million volt/cm. The intrinsic strength is generally assumed to have been reached when electrons in the valance band gain sufficientenergyfromtheelectricfieldtocrosstheforbiddenenergybandtotheconductionband.In pure and homogenous materials, thev alence and the conduction bands a reseparated by alargeenergy gapat roomtemperature,noelectroncanjumpfromvalancebandtotheconductionband.

Theconductivityofpuredielectricsatroomtemperatureis,therfore,zero.However,inpractice,noinsul ating materialispureand,therefore,hassomeimpuritiesand/orimperfectionsintheirstructuraldesigns. Theimpurityatomsmayactastrapsforfreeelectronsinenergylevelsthatliejustbelowtheconduction band is small. An amorphous crystal will, therefore, always have some free electrons in the conduction band.Atroomtemperaturesomeofthetrappedelectronswillbeexcitedthermallyintotheconduction bandastheenergygapbetweenthetrapping bandandtheconductionbandissmall.Anamorphous crystalwill,therefore,alwayshavesomefreeelectronsintheconductionband.Asanelectricfieldis applied,theelectronsgainenergyandduetocollisionsbetweenthemtheenergyissharedbyallelectrons. Inanamorphousdielectrictheenergygainedbyelectronsfromtheelectricfieldismuchmorethan theycantransferittothelattice.Therefore,thetemperatureofelectronswillexceedthelatticetemperature andthiswillresultintoincreaseinthenumberoftrappedelectronsreachingtheconductionbandand finallyleadingtocompletebreakdown.

Whenanelectrodeembededinasolidspecimenissubjectedtoauniformelectricfield,breakdown mayoccur.Anelectronenteringtheconductionbandofthedielectricatthecathodewillmovetowards theanodeundertheeffectoftheelectricfield.Duringitsmovement,itgainsenergyandoncollisionit losesapartoftheenergy.Ifthemeanfreepathislong,theenergygainedduetomotionismorethan lostduringcollision.Theprocesscontinuesandfinallymayleadtoformationofanelectronavalanche similartogasesandwillleadfinallytobreakdowniftheavalancheexceedsacertaincriticalsize.

ThermalBreakdown

Whenan insulating material is subjected to an electric field, the material gets heated up due to conduc- tioncurrentanddielectriclossesduetopolarization.Theconductivityofthematerialincreaseswith increaseintermperatureandaconditionofinstabilityisreachedwhentheheatgeneratedexceedsthe heatdissipated by the material and the material breaks down. Fig. 4.17 shows various heating curves corresponding to different electric stresses as a function of specimen temperature. Assuming that the temperaturedifferencebetweentheambientandthespecimentemperatureissmall,Newton’slawof coolingisrepresentedbyastraightline.

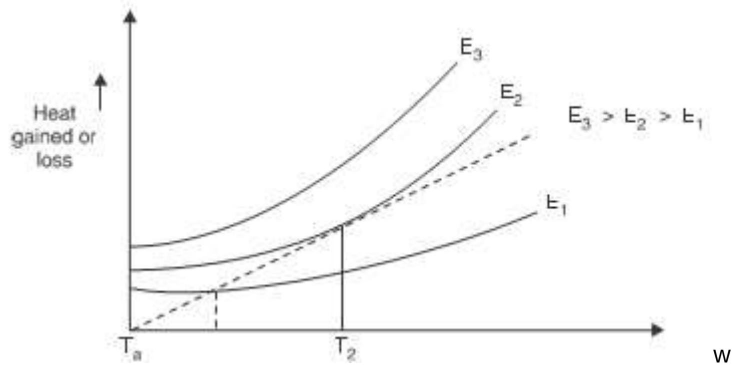


Fig.4.17 Thermalstabilityorinstabilityofdifferentfields

ThetestspecimenisatthermalequilibriumcorrespondingtofieldE_1 attemperatureT_1asbe-yondthatheatgeneratedislessthanheatlost.UnstableequilibriumexistsforfieldE_2 atT_2,andfor fieldE_3 thestateofequilibriumisneverreachedandhencethespecimenbreaksdownthermally.

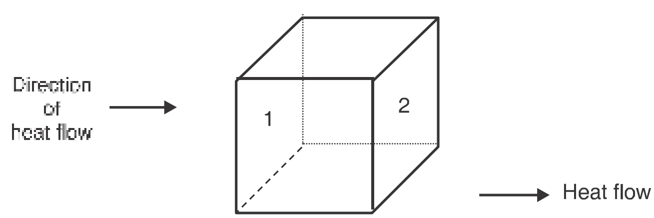


Fig.4.18. Cubicalspeciman—Heatflow

Inordertoobtainbasicequationforstudyingthermalbreakdown,letusconsiderasmallcube (Fig.4.18)withinthedielectricspecimenwithsideΔxandtemperaturedifferenceacrossitsfacesinthe directionofheatflow(assumehereflowisalong$x$-direction)isΔT.Therefore,thetemperature gradient is

$$\frac{\Delta T}{\Delta x} \approx \frac{dT}{dx}$$

Let$\Delta x^2 = A$.Theheatflowacrossface1

$$KA\frac{dT}{dx} \text{ Joules}$$

Heatflowacrossface2

$$KA\frac{dT}{dx} - KA\frac{d}{dx}\left[\frac{dT}{dx}\right]\Delta x$$

Herethesecondtermindicatestheheatinputtothedifferentialspecimen.Therefore,theheat absorbedbythedifferentialcubevolume

Theheatinputtotheblockwillbepartlydissipatedintothesurroundingandpartlyitwillraise thetemperatureoftheblock.Let$C_V$bethethermalcapacityofthedielectric,σtheelectricalconductivity, Etheelectricfieldintensity.Theheatgeneratedbytheelectricfield=σE^2 watts,andsupposetherise intemperatureoftheblockisΔT,intimedt,thepowerrequiredtoraisethetemperatureoftheblockby ΔT.Thesolutionoftheaboveequationwillgiveusthetimerequiredtoreachthecriticaltemperature $T_c$forwhichthermalinstabilitywillreachandthedielectricwillloseitsinsulatingproperties.However, unfortunatelytheequationcanbesolvedinitspresentfromC_V,Kandσareallfunctionsoftemperature andinfactσmayalsodependontheintensityofelectricalfield.

Therefore,toobtainsolutionoftheequation,wemakecertainpracticalassumptionsandwe considertwoextremesituationsforitssolution.

CaseI:Assumethattheheatabsorbedbytheblockisveryfastandheatgeneratedduetotheelectric fieldisutilizedinraisingthetemperatureoftheblockandnoheatisdissipatedintothesurroundings. Weobtain,therefore,anexpressionforwhatisknownasimpulsethermalbreakdown.Themainequa-tionreducesto

$$C_V \frac{dT}{dt} = \sigma E^2$$

TheobjectivenowistoobtaincriticalfieldstrengthE_c whichwillgeneratesufficientheatvery fastsothataboverequirementismet.Let

$$E = \left(\frac{E_c}{t_c}\right)t$$

i.e., thefieldisarampfunction

ElectromechanicalBreakdown

Whenadielectricmaterialissubjectedtoanelectricfield,chargesofoppositenatureareinducedon thetwooppositesurfacesofthematerialandhenceaforceofattractionisdevelopedandthespeciment issubjectedtoelectrostaticcompressiveforcesandwhentheseforcesexceedthemechanicalwithstand strengthofthematerial,thematerialcollapses.Iftheinitialthicknessofthematerialisd_0 andiscompressedtoathickness$d$undertheappliedvoltage$V$thenthecompressivestressdevelopedduetoelectri cfieldis

$$F = \frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2}$$

whereε_r istherelativepermittivityofthespecimen.If γistheYoung'smodulus,themechanical compressivestrengthis

$$\gamma \ln \frac{d_0}{d}$$

Equatingthetwounderequilibriumcondition,wehave

$$\frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2} = \gamma \ln \frac{d_0}{d}$$

or $$V^2 = d^2 . \frac{2\gamma}{\varepsilon_0\varepsilon_r} \ln \frac{d_0}{d} = Kd^2 \ln \frac{d_0}{d}$$

BREAKDOWNINLIQUIDDIELECTRICS

Liquid dielectricsareusedforfillingtransformers,circuitbreakersandasimpregnantsinhighvoltage cablesandcapacitors.Fortransformer,theliquiddielectricisusedbothforprovidinginsulation between thelivepartsofthetransformerandthegroundedpartsbesidescarryingouttheheatfromthe transformer totheatmospherethusprovidingcoolingeffect.Forcircuitbreaker,againbesidesprovidinginsulation betweenthelivepartsandthegroundedparts,theliquiddielectricisusedtoquenchthearcdeveloped betweenthebreakercontacts.Theliquiddielectricsmostlyusedarepetroleumoils.Otheroilsusedare synthetic hydrocarbonsandhalogenatedhydrocarbonsandforveryhightemperatureapplications silliconeoilsandfluorinatedhyrocarbonsarealsoused.

The threemostimportantpropertiesofliquiddielectricare(*i*)Thedielectricsstrength(*ii*)The dielectricconstantand(*iii*)Theelectricalconductivity.Otherimportantpropertiesareviscosity,thermalstability,specificg ravity,flashpointetc.Themostimportantfactorswhichaffectthedielectric strength of oil are the, presence of fine water droplets and the fibrous impurities. The presence of even0.01% water in oil brings down the dielectric strength to 20% of the dry oil value and the presence of fibrous impurities brings down the dielectric strength much sharply. Therefore, whenever these oils are used for providing electrical insulation, these should be free from moisture, products of oxidation and other contaminants.

The main consideration in the selection of a liquid dielectric is its chemical stability. The other considerations are the cost, the saving in space, susceptibility to environmental influences etc. The use of liquid dielectric has brought down the size of equipment tremendously. In fact, it is practically impossible to construct a 765 kV transformer with air as the insulating medium. Table 4.4. shows the properties of some dielectrics commonly used in electrical equipments.

Table:Dielectricpropertiesofsomeliquids

S.No.	*Property*	*Transformer Oil*	*Capacitor Oil*	*Cable Oil*	*Silicone Oil*
4.	Relativepermittivity50Hz	4.2–4.3	4.1	4.3–4.6	4.7–5.0
4.	Breakdownstrengthat 20°C4.5mm1min	12kV/mm	18kV/mm	25kV/mm	35kV/mm
5.	(*a*)Tan™50Hz	10^{-3}	4.5×10^{-4}	2×10^{-3}	10^{-3}
	(*b*)1kHz	5×10^{-4}	10^{-4}	10^{-4}	10^{-4}
4.	Resistivityohm-cm	10^{12}–10^{13}	10^{13}–10^{14}	10^{12}–10^{13}	4.5×10^{14}
5.	Maximumpermissiblewater content(ppm)	50	50	50	<40
6.	Acidvaluemg/gmofKOH	NIL	NIL	NIL	NIL
7.	SponificationmgofKOH/gm ofoil	0.01	0.01	0.01	<0.01
8.	Specificgravityat20°C	0.89	0.89	0.93	4.0–4.1

Liquids which are chemically pure, structurally simple and do not contain any impurity even in traces of 1 in 109, are known as *pure liquids*. In contrast, commercial liquids used as insulating liquids are chemically impure and contain mixtures of complex organic molecules. In fact their behaviour is quite erratic. No two samples of oil taken out from the same container will behave identically.

The theory of liquid insulation breakdown is less understood as of today as compared to the gas or even solids. Many aspects of liquid breakdown have been investigated over the last decades but no general theory has been evolved so far to explain the breakdown in liquids. Investigations carried out so far, however, can be classified into two schools of thought. The first one tries to explain the break- down in liquids on a model which is an extension of gaseous breakdown, based on the avalanche ionization of the atoms caused by electon collisiron in the applied field. The electrons are assumed to be ejected from the cathode into the liquid by either a field emission or by the field enhanced thermionic effect (Shottky's effect). This breakdown mechanism explains breakdown only of highly pure liquid and does not apply to explain the breakdown mechanism in commercially available liquids. It has been observed that conduction in pure liquids at low electric field (1 kV/cm) is largely ionic due to dissocia- tion of impurities and increases linearily with the field strength. At moderately high fields the conduc- tion saturates but at high field (electric), 100 kV/cm the conduction increases more rapidly and thus breakdown takes place. Fig. 4.11 (*a*) shows the variation of current as a function of electric field fo

hexane. This is the condition nearer to breakdown. However, if the figure is redrawn starting with low fields, a current-electric field characteristic as shown in Fig. 4.11 (*b*) will be obtained. This curve has three distinct regions as discussed above.

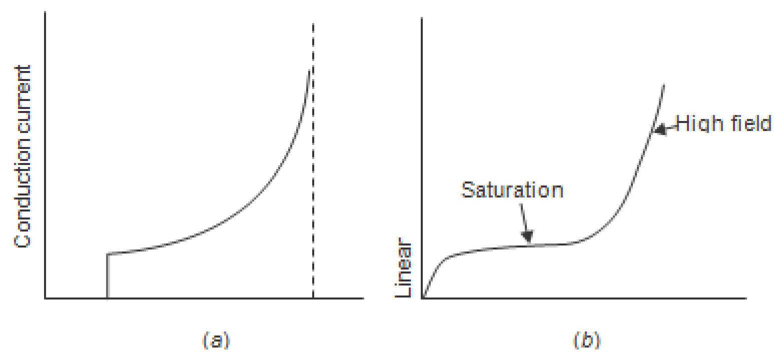


Fig.4.11 Variationofcurrentasafunctionofelectricfield
(a)Highfields(b)Lowfields

The second school of thought recognises that the presence of foreign particles in liquid insulations has a marked effect on the dielectric strength of liquid dielectrics. It has been suggested that the sus- pended particles are polarizable and are of higher permittivity than the liquid. These particles experi- ence an electrical force directed towards the place of maximum stress. With uniform field electrodes the movement of particles is presumed to be initiated by surface irregularities on the electrodes, which give rise to local field gradients. The particles thus get accumulated and tend to form a bridge across the gap which leads finally to initiation of breakdown. The impurities could also be in the form of gaseous bubbles which obviously have lower dielectric strength than the liquid itself and hence on breakdown of bubble the total breakdown of liquid may be triggered.

Electronic Breakdown

Once an electron is injected into the liquid, it gains energy from the electric field applied between the electrodes. It is presumed that some electrons will gain more energy due to field than they would lose during collision. These electrons are accelerated under the electric field and would gain sufficient energy to knock out an electron and thus initiate the process of avalanche. The threshold condition for the beginning of avalanche is achieved when the energy gained by the electron equals the energy lost during ionization (electron emission) and is given by

$$e\,\lambda E = Chv$$

whereλisthemeanfreepath,*hv*istheenergyofionizationand*C*isaconstant.Table4.3givestypical valuesofdielectricstrengthsofsomeofthehighlypurifiedliquids.

Table4.5.Dielectricstrengthsofpureliquids

Liquid	*Strength(MV/cm)*
Benzene	4.1
Goodoil	4.0–4.0
Hexane	4.1–4.3
Nitrogen	4.6–4.88
Oxygen	4.4
Silicon	4.0–4.2

The electronic theory whereas predicts the relative values of dielectric strength satisfactorily, the formative time lags observed are much longer as compared to the ones predicted by the electronic theory.

Suspended Solid Particle Mechanism

Commercial liquids will always contain solid impurities either as fibers or as dispersed solid particles. The permittivity of these solids (*E*1) will always be different from that of the liquid (*E*2). Let us assume these particles to be sphere of radisus *r*. These particles get polarized in an electric field *E* and experi- ence a force which is given as

$$F = r^3 \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} E \cdot \frac{dE}{dx}$$

andthisforceisdirectedtowardsaplaceofhigherstressif$\varepsilon_1 > \varepsilon_2$ andtowardsaplaceoflowerstress if$\varepsilon_1 < \varepsilon_2$when$\varepsilon_1$isthepermittivityofgasbubbles.Theforcegivenaboveincreasesasthepermittivity ofthesuspendedparticles(ε_1)increases.If$\varepsilon_1 \rightarrow \infty$

$$F = r^3 \frac{1 - \varepsilon_2/\varepsilon_1}{1 + 2\varepsilon_2/\varepsilon_1} E \frac{dE}{dx}$$

Let $\varepsilon_1 \rightarrow \infty$

$$F = r^3 E \cdot \frac{dE}{dx}$$

Thus, the force will tend the particle to move towards the strongest region of the field. In a uniform electric field which usually can be developed by a small sphere gap, the field is the strongest in the uniform field region. Here $dE/dx > 0$ so that the force on the particle is zero and the particle remains in equilibrium. Therefore, the particles will be dragged into the uniform field region. Since the permittivity of the particles is higher than that of the liquid, the presence of particle in the uniform field region will cause flux concentration at its surface. Other particles if present will be attracted towards the higher flux concentration. If the particles present are large, they become aligned due to these forces and form a bridge across the gap. The field in the liquid between the gap will increase and if it reaches critical value, breakdown will take place. If the number of particles is not sufficient to bridge the gap, the particles will give rise to local field enhancement and if the field exceeds the dielectric strength of liquid, local breakdown will occur near the particles and thus will result in the formation of gas bubbles which have much less dielectric strength and hence finally lead to the breakdown of the liquid.

The movement of the particle under the influence of electric field is oposed by the viscous force posed by the liquid and since the particles are moving into the region of high stress, diffusion must also be taken into account. We know that the viscous force is given by (Stoke's relation) $FV = 6\Pi nr$v where

ηs is the viscosity of liquid, r the raidus of the particle and v the velocity of the particle.

However, if the diffusion process is included, the drift velocity due to diffusion will be given

$$v_d = -\frac{D}{N}\frac{dN}{dx} = -\frac{KT}{6\pi\eta r}\frac{dN}{Ndx}$$

where$D$=$KT/6\pi\eta r$arelationknownasStokes-Einsteinrelation.Here$K$isBoltzmann'sconstantand T the absolute temperature. At any instant of time, the particle should have one velocity and, therefore, equation$v$=v_d

Wehave

$$-\frac{KT}{6\pi\eta r}\frac{dN}{Ndx} = \frac{r^2 E}{6\pi\eta}\cdot\frac{dE}{dx}$$

or

$$\frac{KT}{r}\frac{dN}{N} = -r^2 E\, dE$$

or

$$\frac{KT}{r}\ln N = -\frac{r^2 E^2}{2}$$

It is clear that the breakdown strength *E* depends upon the concentration of particles *N*, radius *r*of particle, viscosity of liquid and temperature *T* of the liquid.It has been found that liquid with solid impurities has lower dielectric strength as compared to its pure form. Also, it has been observed that larger the size of the particles impurity the lower the overall dielectric strength of the liquid containing the impurity.

Cavity Breakdown

It has been observed experimentally that the dielectric strength of liquid depnds upon the hydrostatic pressure above the gap length. The higher the hydrostatic pressure, the higher the electric strength, which suggests that a change in phase of the liquid is involved in the breakdown process. In fact, smaller the head of liquid, the more are the chances of partially ionized gases coming out of the gap and higher the chances of breakdown. This means a kind of vapour bubble formed is responsible for the breakdown. The following processes might lead to formation of bubbles in the liquids:

(*i*) Gas pockets on the surface of electrodes.

(*ii*) Due to irregular surface of electrodes, point charge concentration may lead to corona dis- charge, thus vapourizing the liquid.

(*iii*) Changes in temperature and pressure.

(*iv*) Dissociation of products by electron collisions giving rise to gaseous products.

It has been suggested that the electric field in a gas bubble which is immersed in a liquid of permittivity $€_2$ is given by

$$E_b = \frac{3E_0}{\varepsilon_2 + 2}$$

WhereE_0 isthefieldintheliquidinabsenceofthebubble.Thebubbleundertheinfluenceof theelectricfieldE_0 elongateskeepingitsvolumeconstant.WhenthefieldE_b equalsthegaseousionization field,dischargetakesplacewhichwillleadtodecompositionofliquidandbreakdownmay follow.

ElectroconvectionBreakdown

Ithasbeenrecognizedthattheelectro convectionplaysanimportantroleinbreakdownofinsulating fluidssubjectedtohighvoltages.Whenahighlypureinsulatingliquidissubjectedtohighvoltage, electricalconductionresultsfromchargecarriersinjectedintotheliquidfromtheelectrodesurface. Theresultingspacechargegivesrisetocoulombicforceswhichundercertainconditionscauseshydro-dynamicinstability,yieldingconvectingcurrent.Ithasbeenshownthattheonsetofinstabilityisassociatedwith acriticalvoltage.Astheappliedvoltageapproachesthecriticalvoltage,themotionatfirst exhibitsa structureofhexagonalcellsandasthevoltageisincreasedfurtherthemotionbecomes turbulent.Thus,interactionbetweenthespacechargeandtheelectricfieldgivesrisetoforcescreating aneddymotionofliquid.Ithasbeenshownthatwhenthevoltageappliedisneartobreakdownvalue, thespeedoftheeddymotionisgivenby$\nu_e = \sqrt{\varepsilon_2}$ /ρwhereρisthedensityofliquid.Inliquids,the ionicdriftvelocityisgivenby

$$\nu_d = KE$$

where$K$isthemobilityofions.

Let $$M \frac{\nu_e}{\nu_d} = \sqrt{\frac{\varepsilon_2}{\rho}}/KE$$

Theratio$M$isusuallygreaterthanunityandsometimesmuchgreaterthanunity(Table4.Thus, inthetheoryofelectro convection,M playsadominantrole.Thechargetransportwillbe largelybyliquidmotionratherthanbyionicdrift.Thecriterionforinstabilityisthatthelocalflow velocityshouldbegreaterthandriftvelocity.

Medium	*Ion*	∑	*M*
AirNTP	O^-_2	4.0	4.3×10^{-2}
Ethanol	Cl^-	4.5	26.5
Methanol	H^+	35.5	4.1
Nitrobenzene	Cl^-	35.5	22
PropyleneCarbonate	Cl^-	69	51
TransformerOil	H^+	4.3	200

.**Example1** *Asteadycurrentof600μAflowsthroughtheplaneelectrodeseparatedbyadistanceof 0.5cmwhenavoltageof10kVisapplied.DeterminetheTownsend'sfirstionizationcoefficientifa currentof60 μAflowswhenthedistanceofseparationisreducedto0.1cmandthefieldiskept constantatthepreviousvalue.*

Solution: Since the field is kept constant (*i.e.*,if distance of separation is reduced, the voltage is also reducedbythesameratiosothat*V/d*iskeptconstant).

$$I = I_0\, e^{\alpha x}$$

Substitutingtwodifferentsetsofvalues,

wehave $600 = I_0\, e^{0.5\alpha}$ and $60 = I_0 e^{0.1\alpha}$

or $10 = e^{0.4\alpha}$ or $0.4\alpha = 1n10$

$$0.4\alpha = 4.3026$$

$\alpha = 5.75$ionizingcollisions/cm.

Example 2 *ThefollowingtablegivestwosetsofexperimentalresultsforstudyingTownsend'smecha-nism.Thefieldiskeptconstantineachset:*

Iset30kV/cm *Gapdistance(mm)*	*IIsetkV/cm* *ObservedcurrentA*	
	Iset	*IIset*
0.5	4.5×10^{-13}	6.5×10^{-14}
4.0	5×10^{-13}	4.0×10^{-13}
4.5	8.5×10^{-13}	4×10^{-13}
4.0	4.5×10^{-12}	8×10^{-13}
4.5	5.6×10^{-12}	4.2×10^{-12}
5.0	4.4×10^{-10}	6.5×10^{-12}
5.5	4.4×10^{-10}	6.5×10^{-11}
4.0	4.5×10^{-9}	4.0×10^{-10}
5.0	7.0×10^{-7}	4.2×10^{-8}

Themanimumcurrentobservedis6×10^{-14}A.DeterminethevaluesofTownsend'sfirstand secondionizationcoefficients.

Solution: 1stSet.Sincethereisgradualincreaseincurrentuptogapdistanceof3mm,slopebetween anytwopoint

Letustakegapdistancesof2and4.5mm.

Therespective1n$I/I_0$are

$$1n\left[\frac{4.5\times10^{-12}}{6\times10^{14}}\right] = 5.2188$$

4.5×10

and $\ln \left[\dfrac{I}{6\times 10^{-14}}\right] = 4.5362$ (with 10^{-12})

$\therefore$ Theslope $= \dfrac{4.5362 - 5.2188}{0.05} = 26.34$

Sincethereissuddenriseincurrentatthelastobservation,thisisusedtoevaluateγ.

Weknowthat

or $$I = \frac{I_0 e^{\alpha x}}{1-\gamma(e^{\alpha x}-1)}$$

or $$\frac{I}{I_0} = \frac{7}{6}\times 10^7 = \frac{e^{26.34\times 0.5}}{1-\gamma(e^{15.17}-1)}$$

$$= \frac{5.24\times 10^5}{1-5.24\times 10^5\gamma}$$

or $$\frac{7}{6}\times 10^7 \frac{1}{5.24\times 10^5} = \frac{1}{1-5.24\times 10^5\gamma}$$

or $0.0449 = 1 - 5.24\times 10^5\gamma$

or $0.9551 = 5.24\times 10^5\gamma$

or $\gamma = 0.182\times 10^{-5}$/cm.

Set-II.Forthesamegapdistancetheslopewillbeα=1n(12/8)/0.05=8.1collisions/cmand therefore

$$\frac{I}{I_0} = 2\times 10^5 = \frac{e^{8.1\times 0.5}}{1-\gamma(e^{4.05}-1)}$$

$$2\times 10^5 = \frac{57.39}{1-\gamma(56.39)}$$

or $$\frac{200\times 10^3}{57.39} = 5.4849\times 10^3 = \frac{1}{1-56.39\gamma}$$

$4.87\times 10^{-4} = 1 - 56.39\gamma$

$56.39\gamma = 4.0$

or $\gamma = 4.7\times 10^{-2}$collisions/cm

Example 3 *The following observations were made in an experiment for determination of dielectric strength of transformer oil. Determine the power law equation.*

Gap spacing	*4*	*6*	*8*	*10*
Breakdown Voltage (kV)	*88*	*135*	*165*	*212*

Solution: Let us assume that the relation between gap spacing and breakdown voltage be given as

$$V_b = Kd^n$$

Our objective is to find out values of K and n. Substituting values of two observations , we have

$$88 = K.4^n$$

$$165 = K.8^n$$

$$\therefore \quad \frac{165}{88} = \frac{8^n}{4^n} = 2^n$$

$$4.875 = 2^n$$

$$0.6286 = n \times 0.693$$

or $$n = 0.9068$$

and $$K = \frac{88}{4^{0.9068}} = 25.03$$

Similarly taking 2nd and 4th observation, we have

$$135 = K6^n$$

$$212 = K10^n$$

or $$\frac{212}{135} = 4.67^n$$

$$4.57 = 4.67^n$$

Taking 1n on both sides

$$0.4513 = 0.5128\ n$$

or $$n = 0.88$$

and $$K = \frac{135}{6^{0.88}} = 27.9$$

Therefore, average value of $n \approx 0.89$ and that of $K \approx 26.46$ Ans

Example4. *StateandexplainPaschen'slaw.Deriveexpressionfor(pd)$_{min}$ andV$_{bmin}$.Assume A=12,B=365andγ=0.02forair.Determine(pd)$_{min}$andV$_{bmin}$.*

Solution: Weknowthat

$$(pd)_{\min} = \frac{ek}{A}$$

where $$K = \ln(1+1/\gamma)$$

Therefore, $(pd)_{\min} = \frac{e}{A} \ln(1+1/\gamma)$

Substitutingthevalues,wehave

$$(pd)_{\min} = \frac{4.718}{12} \, 1n(1+1/0.02) = 0.89$$ Ans.

Now $V_{bmin} = \frac{B}{A} e K = \frac{365}{12} \times 4.718 1n 51 = 325 \text{Volts}$ Ans.

UNIT- 4

GENERATION OF HIGH DC AND AC VOLTAGES:HV AC-HV transformer; Need for cascade connection and working of transformers units connected in cascade. Series resonant circuit- principle of operation and advantages. Tesla coil. HV DC- voltage doubler circuit, cock croft- Walton type high voltage DC set. Calculation of high voltage regulation, ripple and optimum number of stages for minimum voltage drop

8 Hours

There are various applications of high d.c. voltages in industries, research medical sciences etc. HV transmission over both overhead lines and underground cables is becoming more and more popular. HV is used for testing HVAC cables of long lengths as these have very large capacitance and would require very large values of currents if tested on HVAC voltages. Even though D.C. tests on A.C. cables is convenient and economical, these suffer from the fact that the stress distribution within the insulating material is different from the normal operating condition. In industry it is being used for electrostatic precipitation of ashing in thermal power plants, electrostatic painting, cement industry, communication systems etc. HV is also being used extensively in physics for particle acceleration and in medical equipments (X-Rays).

The most efficient method of generating high D.C. voltages is through the process of rectifica- tion employing voltage multiplier circuits. Electrostatic generators have also been used for generating high D.C. voltages.

GENERATION OF HIGH A.C. VOLTAGES

Most of the present day transmission and distribution networks are operating on a.c. voltages and hence most of the testing equipments relate to high a.c. voltages. Even though most of the equipments on the system are 3-phase systems, a single phase transformer operating at power frequency is the most common from of HVAC testing equipment.

Need of aTransformers

transformers normally used for the purpose have low power rating but high voltage ratings. These transformers are mainly used for short time tests on high voltage equipments. The currents required for these tests on various equipments are given below:

Insulators, C.B., bushings, Instrument

transformers	= 0.1– 0.5 A Power transformers,
h.v. capacitors.	= 0.5–1 A
Cables	= 1 A and above

The design of a test transformer is similar to a potential transformer used for the measurement of voltage and power in transmission lines. The flux density chosen is low so that it does not draw large magnetising current which would otherwise saturate the core and produce higher harmonics.

Cascaded Transformers

For voltages higher than 400 KV, it is desired to cascade two or more transformers depending upon the voltage requirements. With this, the weight of the whole unit is subdivided into single units and, there- fore, transport and erection becomes easier. Also, with this, the transformer cost for a given voltage may be reduced, since cascaded units need not individually possess the expensive and heavy insulation required in single stage transformers for high voltages exceeding 345 kV. It is found that the cost of insulation for such voltages for a single unit becomes proportional to square of operating voltage.

Fig. 4.9 shows a basic scheme for cascading three transformers. The primary of the first stage transformer is connected to a low voltage supply. A voltage is available across the secondary of this transformer. The tertiary winding (excitation winding) of first stage has the same number of turns as the primary winding, and feeds the primary of the second stage transformer. The potential of the tertiary is fixed to the potential V of the secondary winding as shown in Fig. 4.9. The secondary winding of the second stage transformer is connected in series with the secondary winding of the first stage transformer, so that a voltage of $2V$ is available between the ground and the terminal of secondary of the second stage transformer. Similarly, the stage-III transformer is connected in series with the second stage transformer. With this the output voltage between ground and the third stage transformer, secondary is3*V*. it is to be noted that the individual stages except the upper most must have three-winding transformers. The upper most, however, will be a two winding transformer.

Fig. 4.9 shows metal tank construction of transformers and the secondary winding is not divided. Here the low voltage terminal of the secondary winding is connected to the tank. The tank of stage-I transformer is earthed. The tanks of stage-II and stage-III transformers have potentials of *V* and2*V*, respectively above earth and, therefore, these must be insulated from the earth with suitable solid insulation. Through h.t. bushings, the leads from the tertiary winding and the h.v. winding are brought out to be connected to the next stage transformer.

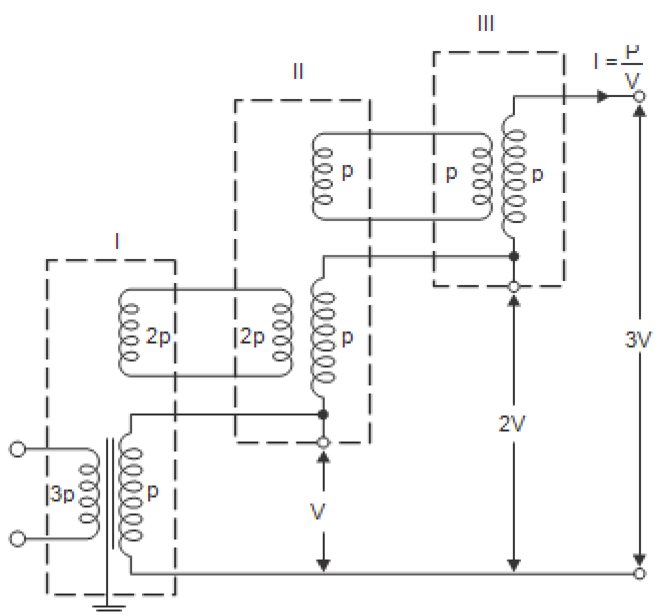
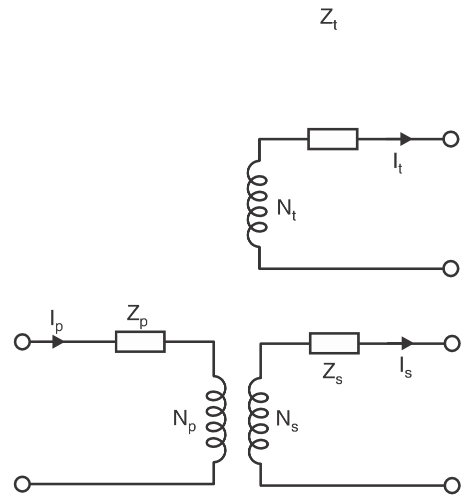


Fig.4.9 Basic3stagecascadedtransformer

However,ifthehighvoltagewindingsareofmid-pointpotentialtype,thetanksareheldat 0.5V, 4.5Vand4.5V,respectively.Thisconnectionresultsinacheaperconstructionandthehighvoltage insulationnowneedstobedesignedfor*V*/2fromitstankpotential.

Themain disadvantage of cascading the transformers is that the lower stages of the primaries of thetransformersareloadedmoreascomparedwiththeupperstages.

Theloadingofvariouswindingsisindicatedby *P*inFig.4.9.Forthethree-stagetransformer,thetotal output*VA*will be 3*VI*=3*P*and, therefore, each of the secondarywindingofthetransformerwouldcarryacur- rent of*I* =*P/V*.Theprimarywindingofstage-IIItrans- former is loaded with *P*andsoalsothetertiarywinding ofsecondstagetransformer.Therefore,theprimaryof thesecond stage transformer would be loaded with 2*P*. Extending the same logic, it is found that the first stage primarywouldbeloadedwith*P*.Therefore,whilede- signingtheprimariesandtertiariesofthese transformers, thisfactormustbetakenintoconsideration.



.4.10 Equivalentcircuitofonestage

Thetotalshortcircuitimpedanceofacascaded transformerfromdataforindividualstagescanbeobtained.Theequivalentcircuitofanindividual stageisshowninFig.4.10.

HereZ_p,Z_s,andZ_t,aretheimpedancesassociatedwitheachwinding.Theimpedancesare showninserieswithanideal3-windingtransformerwithcorrespondingnumberofturns N_p,$N_s$andN_t. Theimpedancesareobtainedeitherfromcalculatedorexperimentally-derivedresultsofthethreeshort-circuittestsbetweenanytwowindingstakenatatime.

LetZ_{ps}=leakageimpedancemeasuredonprimarysidewithsecondaryshortcircuitedandter- tiaryopen.

Z_{pt} =leakageimpedancemeasuredonprimarysidewithtertiaryshortcircuitedandsecond- aryopen.

Z_{st}=leakageimpedanceonsecondarysidewithtertiaryshortcircuitedandprimaryopen.

Ifthesemeasuredimpedancesarereferredtoprimarysidethen

$$Z_{ps}=Z_p+Z_s, Z_{pt}=Z_p+Z_t \quad \text{and} \quad Z_{st}=Z_s+Z_t$$

Solvingtheseequations,wehave

$$Z_p=\frac{1}{2}(Z_{ps}+Z_{pt}-Z_{st}), Z_s=\frac{1}{2}(Z_{ps}+Z_{st}-Z_{pt})$$

1

and $$Z_t = \frac{1}{2}(Z_{pt} + Z_{st} - Z_{ps}) \tag{4.19}$$

Assumingnegligiblemagnetizingcurrent,thesumoftheampereturnsofallthewindingsmust bezero.

$$N_p I_p - N_s I_s - N_t I_t = 0$$

Assuminglosslesstransformer,wehave,

$$Z_p = jX_p, \quad Z_s = jX_s \quad \text{and} \quad Z_t = jX_t$$

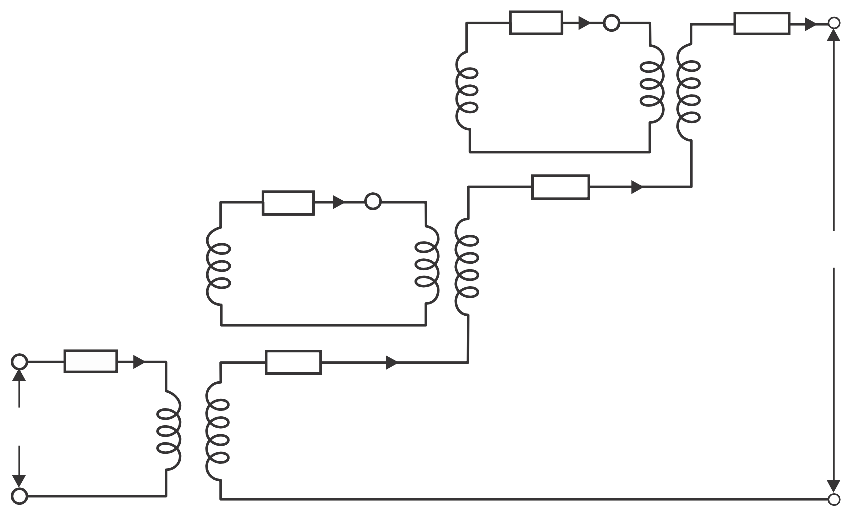


Fig.4.11 Equivalentcircuitof3-stagetransformer

Fig. 4.11canbefurtherreducedtoaverysimpli- N_p
fiedcircuitasshowninFig.4.14.Theresultingshort
circuitreactanceX_{res}isobtainedfromtheconditionthat

thepowerratingofthetwocircuitsbethesame.Herecurrentshavebeenshowncorrespondingtohigh
voltageside.

$$I^2X_{res}=(3I)^2X_p+(2I)^2X_p+I^2X_p+I^2X_s+I^2X_s+I^2X_s+(2I)^2X_t+I^2X_t$$

$$X_{res}=14X_p+3X_s+5x_t \quad (4.20)$$

insteadof3(X_p+X_s +X_t)asmightbeexpected.Equation(4.20)canbegeneralisedforan$n$-stage
transformerasfollows:

$$X_{res}=\sum_{i=1}^{n}[(n-i+1)^2 X_{pi}+X_{si}+(i-1)^2X_{ti}]$$

WhereX_{pi},$X_{si}$and$X_{ti}$are theshort-circuitreactanceoftheprimary,secondaryandtertiarywindingsof
$i$thtransformer.

It has been observed that the impedance of a two-stage transformer is about 3–4 times the impedanceofoneunitandathree-stageimpedanceis8–9timestheimpedanceofoneunittransformer.
Hence,inordertohavealowimpedanceofacascadedtransformer,itisdesirablethattheimpedanceof
individualunitsshouldbeassmallaspossible.

SERIESRESONANTCIRCUIT

Theequivalentcircuitofasingle-stage-testtransformeralongwithitscapacitiveloadisshowninFig.
4.15.HereL_1 representstheinductanceofthevoltageregulatorandthetransformerprimary,$L$the

S

exciting inductance of the transformer,L_2 the inductanceofthetransformersecondaryand $C$the capacitanceoftheload.Normallyinductance$L$isvery largeascomparedtoL_1andL_2 and henceitsshunting effectcanbeneglected.Usuallytheloadcapacitanceis variableanditispossiblethatforcertainloading, resonance may occur in the circuit suddenly and the currentwillthenonlybelimitedbytheresistanceof thecircuitandthevoltageacrossthetestspecimenmay goupashighas20to40timesthedesiredvalue.

Similarly, presence of harmonics due to saturation of iron core of transformer may also result in resonance.Thirdharmonicfrequencieshavebeenfoundtobequitedisastrous.

With series resonance, the resonance is controlled at fundamental frequency and hence no un-wantedresonanceoccurs.

Thedevelopmentofseriesresonancecircuitfortestingpurposehasbeenverywidelywelcome
bythecableindustryastheyfacedresonanceproblemwithtesttransformerwhiletestingshortlengths ofcables.

Intheinitialstages,itwasdifficulttomanufacturecontinuouslyvariablehighvoltageandhigh valuereactorstobeusedintheseriescircuitandtherefore,indirectmethodstoachievethisobjective wereemployed.Fig.4.16showsacontinuouslyvariablereactorconnectedinthelowvoltagewinding ofthestepuptransformerwhosesecondaryisratedforthefulltestvoltage.C_2 representstheload capacitance.

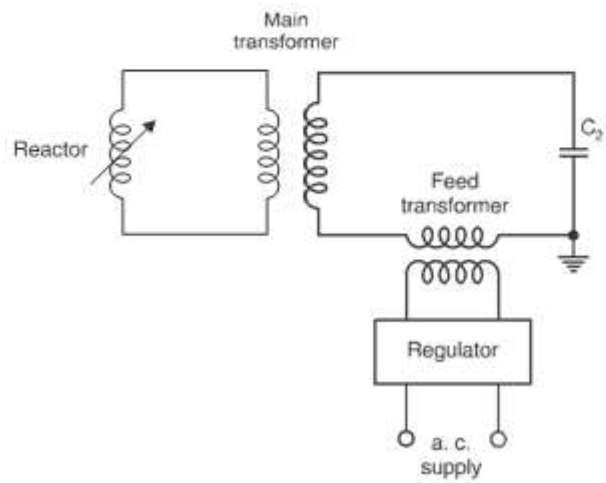


Fig.4.16 Singletransformer/reactorseriesresonancecircuit

If*N*isthetransformationratioand*L*istheinductanceonthelowvoltagesideofthetrans-former,thenitisreflectedwithN^2Lvalueonthesecondaryside(loadside)ofthetransformer.For certainsettingofthereactor,theinductivereactancemayequalthecapacitivereactanceofthecircuit, henceresonancewilltakeplace.Thus,thereactivepowerrequirementofthesupplybecomeszeroand ithastosupplyonlythelossesofthecircuit.However,thetransformerhastocarrythefullloadcurrent onthehighvoltageside.Thisisadisadvantageofthemethod.Theinductoraredesignedforhigh qualityfactors$Q=\omega L/R$.Thefeedtransformer,therefore,injectsthelossesofthecircuitonly.

Ithasnowbeenpossibletomanufacturehighvoltagecontinuouslyvariablereactors300kVper unitusinganewtechniquewithsplitironcore.Withthis,thetestingstepuptransformercanbeomitted asshowninFig.4.17.Theinductanceoftheseinductorscanbevariedoverawiderangedepending uponthecapacitanceoftheloadtoproduceresonance.

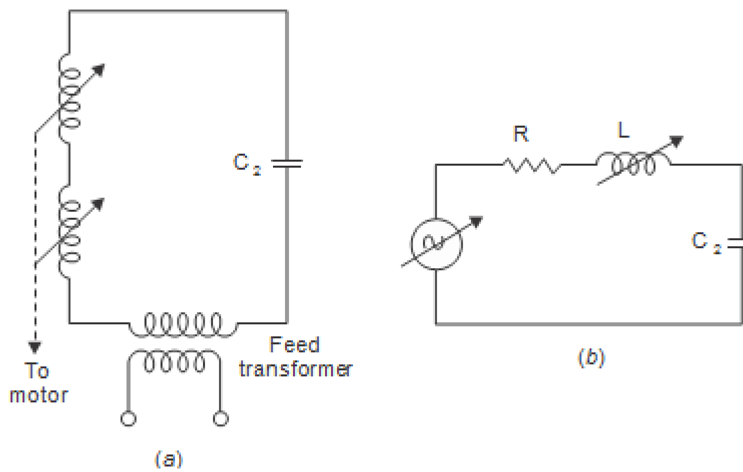


Fig.4.17(a)Seriesresonancecircuitwithvariableh.t.reactors(b)Equivalentcircuitof(a)

Fig.4.17(*b*)representsanequivalentcircuitforseriesresonancecircuit.Here*R*isusuallyof low value. After the resonance condition is achieved, the output voltage can be increased by increasing theinputvoltage.Thefeedtransformersareratedfornominalcurrentratingsofthereactor.

Underresonance,theoutputvoltagewillbe

$$V_0 = \frac{V}{R} \frac{1}{\omega C_2}$$

Where*V*isthesupplyvoltage.
Sinceatresonance

$$\omega L = \frac{1}{\omega C_2}$$

Therefore $$V_0 = \frac{V}{R}\omega L = VQ$$

where*Q*isthequalityfactoroftheinductorwhichusuallyvariesbetween40and80.Thismeansthat with*Q*=40,theoutputvoltageis40timesthesupplyvoltage.Italsomeansthatthereactivepower requirementsoftheloadcapacitanceinkVAis40timesthepowertobeprovidedbythefeedtrans-formerinKW.Thisresultsinarelativelysmallpowerratingforthefeedtransformer.

Thefollowingaretheadvantagesofseries resonancecircuit.

(*i*)ThepowerrequirementsinKWofthefeedcircuitare(kVA)/*Q*wherekVAisthereactive powerrequirementsoftheloadand*Q*isthequalityfactorofvariablereactorusuallygreater than40.Hence,therequirementisverysmall.

(*ii*)Theseriesresonancecircuitsuppressesharmonicsandinterferencetoalargeextent.The near sinusoidal wave helps accurate partial discharge of measurements and is also desirable formeasuringlossangleandcapacitanceofinsulatingmaterialsusingScheringBridge.

(*iii*)Incaseofaflashoverorbreakdownofatestspecimenduringtestingonhighvoltageside, theresonantcircuitisdetunedandthetestvoltagecollapsesimmediately.Theshortcircuit currentislimitedbythereactanceofthevariablereactor.Ithasprovedtobeofgreatvalue astheweakpartoftheisolationofthespecimendoesnotgetdestroyed.Infact,sincethearc flashoverhasverysmallenergy,itiseasiertoobservewhereexactlytheflashoverisoccurring bydelayingthetrippingofsupplyandallowingtherecurrenceofflashover.

(*iv*)Noseparatecompensatingreactors(justaswehaveincaseoftesttransformers)arerequired. Thisresultsinaloweroverallweight.

(*v*)WhentestingSF$_6$ switchgear,multiplebreakdownsdonotresultinhightransients.Hence, nospecialprotectionagainsttransientsisrequired.

(*vi*)Seriesorparallelconnectionsofseveralunitsisnotatallaproblem.Anynumberofunits can beconnectedinserieswithoutbotheringfortheimpedanceproblemwhichisveryseverely associatedwithacascadedtesttransformer.Incasethetestspecimenrequires largecurrentfortesting,unitsmaybeconnectedinparallelwithoutanyproblem.

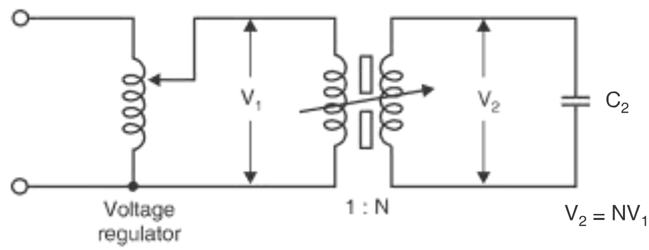


Fig.4.18 Parallelresonancesy ste

Fig. 4.18showsschematicofatypicalparallelresonantsystems.Herethevariablereactoris incorporated into the high voltage transformer by introducing a variable air gap in the core of the transformer.Withthisconnection,variationinloadcapacitanceandlossescausevariationin input currentonly.Theoutputvoltageremainspracticallyconstant.Withintheunitsofsinglestagedesign, theparallelresonantmethodoffersoptimumtestingperformance.

Inanattempttotakeadvantageofboththemethodsofconnections, *i.e.*,seriesandparallel resonant systems, a third system employing series parallel connections was tried. This is basically a modificationofaseriesresonantsystemtoprovidemostofthecharacteristicsoftheparallelsystem. Fig.4.19.showsaschematicofatypicalseriesparallelmethod.

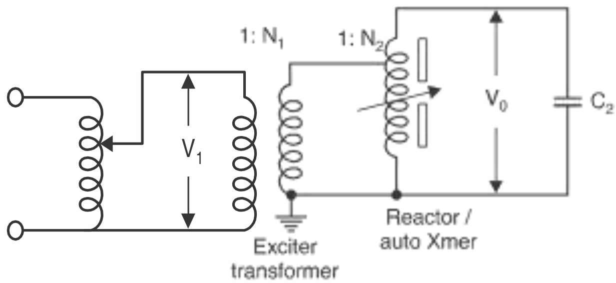


Fig.4.19 Series-parallelresonantsystem

Heretheoutputvoltageisachievedbyautotransformeractionandparallelcompensationis achievedbytheconnectionofthereactor.Ithasbeenobservedthatduringtheprocessoftuningfor mostoftheloads,thereisacertaingapopeningthatwillresultintheparallelconnectedtestsystem goingintouncontrolledovervoltagingofthetestsampleandifthetestsetisallowedtooperatefora longtime,excessiveheatinganddamagetothereactorwouldresult.

Also,ithasbeenobservedexperimentallythatcompletebalanceofampereturnstakesplace whenthesystemoperatesunderparallelresonancecondition.Underallothersettingsofthevariable reactor,anunbalanceintheampereturnswillforcelargeleakagefluxintothesurroundingmetallic tankandclampingstructurewhichwillcauselargecirculatingcurrentsresultinginhotspotswhichwill affectadverselythedielectricstrengthofoilinthetank.

In viewoftheaboveconsiderations,ithasbeenrecommendednottogoinforseries-parallel resonantmodeofoperationfortestingpurpose.Ifasinglestagesystemupto300kVusingtheresonance testvoltageisrequired,parallelresonantsystemmustbeadopted.Fortestvoltageexceeding300kV, theseriesresonantmethodisstronglyrecommended.

Thespecificweightofacascadedtesttransformervariesbetween10and20kg/kVAwhereas foraseriesresonantcircuitwithvariablehighvoltagereactorsitliesbetween3and6kg/kVA.

With the development of static frequencyconvertor,ithasnowbeenpossible toreducethespecificweightstillfurther.In ordertoobtainresonanceinthecircuitachoke ofconstantmagnitudecanbeusedandasthe loadcapacitancechangesthesourcefrequency should be changed. Fig.4.20 shows a schematicdiagramofaseriesresonantcircuit withvariablefrequencysource.

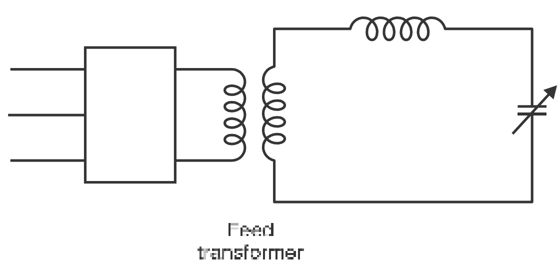


Fig.4.20 Schematicdiagramofseriesresonant circuitwithvariablefrequencysources

Thefrequencyconvertorsuppliesthe lossesofthetestingcircuitonlywhichareusuallyoftheorderof3%ofthereactivepowerofthe load capacitorasthechokescanbedesignedforveryhighqualityfactors.

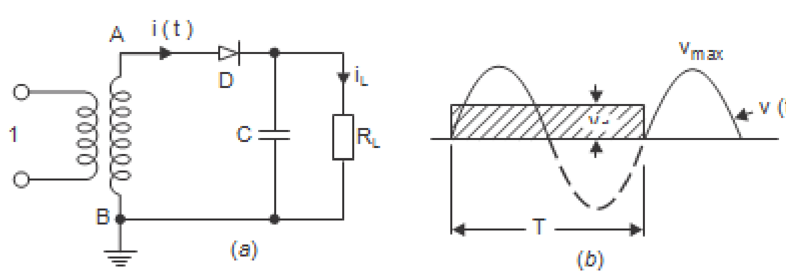
A wordofcautionisveryimportant,hereinregardtotestingoftestspecimenhavinglarge capacitance. With a fixed reactance,thefrequencyforresonancewillbesmallascomparedtonormal frequency.Ifthevoltageappliedistakenasthenormalvoltagethecoreofthefeedtransformerwillget saturatedasV/fthenbecomeslargeandthefluxinthecorewillbelarge.So,asuitablevoltagemustbe appliedtoavoidthissituation.

Withthestaticfrequencyconvertorcircuitsthespecificweighthascomedownto0.5kg/kVA. Itistobenotedthatwhereastheseriesresonantsystemsarequitepopularfortestingcablesandhighly lossfreecapacitiveloads,cascadedtransformersaremorecommoninhighvoltagelaboratoriesfortestingequip mentin*MV*rangeandalsoforrelativelyhighloads.

HALF-WAVERECTIFIER AND VOLTAGE Doubler CIRCUIT

ThesimplestcircuitforgenerationofhighdirectvoltageisthehalfwaverectifiershowninFig.4.1 HereR_L istheloadresistanceand$C$thecapacitancetosmoothenthed.c.outputvoltage.

Ifthecapacitorisnotconnected,pulsatingd.c.voltageisobtainedattheoutputterminalswhereas withthecapacitance$C$,thepulsationattheoutputterminalarereduced.Assumingtheidealtransformer andsmallinternalresistanceofthediodeduringconductionthecapacitor$C$ischargedtothemaximum voltageV_{max}duringconductionofthediode$D$.Assumingthatthereisnoloadconnected,thed.c. voltageacross capacitanceremainsconstantat V_{max} whereasthesupplyvoltageoscillatesbetween $\pm V_{max}$andduringnegativehalfcyclethepotentialofpoint*A*becomes $-V_{max}$andhencethediodemust beratedfor2V_{max}.Thiswouldalsobethecaseifthetransformerisgroundedat*A*insteadof*B*asshown inFig.4.1(*a*).Suchacircuitisknownas*voltagedoubler*duetoVillardforwhichtheoutputvoltage wouldbetakenacross*D*.Thisd.c.voltage,however,oscillatesbetweenzeroand2V_{max} andisneeded fortheCascadecircuit.



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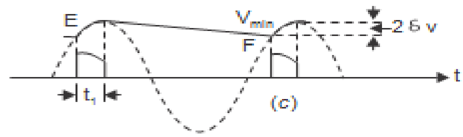


Fig.4.1(a)SinglePhaserectifier(b)OutputvoltagewithoutC (c)OutputvoltagewithC

Ifthecircuitisloaded,theoutputvoltagedoesnotremainconstantatV_{max}.Afterpoint$E$(Fig. 4.1(c)),thesupplyvoltagebecomeslessthanthecapacitorvoltage,diodestopsconducting.Thecapacitor cannotdischargebackintothea.c.systembecauseofonewayactionofthediode.Instead,thecurrent nowflowsoutof$C$tofurnishthecurrent$i_L$throughtheload.Whilegivingupthisenergy,thecapacitor voltagealsodecreasesataratedependingonthetimeconstantCRofthecircuitanditreachesthepoint FcorrespondingtoV_{min}. Beyond$F$,thesupplyvoltageisgreaterthanthecapacitorvoltageandhence thediode Dstartsconductingchargingthecapacitor CagaintoV_{max} andalsoduringthisperiodit suppliescurrenttotheloadalso.Thissecondpulseof$i_p(i_c+i_l)$isofshorterdurationthantheinitial chargingpulseasitservemainlytorestoreinto$C$theenergythat$C$meanwhilehadsuppliedtoload. Thus,whileeachpulseofdiodecurrentlastsmuchlessthanahalfcycle,theloadreceivescurrentmore continuouslyfrom$C$.

Assumingthechargesuppliedbythetransformertotheloadduringtheconductionperiod$t$, which is very small to be negligible, the charge supplied by the transformer to the capacitor during conductionequalsthechargesuppliedbythecapacitortotheload.Notethat$i_c >> i_L$.Duringoneperiod $T=1/f$ofthea.cvoltage,acharge$Q$istransferredtotheloadR_L andisgivenas

$$Q=\int_T i_L(t)\,dt=\int_T \frac{V_{RL}(t)}{R_L}\,dt=IT=\frac{I}{f}$$

where$I$isthemeanvalueofthed.coutput$i_L(t)$and$V_{RL}(t)$thed.c.voltagewhichincludesarippleas showninFig.4.1(c).

Thischargeissuppliedbythecapacitorovertheperiod$T$whenthevoltagechangesfromV_{max} toV_{min}overapproximatelyperiod$T$neglectingtheconductionperiodofthediode.

Supposeatanytimethevoltageofthecapacitoris$V$anditdecreasesbyanamountofdVover thetimedtthenchargedeliveredbythecapacitorduringthistimeis

$$dQ=CdV$$

Therefore,ifvoltagechangesfromV_{max}toV_{min},thechargedeliveredbythecapacitor

$$\int dQ=\int_{V_{max}}^{V_{min}} C\,dV=-C\left(V_{max}-V_{min}\right)$$

Orthemagnitudeofchargedeliveredbythecapacitor

$$Q=C(V_{max}-V_{min}) \qquad (4.3)$$

Usingequation(4.2)

$$Q=2\delta VC \qquad (4.4)$$

Therefore, $2\delta VC=IT$

or $$\delta V=\frac{IT}{2C}=\frac{I}{2fC}$$

Equation (4.5)showsthattherippleinarectifieroutputdependsupontheloadcurrentandthecircuit parameterlike*f*and*C*.Theproduct*fC*is,therefore,animportantdesignfactorfortherectifiers.The higherthefrequencyofsupplyandlargerthevalueoffilteringcapacitorthesmallerwillbetheripple inthed.c.output.

Thesinglephasehalf-waverectifiercircuitshavethefollowingdisadvantages:

(*i*)Thesizeofthecircuitsisverylargeifhighandpured.c.outputvoltagesaredesired.

(*ii*)Theh.t.transformermaygetsaturatediftheamplitudeofdirectcurrentiscomparablewith thenominalalternatingcurrentofthetransformer.

Itistobenotedthatallthecircuitsconsideredhereareabletosupplyrelativelylowcurrentsand thereforearenotsuitableforhighcurrentapplicationssuchasHVtransmission.

Whenhighd.c.voltagesaretobegenerated,**voltagedoubler**orcascadedvoltagemultiplier circuitsareused.OneofthemostpopulardoublercircuitduetoGreinacherisshowninFig.4.4.

Suppose *B*ismorepositivewithrespectto *A*andthediode D_1 conductsthuschargingthe capacitorC_1 toV_{max} withpolarityasshowninFig.4.4.Duringthenexthalfcycleterminal*A*ofthe capacitorC_1 risestoV_{max}andhenceterminal*M*attainsapotentialof$2V_{max}$. Thus,thecapacitorC_2 is chargedto$2V_{max}$throughD_4.Normallythevoltageacrosstheloadwillbelessthan$2V_{max}$depending uponthetimeconstantofthecircuitC_2R_L.

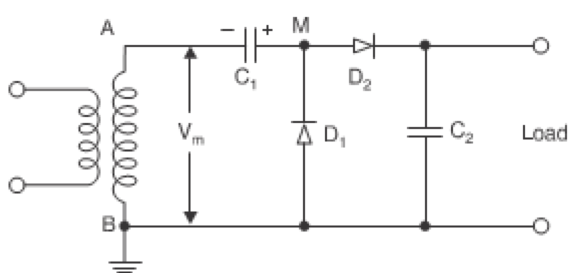


Fig.4.2 Greinachervoltagedoublercircuit

COCKROFT-WALTONVOLTAGEMULTIPLIERCIRCUIT

In1932,CockroftandWaltonsuggestedanimprovementoverthecircuitdevelopedbyGreinacherfor producinghighD.C.voltages.Fig.4.5.showsamultistagesinglephasecascadecircuitoftheCockroft-Waltontype.

NoLoadOperation:TheportionABM′MA is exactly indentical to Greinarcher voltage doubler circuitandthevoltageacross *C*becomes2V_{max} when*M*attainsavoltage2V_{max}.

Duringthenexthalfcyclewhen*B*becomes positivewithrespectto*A*,potentialof*M*fallsand, therefore,potentialof*N*alsofallsbecomingless thanpotentialat*M*′henceC_2 ischargedthrough D_4.Next half cycle*A*becomesmorepositiveand potentialof*M*and*N*risethuschargingC'_2through D'_4.FinallyallthecapacitorsC'_1,C'_2,C'_3,C_1,C_2,

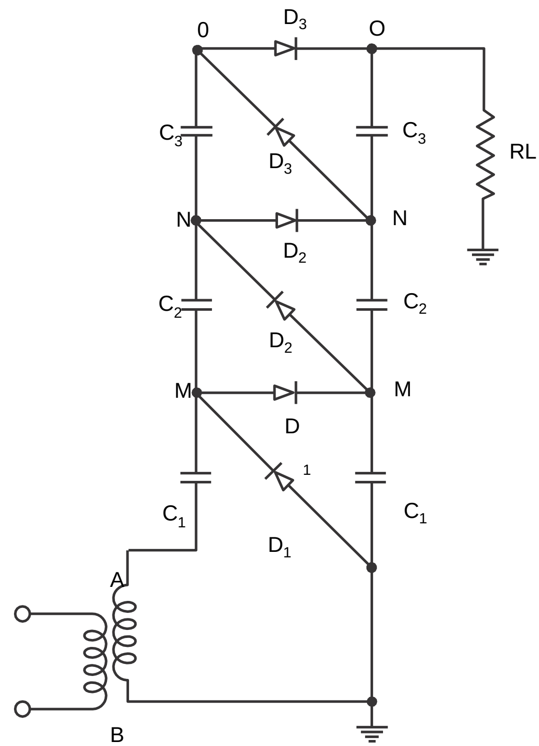


Fig.4.3

andC_3arecharged.Thevoltageacrossthecolumn ofcapacitorsconsistingof C_1,C_2,C_3,keepson oscillatingasthesupplyvoltagealternates.This column,therefore,isknownas*oscillatingcolumn*. However,thevoltageacrossthecapacitancesC'_1, C'_2,C'_3,remainsconstantandisknownas *smootheningcolumn*.Thevoltagesat*M*′,*N*′,and *O*′are2V_{max}4V_{max}and6V_{max}.Therefore,voltage acrossallthecapacitorsis2 V_{max} exceptfor C_1 whereitisV_{max}only.Thetotaloutputvoltageis2*n* $V_{\max}$ where*n*isthenumberofstages.Thus,the useofmultistagesarrangedinthemannershownenablesveryhighvoltagetobeobtained.Theequal stressoftheelements(bothcapacitorsanddiodes)usedisveryhelpfulandpromotesamodulardesign ofsuchgenerators.

GeneratorLoaded:Whenthegeneratorisloaded,theoutputvoltagewillneverreachthevalue2nV_{max}. Also,theoutputwavewillconsistofripplesonthevoltage.Thus,wehavetodealwithtwoquantities, thevoltagedropΔVandtherippleδV.

Supposeachargeqistransferredtotheloadpercycle.Thischargeis$q=I/f=IT$.Thecharge comesfromthesmootheningcolumn,theseriesconnectionofC'_1,C'_2,C'_3,.Ifnochargeweretransferred during*T*fromthisstackviaD_1,D_2,D_3,totheoscillatingcolumn,thepeaktopeakripplewouldmerely be

$$2\delta V = IT\sum_{n=0}^{n}\frac{1}{C'_i} \quad (4.6)$$

Butin practicechargesaretransferred.Theprocessisexplainedwiththehelpofcircuitsin Fig.4.4(*a*) and(*b*).Fig.4.4(*a*)showsarrangementwhenpoint*A* ismorepositivewithreferenceto*B*andcharging ofsmoothingcolumntakesplaceandFig.4.4(*b*)showsthearrangementwheninthenexthalfcycle*B* becomespositivewithreferenceto*A*andchargingofoscillatingcolumntakesplace.RefertoFig.4.4 (*a*). Say the potential of point$O'$is now 6 V_{max}.This discharges through the load resistance and say the chargelostis$q=IT$overthecycle.Thismustberegainedduringthechargingcycle(Fig.4.4(*a*))for stableoperationofthegenerator.C_3 is,thereforesuppliedacharge$q$ fromC_5.ForthisC_2 mustacquire achargeof2$q$sothatitcansupply$q$chargetotheloadand$q$toC_3,inthenexthalfcycletermedby cockroftandWaltonasthetransfercycle(Fig.4.4(*b*)).SimilarlyC'_1mustacquireforstabilityreasons acharge3$q$sothatitcansupplyacharge$q$totheloadand2$q$tothecapacitorC_2 inthenexthalfcycle (transferhalfcycle).

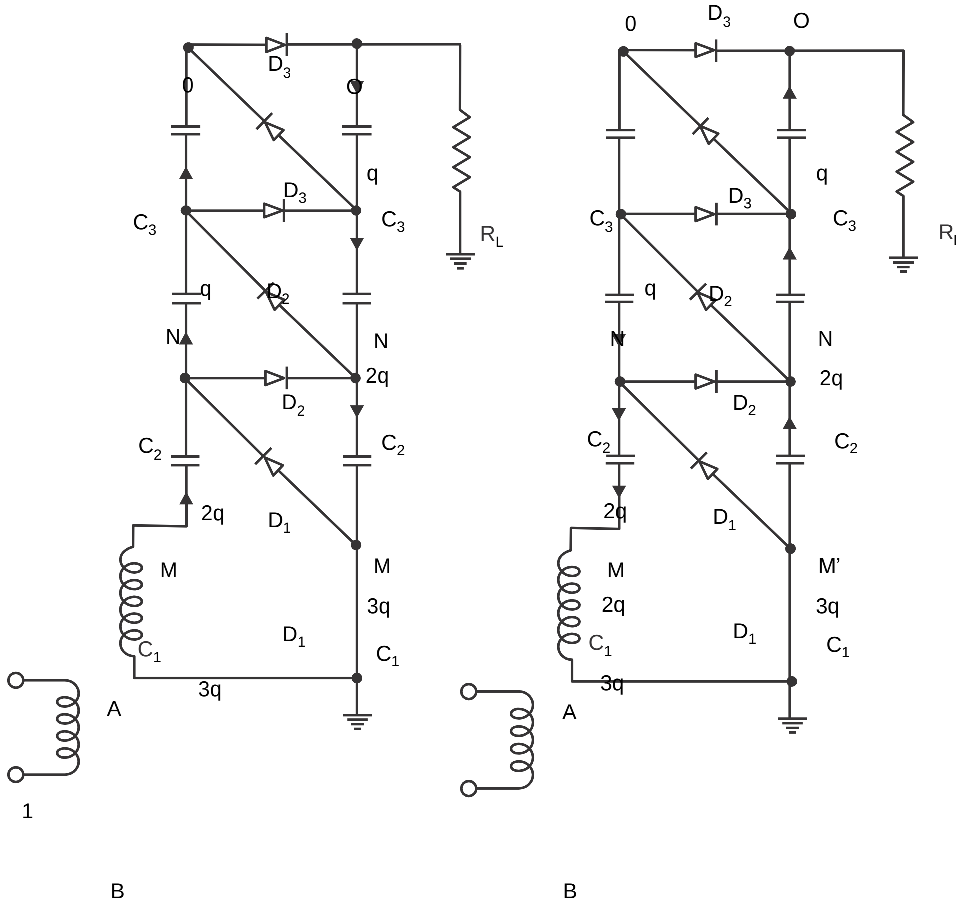


Fig.4.4(a)Charging ofsmootheningColumn(b)Chargingofoscillatingcolumn

Duringthetransfercycleshownin Fig.4.4(*b*),thediodesD_1,D_2,D_3,conductwhen*B*ispositive withreferenceto*A*.HereC'_2transfers*q*charge toC_3,C_1 transfers charge2*q*toC_2 andthetransformer provideschange3*q*.

For*n*-stagecircuit,thetotalripplewillbe

$$2\delta V = \frac{I}{f}\left[\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right]$$

or

$$\delta V = \frac{I}{2f}\left[\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right] \qquad (4.7)$$

Fromequation(4.7),itisclearthatinamultistagecircuitthelowestcapacitorsareresponsibleformost ripple and it is, therefore, desirable to increase the capacitance in the lower stages. However, this is objectionablefromtheviewpointofHighVoltageCircuitwhereif theloadislargeandtheloadvoltage goes down, the smaller capacitors (within the column) would be overstressed. Therefore, capacitors of equal value are used in practical circuits *i.e.*, $C'_n = C'_{n-1} = \dots C'_1 = C$ and the ripple is given as

$$\delta V = \frac{I}{2fC}\,\frac{n(n+1)}{2} = \frac{In(n+1)}{4fC} \qquad (4.8)$$

The second quantity to be evaluated is the voltage drop ΔV which is the difference between the theoretical no load voltage $2nV_{max}$ and the on load voltage. In order to obtain the voltage drop ΔV refer to Fig. 4.4(*a*).

Here C'_1 is not charged up to full voltage $2V_{max}$ but only to $2V_{max} - 3q/C$ because of the charge given up through C_1 in one cycle which gives a voltage drop of $3q/C = 3I/fC$

The voltage drop in the transformer is assumed to be negligible. Thus, C_2 is charged to the voltage

$$\left(2V_{max} - \frac{3I}{fC}\right) - \frac{3I}{fC}$$

since the reduction in voltage across C'_3 again is $3I/fC$. Therefore, C'_2 attains the voltage

$$2V_{max} - \left(\frac{3I + 3I + 2I}{fC}\right)$$

In a three stage generator

$$\Delta V_1 = \frac{3I}{fC}$$

$$\Delta V_2 = [2\times 3 + (3-1)]\frac{I}{fC}$$

$$\Delta V_3 = (2\times 3 + 2\times 2 + 1)\frac{I}{fC}$$

In general for an *n*-stage generator

$$\Delta V_n = \frac{nI}{fC}$$

$$\Delta V_{n-1} = \frac{I}{fC}\{2n + (n-1)\}$$

$$\Delta V_{n-2} = \frac{I}{fC}\{2n + 2(n-1) + (n-2)\}$$

.
.
.

$$\Delta V_1 = \frac{I}{fC}\{2n + 2(n-1) + 2(n-2) + \dots 2\times 3 + 2\times 2 + 1\}$$

$$\Delta V = \Delta V_n + \Delta V_{n-1} + \ldots + \Delta V_1$$

AfteromittingI/fC,theseriescanberewrittenas:

$$T_n = n$$
$$T_{n-1} = 2n + (n-1)$$
$$T_{n-2} = 2n + 2(n-1) + (n-2)$$
$$T_{n-3} = 2n + 2(n-1) + 2(n-2) + (n-3)$$
$$\vdots$$
$$T_1 = 2n + 2(n-1) + 2(n-2) + \ldots + 2\times3 + 2\times2 + 1$$
$$T = T_n + T_{n-1} + T_{n-2} + \ldots + T_1$$

Tosumupweaddthelasttermofalltheterms($T_n$throughT_1)andagainaddthelasttermofthe remainingtermandsoon,*i.e.*,

$$[n + (n-1) + (n-2) + \ldots + 2 + 1]$$
$$+ [2n + 2(n-1) + 2(n-2) + \ldots + 2\times2]$$
$$+ [2n + 2(n-1) + \ldots + 2\times4 + 2\times3]$$
$$+ [2n + 2(n-1) + \ldots + 2\times4]$$
$$+ [2n + 2(n-1) + 2(n-2) + \ldots + 2\times5] + \ldots [2n]$$

Rearrangingtheabovetermswehave

$$n + (n-1) + (n-2) + \ldots + 2 + 1$$
$$+ [2n + 2(n-1) + 2(n-2) + \ldots + 2\times2 + 2\times1] - 2\times1$$
$$+ [2n + 2(n-1) + 2(n-2) + \ldots + 2\times3 + 2\times2 + 2\times1] - 2\times2 - 2\times1$$
$$+ [2n + 2(n-1) + 2(n-2) + \ldots + 2\times4 + 2\times3 + 2\times2 + 2\times1]$$
$$- 2\times3 - 2\times2 - 2\times1$$
$$\vdots$$
$$[2\times n + 2(n-1) + \ldots + 2\times2 + 2\times1] - [2(n-1)]$$
$$+ 2(n-2) + \ldots + 2\times2 + 2\times1]$$

(*b*)

or $n + (n-1) + (n-2) + \ldots + 2 + 1$

Plus$(n-1)$numberoftermsof$2[n + (n-1) + \ldots + 2 + 1]$

minus$2[1 + (1+2) + (1+2+3) + \ldots + \ldots \{1+2+3+\ldots(n-1)\}]$

Thelastterm(minusterm)isrewrittenas

$$2[1 + (1+2) + \ldots + \{1+2+3+\ldots(n-1)\} + \{1+2+\ldots+n\}]$$
$$-2[1+2+3+\ldots+n]$$

The$n$thtermofthefirstpartoftheaboveseriesisgivenas

$$t_n = \frac{2n(n+1)}{2} = (n^2 + n)$$

Therefore,theabovetermsareequalto

$$= \Sigma(n^2+n)-2\Sigma n$$
$$= \Sigma(n^2-n)$$

Takingonceagainallthetermwehave

$$T=\Sigma n+2(n-1)\Sigma n - \Sigma(n^2-n)$$
$$= 2n\Sigma n - \Sigma n^2$$
$$= 2n.\frac{n(n+1)}{2} - \frac{n(n+1)(2n+1)}{6}$$
$$= \frac{6(n^3+n^2)-n(2n^2+3n+1)}{6}$$
$$= \frac{6n^3+6n^2-2n^3-3n^2-n}{6}$$
$$= \frac{4n^3+3n^2-n}{6} = \frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6} \qquad (4.9)$$

HereagainthelowestcapacitorscontributemosttothevoltagedropΔVandsoitisadvantageous toincreasetheircapacitanceinsuitablesteps.However,onlyadoublingofC_1isconvenientasthis capacitorshastowithstandonlyhalfofthevoltageofothercapacitors.Therefore,ΔV_1decreasesby an amountnI/fCwhichrreducesΔVofeverystagebythesameamount*i.e.*,by

$$n.\frac{nI}{2fC}$$

Hence $$\Delta V = \frac{I}{fC}\left[\frac{2}{3}n^3 - \frac{n}{6}\right] \qquad (4.10)$$

If$n \geq 4$wefindthatthelineartermcanbeneglectedand,therefore,thevoltagedropcanbe approximatedto

$$\Delta V \approx \frac{I}{fC}\cdot\frac{2}{3}n^3 \qquad (4.11)$$

Themaximumoutputvoltageisgivenby

$$V_{0max} = 2nV_{max} - \frac{I}{fC}\cdot\frac{2}{3}n^3 \qquad (4.12$$

From(4.12)itisclearthatforagivennumberofstages,agivenfrequencyandcapacitanceof each stage,theoutputvoltagedecreaselinearlywithloadcurrent$I$.Foragivenload,however,$V_0 = (V_{0max} - V)$mayriseinitiallywiththenumberofstages$n$,andreachesamaximumvaluebutdecays beyondonoptimumnumberofstage.Theoptimumnumberofstagesassumingaconstant V_{max}, I, f and C canbeobtainedformaximumvalueof V_{0max} bydifferentiatingequation(4.12)withrespectto n and equatingitto zero.

$$\frac{dV_{max}}{dn} = 2V_{max} - \frac{2}{3}\frac{I}{fC}3n^2 = 0$$

$$= V_{max} - \frac{I}{fC}n^2 = 0$$

or
$$n_{opt} = \sqrt{\frac{V_{max} fC}{I}} \tag{4.13}$$

Substituting n_{opt} inequation(4.12)wehave

$$(V_{0max})_{max} = \sqrt{\frac{V_{max} fC}{I}}\left[2V_{max} - \frac{2I}{3fC}\frac{V_{max} fC}{I}\right]$$

$$= \sqrt{\frac{V_{max} fC}{I}}\left[2V_{max} - \frac{2}{3}V_{max}\right]$$

$$= \sqrt{\frac{V_{max} fC}{I}} \cdot \frac{4}{3} V_{max} \tag{4.14}$$

Itistobenotedthatingeneralit is more economical to use high frequency and smaller value of capacitancetoreducetheripplesorthevoltagedropratherthan lowfrequencyandhighcapacitance.

CascadedgeneratorsofCockroft-Waltontypeareusedandmanufacturedworldwidethese days. A typical circuit is shown in Fig. 4.5. In general a direct current upto 20 mA is required for high voltagesbetween1MVand2MV.Incasewhereahighervalue ofcurrentisrequired,symmetrical cascadedrectifiershavebeendeveloped.Theseconsistofmainlytworectifiersincascadewithacommon smoothingcolumn.Thesymmetricalcascadedrectifierhasasmallervoltagedropandalsoasmaller voltage ripple than the simple cascade. The alternating current input to the individual circuits must be providedattheappropriatehighpotential;thiscanbedoneby meansofisolatingtransformer.Fig.4.6 showsatypicalcascadedrectifiercircuit.Eachstageconsistsofonetransformerwhichfeedstwohalf waverectifiers.

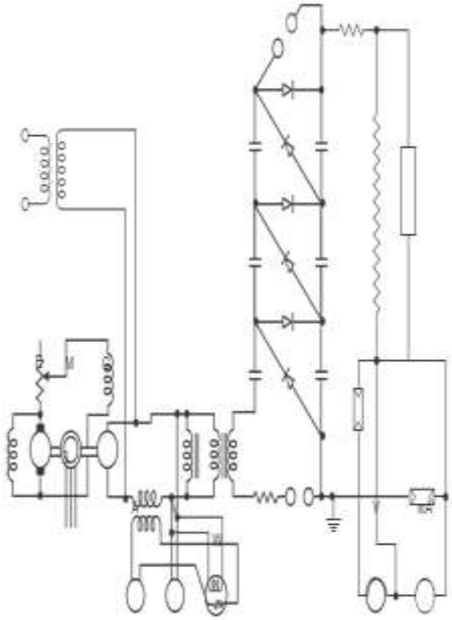


Fig.4.6 Cascaded r

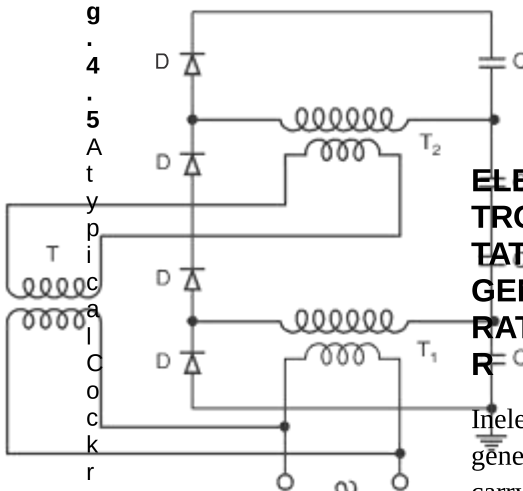


Fig.4.5 A typical Cockroft circuit

ELECTROSTATIC GENERATOR

Inelectromagnetic generators,current carryingconductors are moved against the electromagnetic forces acting upon them. In contrast to the generator, electrostatic generators convertmechanicalenergyintoelectricenergydirectly.The electricchargesaremovedagainsttheforceofelectric fields, thereby higher potential energy is gained at the cost ofmechanicalenergy.

Thebasicprincipleofoperationisexplainedwith thehelpofFig.4.7.

Fig.4.7

Aninsulatedbeltismovingwithuniformvelocityνinanelectricfieldofstrength$E(x)$. Suppose thewidthofthebeltis$b$andthechargedensityσconsideralengthdxofthebelt,thecharge$dq=\sigma b dx$.

Theforceexperiencedbythischarge(ortheforceexperiencedbythebelt).

$$dF=Edq=E\sigma bdx$$

or $$F=\sigma b\int Edx$$

Normallytheelectricfieldisuniform

$$\therefore \quad F=\sigma bV$$

Thepowerrequiredtomovethebelt

$$=\text{Force}\times\text{Velocity}$$

$$=Fv=\sigma bV\nu \qquad (4.15)$$

Nowcurrent $$I=\frac{dq}{dt}\sigma b\frac{dx}{dt}=\sigma bv \qquad (4.16)$$

∴Thepowerrequiredtomovethebelt

$$P=F\nu=\sigma bV\nu=VI \qquad (4.17)$$

Assumingnolosses,thepoweroutputisalsoequaltoVI.

Fig.4.8showsbeltdrivenelectrostaticgeneratordevelopedbyVandeGraafin1934.Aninsulatingbeltisrunoverpulleys.Thebelt,thewidthofwhichmayvaryfromafewcmstometresisdriven ataspeedofabout15to30m/sec,bymeansofamotorconnectedtothelowerpulley.Thebeltnearthe lower pullyischargedelectrostaticallybyanexcitationarrangement.Thelowerchargesprayunit consistsofanumberofneedlesconnectedtothecontrollabled.c.source(10kV–100kV)sothatthe dischargebetweenthepointsandthebeltismaintained.Thechargeisconveyedtotheupperendwhere itiscollectedfromthebeltbydischargingpointsconnectedtotheinsideofaninsulatedmetalelectrode throughwhichthebeltpasses.Theentireequipmentisenclosedinanearthedmetaltankfilledwith insulatinggasesofgooddielectricstrengthviz.SF_6 etc.Sothatthepotentialoftheelectrodecouldbe raisedtorelativelyhighervoltagewithoutcoronadischargesorforacertainvoltageasmallersizeof the equipment will result. Also, the shape of the h.t., electrodeshould be such that the surface gradient of electric field is made uniform to reduce again corona discharges, even though it is desirable to avoid coronaentirely.Anisolatedsphereisthemostfavourableelectrodeshapeandwillmaintainauniform field*E*withavoltageof*Er*where*r*istheradiusofthesphere.

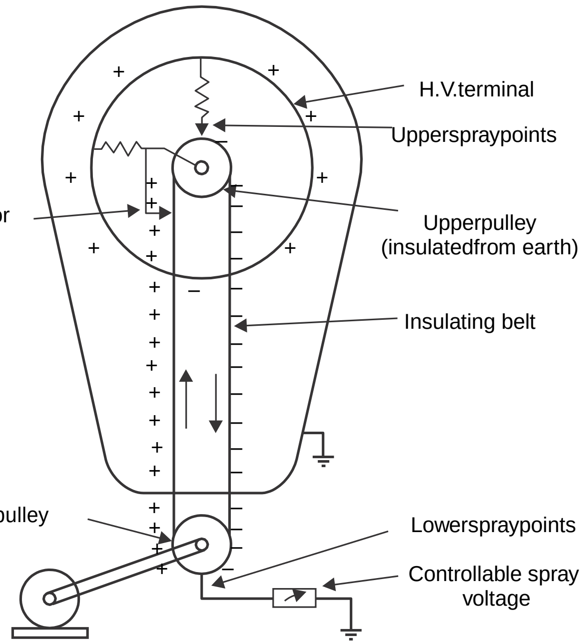


Fig.4.8 VandeGraafgenerator

Astheh.t.electrodecollectschargesitspotentialrises.Thepotentialatanyinstantisgivenas $V=q/C$where$q$is the charge collected at that instant. It appears as though if the charge were collected foralongtimeanyamountofvoltagecouldbegenerated.However,asthepotentialofelectroderises, thefieldsetupbytheelectrodeincreasesandthatmayionisethesurroundingmediumand,therefore, thiswouldbethelimitingvalueofthevoltage.Inpractice,equilibriumisestablishedataterminal voltagewhichissuchthatthechargingcurrent

$$\left[I = C\frac{dV}{dt} \right]$$

equalsthedischargecurrentwhichwillincludetheloadcurrentandtheleakageandcoronalosscurrents. Themovingbeltsystemalsodistortstheelectricfieldand,therefore,itisplacedwithinproperlyshaped fieldgradingrings.Thegradingisprovidedbyresistorsandadditionalcoronadischargeelements.

Thecollectorneedlesystemisplacednearthepointwherethebeltenterstheh.t.terminal.A secondpointsystemexcitedbyaself-inducingarrangementenablesthedowngoingbelttobecharged tothepolarityoppositetothatoftheterminalandthustherateofchargingofthelatter,foragiven speed,isdoubled.Theselfinducingarrangementrequiresinsulatingtheupperpulleyandmaintaining itatapotentialhigherthanthatoftheh.t.terminalbyconnectingthepulleytothecollectorneedle

system. Thearrangementalsoconsistsofarowofpoints(shownasupperspraypointsinFig.4.8) connectedtotheinsideoftheh.t.terminalanddirectedtowardsthepulleyaboveitspointsofentryinto theterminal.Asthepulleyisatahigherpotential(positive),thenegativechargesduetocoronadischarge attheupperspraypointsarecollectedbythebelt.Thisneutralisesanyremainingpositivechargeonthe beltandleavesanexcessofnegativechargesonthedowngoingbelttobeneutralisedbythelower spraypoints.Sincethesenegativechargesleavetheh.t.terminal,thepotentialoftheh.t.terminalis raisedbythecorrespondingamount.

Inorder to have a rough estimate of the current supplied by the generator, let us assume that the electricfield$E$isnormaltothebeltandishomogeneous.

Weknowthat$D=\epsilon_0 E$where$D$isthefluxdensityandsincethemediumsurroundingtheh.t. terminalissayair$\epsilon_r=1$and$\epsilon_0=8.854\times10^{-12}$F/metre.

AccordingtoGausslaw,$D=\sigma$thesurfacechargedensity.

Therefore, $$D=\sigma=\epsilon_0 E \qquad (4.18)$$

Assuming $E=30$kV/cm or 30,000kV/m

$$\sigma=8.854\times10^{-12}\times3000\times10^{3}$$
$$=26.562\times10^{-6}\,\text{C/m}^2$$

Assumingforatypicalsystem$b$=1metreandvelocityofthebelt$v$=10m/sec,andusing equation(4.16),thecurrentsuppliedbythegeneratorisgivenas

$$I=\sigma b v$$
$$=26.562\times10^{-6}\times1\times10$$
$$=26.562\times10^{-5}\,\text{Amp}$$
$$=265\,\mu\text{A}$$

From equation(4.16)itisclearthatcurrent$I$dependsuponσ,$b$and$v$.Thebeltwidth(b)andvelocity $v$being limited by mechanical reasons, the current can be increased by having higher value of σ.σcanbe increasedbyusinggasesofhigherdielectricstrengthsothatelectricfieldintensity *E*couldbe increasedwithouttheinceptionofionisationofthemediumsurroundingtheh.t.terminal.However, withallthesearrangements,theactualshortcircuitcurrentsarelimitedonlytoafewmAevenforlarge generators

.

Theadvantagesofthegeneratorare:

(*i*)Veryhighvoltagescanbeeasilygenerated

(*ii*)Ripplefreeoutput

(*iii*)Precisionandflexibilityofcontrol

Thedisadvantagesare:

(*i*)Lowcurrentoutput

(*ii*)Limitationsonbeltvelocityduetoitstendencyforvibration.Thevibrationsmaymakeit difficulttohaveanaccurategradingofelectricfields

Thesegeneratorsareusedinnuclearphysicslaboratoriesforparticleaccelerationandotherprocesses inresearchwork.

Example 1.*AtenstageCockraft-Waltoncircuithasallcapacitorsof0.06μF.Thesecondaryvoltage ofthesupplytransformeris100kVatafrequencyof150Hz.Iftheloadcurrentis1mA,determine(i) voltageregulation(ii)theripple(iii)theoptimumnumberofstagesformaximumoutputvoltage(iv) themaximumoutputvoltage.*

Solution: Given$C$=0.06μF,I=1mA,f=150Hz

n=10

Voltagedrop $$V=\frac{I}{fC}\left[\frac{2}{3}n^3+\frac{n^2}{2}+\frac{n}{6}\right]\approx\frac{I}{fC}\left[\frac{2}{3}n^3+\frac{n^2}{2}\right]$$

$$=\frac{1\times10^{-3}}{150\times0.06\times10^{-6}}\left[\frac{2}{3}\times10^3+\frac{10^2}{2}\right]$$

10^3

$$= \frac{666.6+50}{5.0\times3} = \frac{717\times10^{3}}{3\times3} = 80\text{kV}$$

Therefore, percentage voltage regulation

$$\frac{80\times100}{2\times10\times100} = 4\%$$

(*ii*) The ripple voltage $\delta V = \frac{I}{fC}\frac{n(n+1)}{2}$

$$= \frac{1\times10^{-3}\times55}{150\times0.06\times10^{-6}}$$

$= 6.1\text{kV}$

$$\therefore \%\ \text{ripple} = \frac{6.1\times100}{2\times10\times100}$$

$$= 0.3\%\quad \textbf{Ans.}$$

(*iii*) Optimum no. of stages $= \sqrt{\frac{V_{max}\,fC}{I}}$

$$= \sqrt{\frac{100\times150\times0.06\times10^{-6}\times10^{3}}{10^{-3}}} = 30\quad \textbf{Ans.}$$

(*iv*) The maximum output voltage

$$= 30\times\frac{4}{3}\times V_{max}$$

$$= 30\times\frac{4}{3}\times100 = 4000\ \text{KV}\quad \textbf{Ans.}$$

Example 2.*A100kVA250V/200kVfeedtransformerhasresistanceandreactanceof1%and5% respectively.Thistransformerisusedtotestacableat400kVat50Hz.Thecabletakesacharging currentof0.5Aat400kV.Determinetheseriesinductancerequired.Assume1%resistance ofthe inductor.Alsodetermineinputvoltagetothetransformer.Neglectdielectriclossofthecable.*

Solution: ThecircuitisdrawninFig.Ex.4.2

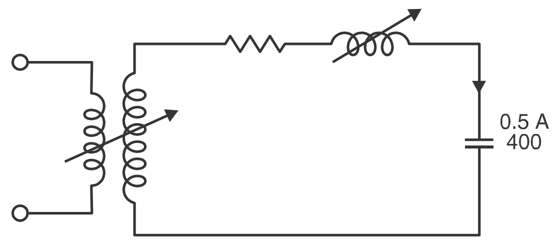


Fig.Ex.4.2

Theresistanceand reactanceofthetrans-formerare

$$\frac{1}{100} \times \frac{200^2}{0.1} \; 4K\Omega$$

$$\frac{5}{100} \times \frac{200^2}{0.1} \; 20K\Omega$$

Theresistanceoftheinductorisalso4KΩ.
Thecapacitivereactanceofcapacitor(TestSpecimen)

$$= \frac{400}{0.5} = 800K\Omega$$

Forresonance $X_L = X_C$

Inductivereactanceoftransformeris20KΩ.Therefore,additionalinductivereactancerequired willbe

800–20=780KΩ

Theinductancerequired $= \frac{780 \times 1000}{314} = 2484H$

Totalresistanceofthecircuit=8KΩ
underresonanceconditionthesupplyvoltage

(Secondaryvoltage) $= IR = 0.5 \times 8 = 4kV$

Therefore,primaryvoltage $= 4 \times \frac{250}{200}$

=5volts **Ans.**

Questions:

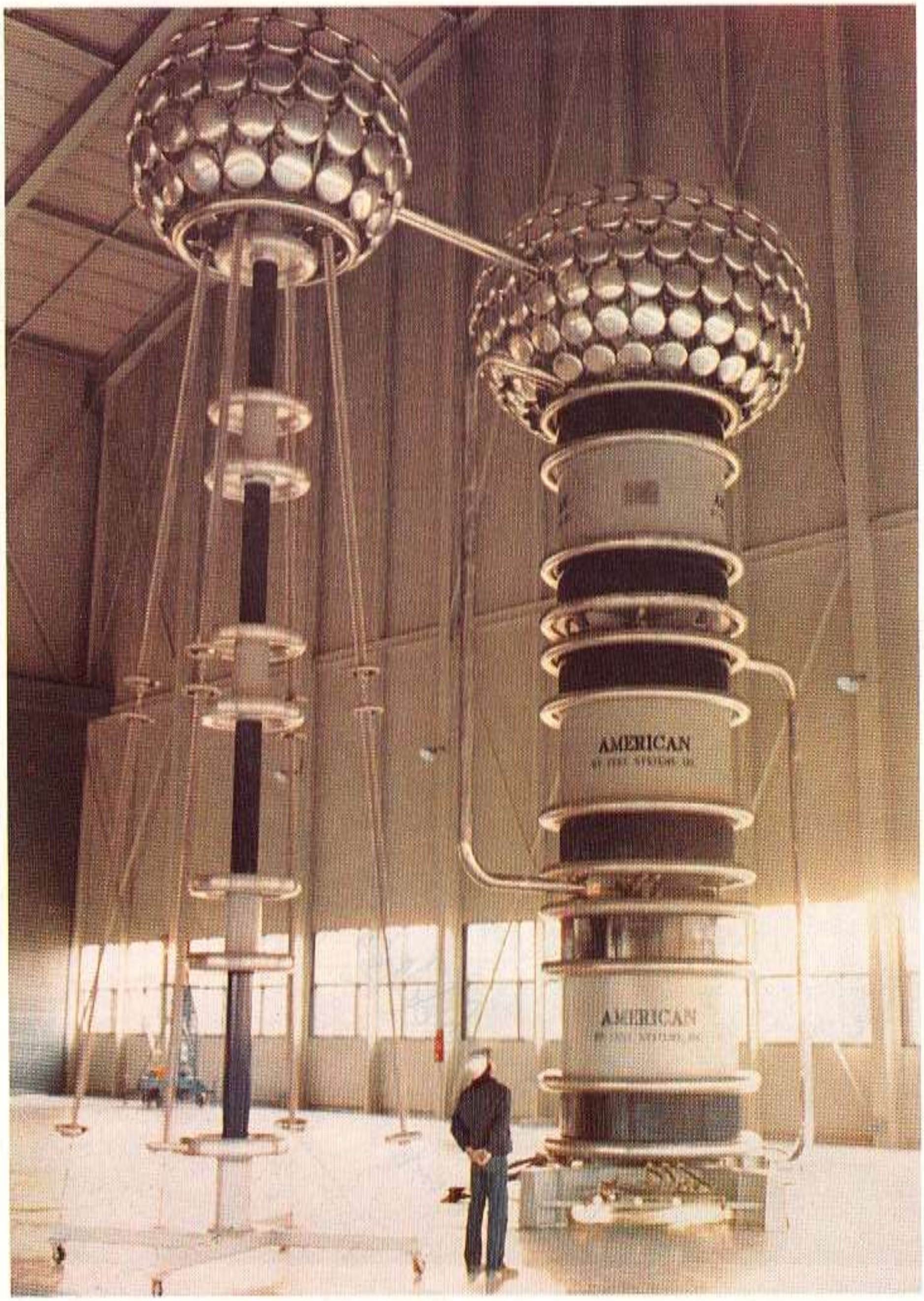
1.Explainandcomparetheperformanceofhalfwaverectifierandvoltagedoublercircuitsforgenerationof highd.c.voltages.

2.Defineripplevoltage.Showthattheripplevoltageinarectifiercircuitdependsupontheloadcurrentand thecircuitparameters.

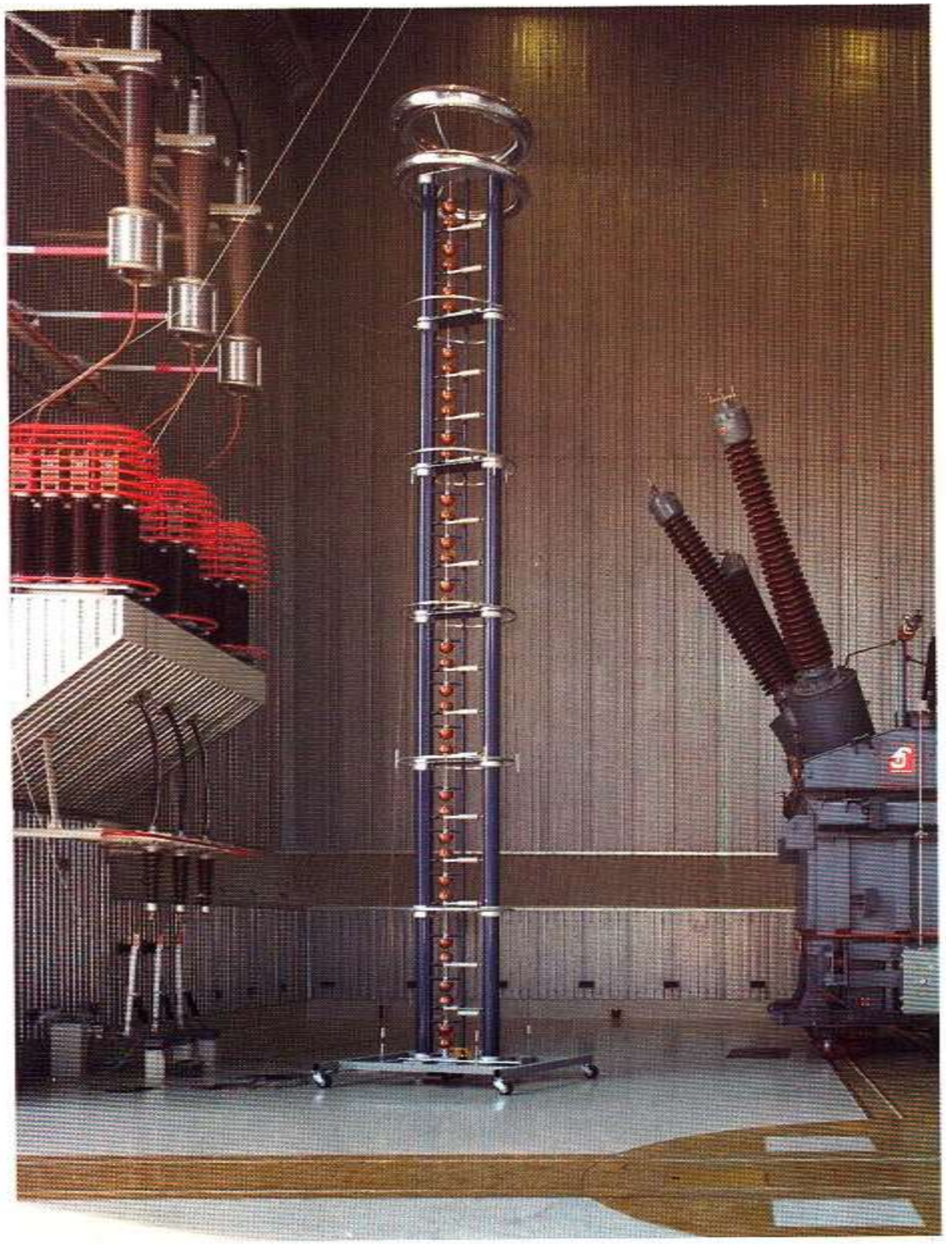
3.Explain with neat sketches Cockroft-Walton voltage multiplier circuit. Explain clearly its operationwhen thecircuitis(i)unloaded(ii)loaded.

4. DeriveanexpressionforripplevoltageofamultistageCockroft-WaltonCircuit.
5. Deriveanexpressionforthevoltageoutputunderloadcondition.Hence,deducetheconditionforoptimal numberofstageifamaximumvalueofoutputvoltageisdesired.
6. Describewithneatdiagramtheprincipleofoperationandapplicationofasymmetricalcascadedrectifier.
7. Explainclearlythebasicprincipleofoperationofanelectrostaticgenerator.Describewithneatdiagram theprincipleofoperation,applicationandlimitationsofVandeGrafgenerator.
8. Whatisacascadedtransformer?Explainwhycascadingisdone?Describewithneatdiagramathreestage cascadedtransformer.Labelthepowerratingsofvariousstagesofthetransformer.
9. Drawequivalentcircuitofa3-stagecascadedtransformeranddeterminetheexpressionforshortcircuit impedanceofthetransformer.Hencededuceanexpressionfortheshort-circuitimpedanceofan$n$-stage cascadedtransformer.
10. Explain with neat diagram the basic principle of reactive power compensation is high voltage a.c.testing ofinsulatingmaterials.
11. Explain with neat diagram the principle of operation of (i) series (ii)parallelresonantcircuitsforgenerat-inghigha.c.voltages.Comparetheirperformance.
12. Explaintheseries-parallelresonantcircuitanddiscussitsadvantagesanddisadvantages.

DC voltage test set 2000 kV, 10 mA for testing power cables, including a HV measuring resistor and automatic grounding system (foreground)

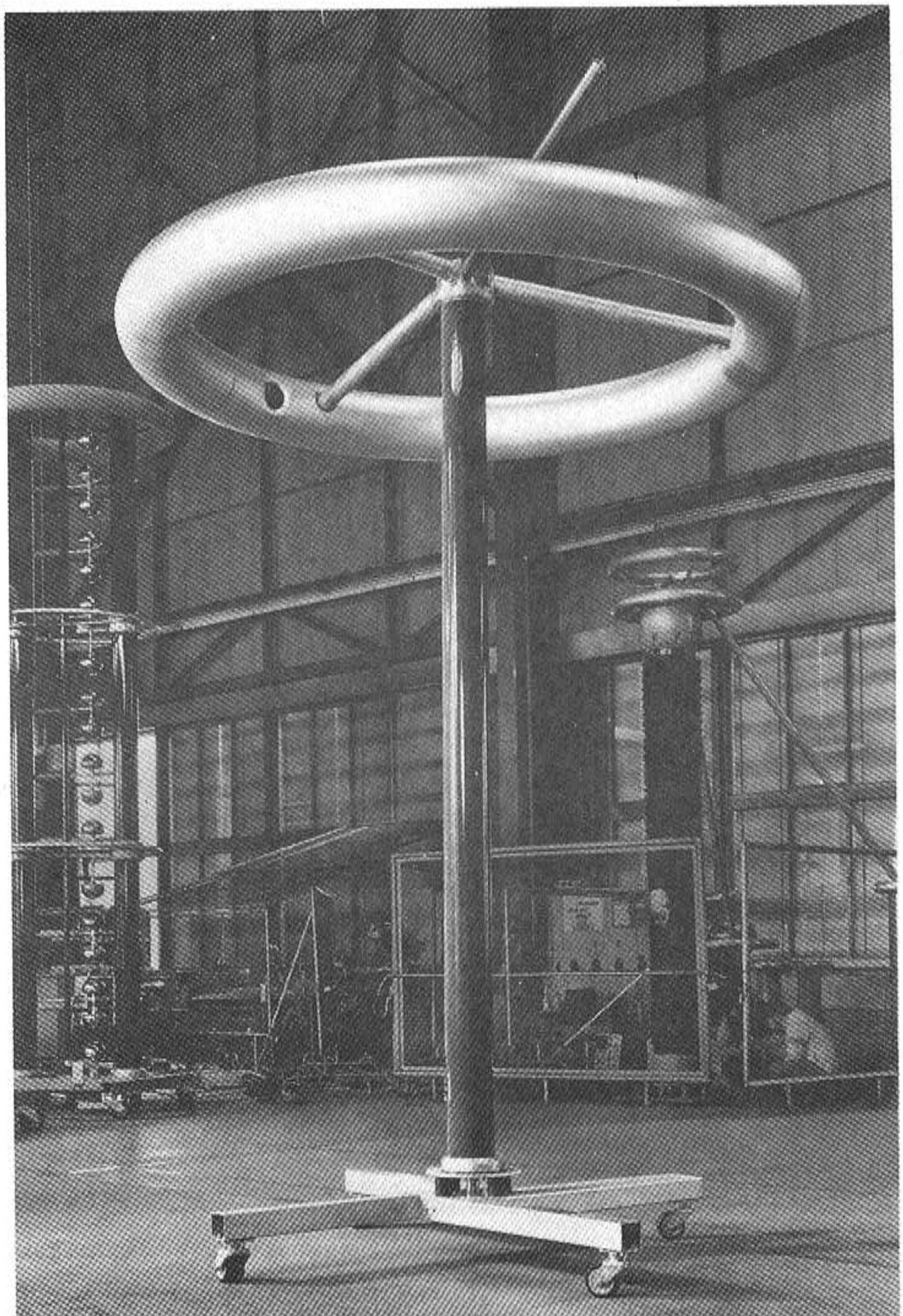


Cascaded serie resonant test system 3 x 350 kV, for the testing of power cables, with AC voltage divider (left)



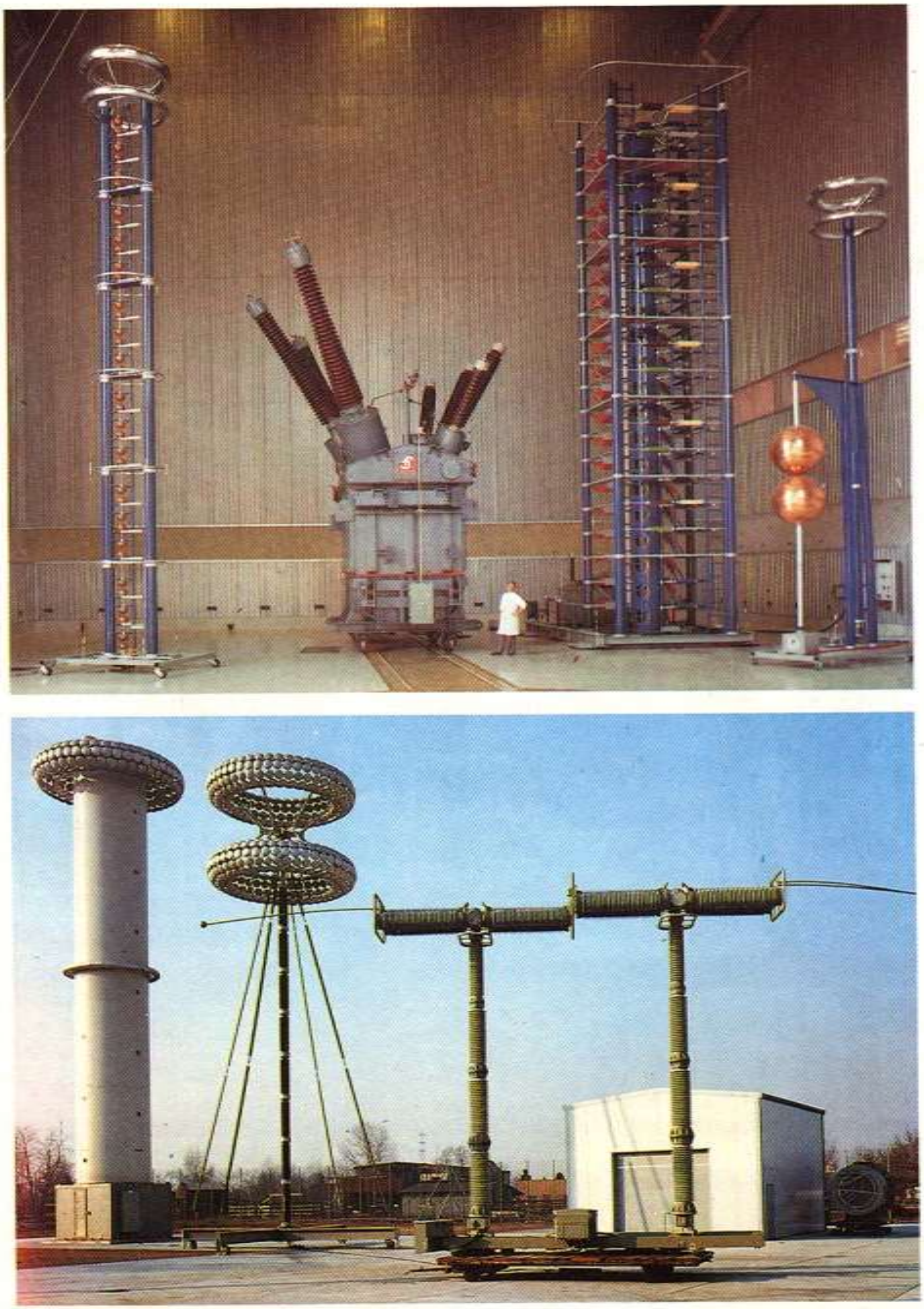
Triggered impulse chopping gap 3600 kV for impulse testing of power transformers

Large outdoor impulse voltage dividers, damped capacitive type with large top electrode for ultra-high switching impulse voltages



Resistive impulse voltage divider 1800 kV

Three-stage cascade transformer 3 x 600 kV, 2 A cont. outdoor type with AC voltage divider 1500 kV



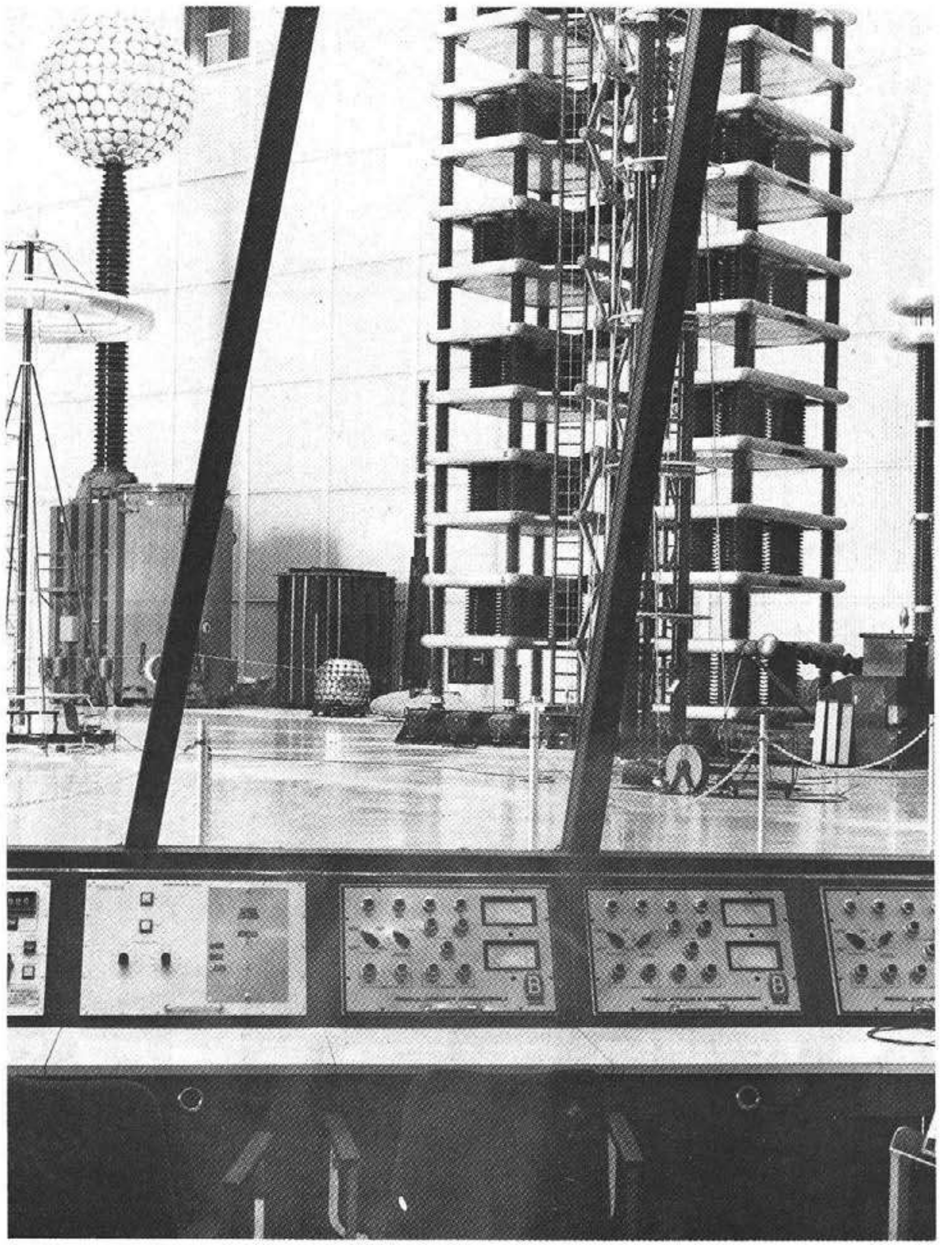
Large impulse voltage generators

Above: Indoor 4000 kV

Below: Outdoor 6400 kV shown together with typical test objects

Above: Large power transformer (center)

Below: Power circuit breakers (foreground right)



View from the control room at IREQ

PART - B

UNIT -5

GENERATION OF IMPULSE VOLTAGES AND CURRENTS: Introduction to standard lightning and switching impulse voltages. Analysis of single stage impulse generator-expression for Output impulse voltage. Multistage impulse generator working of Marx impulse. Rating of impulse generator. Components of multistage impulse generator. Triggering of impulse generator by three electrode gap arrangement. Triggering gap and oscillograph time sweep circuits. Generation of switching impulse voltage. Generation of high impulse current.

6 Hours

DEFINITIONS:IMPULSEVOLTAGE

Animpulsevoltageisaunidirectionalvoltagewhich,withoutappreciableoscillations,risesrapidlyto amaximumvalueandfallsmoreorlessrapidlytozeroFig.5.4.Themaximumvalueiscalledthepeak value of the impulse and the impulse voltage is specified by this value. Small oscillations are tolerated, provided thattheiramplitudeislessthan5%ofthepeakvalueoftheimpulsevoltage.Incaseof oscillationsinthewaveshape,ameancurveshouldbeconsidered.

Ifanimpulsevoltagedevelopswithoutcaus ingflashoverorpuncture,itiscalledafullim causingasuddencollapseoftheimpulsevoltage, itiscalledachoppedimpulsevoltage.Afullim- pulsevoltageischaracterisedbyitspeakvalueand itstwotimeintervals,thewavefrontandwavetail timeintervalsdefinedbelow:

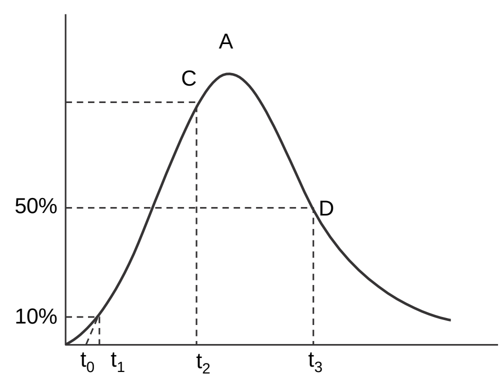


Fig.5.1 Fullimpulsewave

The wavefronttimeofanimpulsewaveis thetimetakenbythewavetoreachtoitsmaxi- mum value starting from zero value. Usually it is difficulttoidentifythestartandpeakpointsofthe waveand,therefore,thewavefronttimeisspecifiedas4.25times(t_2–t_1), wheret_2 isthetimeforthe wavetoreachtoits90%ofthepeakvalueandt_1 isthetimetoreach10%ofthepeakvalue.Since (t_2–t_1)representsabout80%ofthewavefronttime,itismultipliedby4.25togivetotalwavefront time. The point where the line*CB* intersects the time axis is referred to be the nominal starting point of thewave.

Thenominalwavetailtimeismeasuredbetweenthenominalstartingpointt_0 andthepointon thewavetailwherethevoltageis50%ofthepeakvalue*i.e.*wavefailtimeisexpressedas(t_3–t_0).

Thenominalsteepnessofthewavefrontistheaveragerateofriseofvoltagebetweenthepoints onthewavefrontwherethevoltageis10%and90%ofthepeakvaluerespectively.

ThestandardwaveshapespecifiedinBSSandISSisa1/50microsec.wave*i.e.*awavefrontof 1microsec.andawavetailof50microsec.Atoleranceofnotmorethan±50%onthedurationofthe wavefrontand20%onthetimetohalfvalueonthewavetailisallowed.Thewaveiscompletely specifiedas100kV,1/50microsec.where100kVisthepeakvalueofthewave.

The waveshaperecommendedbytheAmericanStandardAssociationis4.5/40microsec.with permissiblevariationsof0.5microsec.onthewavefrontand±10microsec.onthewavetail.Here wavefronttimeistakenas4.67timesthetimetakenbythewavetorisefrom30%to90%ofitspeak valueandwavetailtimeiscomputedasinBSSorISS*i.e.*itisgivenas(t_3 –t_0)Fig.5.4.

ChoppedWave

Ifanimpulsevoltageisappliedtoapieceofinsulationandifaflashoverorpunctureoccurscausing suddencollapseoftheimpulsevoltage,itiscalledachoppedimpulsevoltage.Ifchoppingtakesplace onthefrontpartofthewave,itisknownasfrontchoppedwave,Fig.5.2(*a*)else,itisknownsimplyas achoppedwave,Fig.5.2(*b*).Again,ifchoppingtakesplaceonthefront,itisspecifiedbythepeak valuecorrespondingtothechoppedvalueanditsnominalsteepnessistherateofriseofvoltagemeasuredbetwee nthepointswherethevoltageis10%and90%respectivelyofthevoltageattheinstantofchopping.However,awa vechoppedonthetailisspecifiedonthelinesoffullwave.

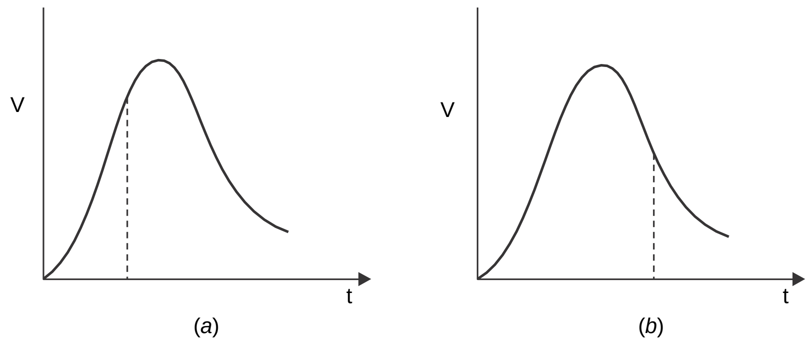


Fig.5.2 Choppedwaves.(a)Frontchoppedwave(b)Choppedwave

ImpulseFlashOverVoltage

Wheneveranimpulsevoltageisappliedtoaninsulatingmediumofcertainthickness,flashovermayor maynottakeplace.Ifoutofatotalofsaytenapplicationsofimpulsevoltageabout5ofthemflashover thentheprobabilityofflashoverwiththatpeakvoltageoftheimpulsevoltageis50%.Therefore,a50 percentimpulseflashovervoltageisthepeakvalueofthatimpulseflashovervoltagewhichcauses flashoveroftheobjectundertestforabouthalfthenumberofapplicationsofimpulses.However,itis tobenotedthattheflashoveroccursataninstantsubsequenttotheattainmentofthepeakvalue.The flashoveralsodependsuponthepolarity,durationofwavefrontandwavetailsoftheappliedimpulse voltages.

Iftheflashoveroccursmorethan50%ofthenumberofapplications,itisdefinedasimpulse flashovervoltageinexcessof50%.

Theimpulseflashovervoltageforflashoveronthewavefrontisthevalueoftheimpulse voltageattheinstantofflashoveronthewavefront.

ImpulsePunctureVoltage

Theimpulsepuncturevoltageisthepeakvalueoftheimpulsevoltagewhichcausespunctureofthe materialwhenpunctureoccursonthewavetailandisthevalueofthevoltageattheinstantofpuncture whenpunctureoccursonthewavefront.

ImpulseRatioforFlashOver

Theimpulseratioforflashoveristheratioofimpulseflashovervoltagetothepeakvalueofpower frequencyflashovervoltage.

Theimpulseratioisnotaconstantforanyparticularobject,butdependsupontheshapeand polarityoftheimpulsevoltage,thecharacteristicsofwhichshouldbespecifiedwhenimpulseratiosare quoted.

ImpulseRatioforPuncture

Theimpulseratioforpunctureistheratiooftheimpulsepuncturevoltagetothepeakvalueofthe powerfrequencypuncturevoltage.

IMPULSEGENERATORCIRCUITS

Fig.5.3representsanexactequivalentcircuitofasinglestageimpulsegeneratoralongwithatypical load.

C_1 isthecapacitanceofthegeneratorchargedfromad.c.sourcetoasuitablevoltagewhich causesdischargethroughthespheregap.ThecapacitanceC_1 mayconsistofasinglecapacitance,in whichcasethegeneratorisknownasasinglestagegeneratororalternativelyifC_1isthetotalcapacitance ofagroupofcapacitorschargedinparallelandthendischargedinseries,itisthenknownasamultistage generator.

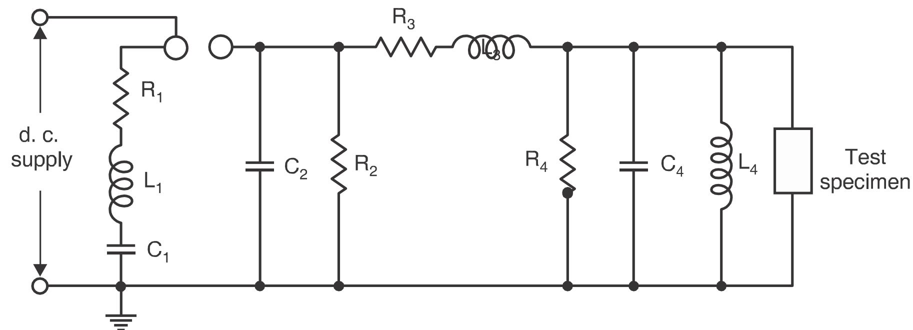


Fig.5.3 Exactequivalentcircuitofasinglestageimpulsegeneratorwithatypicalload

L_1 istheinductanceofthegeneratorandtheleadsconnectingthegeneratortothedischarge circuitandisusuallykeptassmallaspossible.TheresistanceR_1consistsoftheinherentseriesresistance ofthecapacitancesandleadsandoftenincludesadditionallumpedresistanceinsertedwithinthegenerator fordampingpurposesandforoutputwaveformcontrol.L_3,R_3 are theexternalelementswhichmaybe connectedatthegeneratorterminalforwaveformcontrol.R_2 andR_4 control thedurationofthewave. However, R_4 alsoservesasapotentialdividerwhenaCROisusedformeasurementpurposes.C_2andC_4 representthecapacitancestoearthofthehighvoltagecomponentsandleads.C_4 alsoincludesthe capacitanceofthetestobjectandofanyotherloadcapacitancerequiredforproducingtherequired waveshape.L_4representstheinductanceofthetestobjectandmayalsoaffectthewaveshapeappreciably.

Usuallyforpracticalreasons,oneterminaloftheimpulsegeneratorissolidlygrounded.The polarityoftheoutputvoltagecanbechangedbychangingthepolarityofthed.c.chargingvoltage.

Fortheevaluationofthevariousimpulsecircuitelements,theanalysisusingtheequivalent circuit of Fig. 5.3 is quite rigorous and complex. Two simplified but more practical forms of impulse generatorcircuitsareshowninFig.5.4(a)and(b).

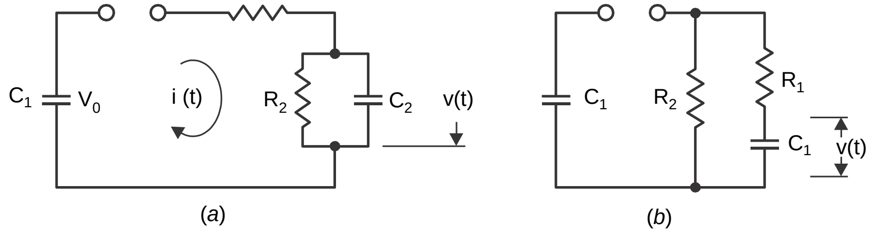


Fig.5.4 Simplifiedequivalentcircuitofanimpulsegenerator

Thetwocircuitsarewidelyusedanddifferonlyinthepositionofthewavetailcontrolresistance $R_{4.}$WhenR_2isontheloadsideofR_1(Fig.*a*)thetworesistancesformapotentialdividerwhichreduces theoutputvoltagebutwhenR_2 isonthegeneratorsideof R_1 (Fig.*b*)thisparticularlossofoutput voltageisabsent.

TheimpulsecapacitorC_1ischargedthroughachargingresistance(notshown)toad.c.voltage V_0andthendischargedbyflashingovertheswitchinggapwithapulseofsuitablevalue.Thedesired impulsevoltageappearsacrosstheloadcapacitance$C_{4.}$Thevalueofthecircuitelementsdetermines theshapeoftheoutputimpulsevoltage.Thefollowinganalysiswillhelpusinevaluatingthecircuit parametersforachievingaparticularwaveshapeoftheimpulsevoltage.

Table5.1
Valuesofαandβfortypicalwaveform

Wave	α	β
0.5/5	4.080	5.922
1/5	4.557	4.366
1/10	4.040	4.961
4.5/40	4.776	4.757
1/50	5.044	5.029

Table5.2

Calculationfora1/50microsec.wave

Timein microsec.	$e^{-0.015t}$	$e^{-6.073t}$	*(2)–(3)*	*4.01749(4)*
0.0	4.0	4.0	0.00	0.0
0.1	0.998501	0.5448199	0.45368	0.4616148
0.2	0.9970045	0.2968287	0.7001757	0.71242
0.3	0.9955101	0.1617181	0.8337919	0.8483749
0.4	0.9940179	0.0881072	0.9059106	0.9217549
0.5	0.992528	0.0480026	0.9445253	0.961045
0.6	0.9910403	0.0261557	0.9648875	0.9817633
0.8	0.9880717	0.0077628	0.9803088	0.9974577
4.0	0.9851119	0.002342	0.9828076	4.0000
4.1	0.9836353	0.0012554	0.9823798	0.995616
4.2	0.982116	0.00068396	0.981477	0.998643
4.0	0.9704455	5.3095×10^{-6}	0.970445	0.987418
10.0	0.8607079	0.0	0.8607079	0.87576
50	0.4723665	0.0	0.4723665	0.4806281
48	0.4867522	0.0	0.4867522	0.49526
47	0.4941085	0.0	0.4941085	0.5627

Table5.4

Approximatecapacitanceofsomeequipments

Equipment	*Capacitance*	γ
Lineinsulators,pininsulators	25pF	1000
Bushings	150to400pF	64.5
Currenttransformers	200to600pF	44.67
Powertransformersupto1MVA	1000to2000pF	14.5
Powertransformersupto50MVA	10,000pF	4.5
Powertransformersabove100MVA	30,000pF	0.83
Cablesamplesfor10mlength	2500pF	10.0
Experimentalsetupmeasuringupto100KV	100pF	250
Capacitor,leadsfora.c.testvoltageupto1000KV	1000pF	25

MULTISTAGEIMPULSEGENERATORCIRCUIT

Inordertoobtainhigherandhigherimpulsevoltage,asinglestagecircuitisinconvenientforthe followingreasons:

(*i*)Thephysicalsizeofthecircuitelementsbecomesverylarge.

(*ii*)Highd.c.chargingvoltageisrequired.

(*iii*)Suppression of corona discharges from the structure and leads during the charging period is difficult.

(*iv*)Switchingofvaryhighvoltageswithsparkgapsisdifficult.

In1923E.Marxsuggestedamultipliercircuitwhichiscommonlyusedtoobtainimpulsevoltages withashighapeakvalueaspossibleforagivend.c.chargingvoltage.

Dependinguponthechargingvoltageavailableandtheoutputvoltagerequiredanumberof identicalimpulsecapacitorsarechargedinparallelandthendischargedinseries,thusobtaininga multipliedtotalchargingvoltagecorrespondingtothenumberofstages.Fig.5.7showsa3-stageimpulse generatorcircuitduetoMarxemploying‘*b*’circuitconnections.TheimpulsecapacitorsC_1arecharged tothe charging voltage V_0throughthehighchargingresistors $R_c$inparallel. When all the gaps$G$break down,theC_1'capacitancesareconnectedinseriessothatC_2 ischargedthroughtheseriesconnection ofallthewavefrontresistancesR_1'andfinallyallC_1'andC_2 willdischargethroughtheresistorsR_2' andR_1'.Usually$R_c >> R_2 >> R_{4.}$

IfinFig.5.7thewavetailresistors R_2'ineachstageareconnectedinparalleltotheseries combinationofR_1',GandC_1',animpulsegeneratoroftypecircuit‘*a*’isobtained.

Inorder that the Marx circuit operates consistently it is essential to adjust the distances between variousspheregapssuchthatthefirstgapG_1 is onlyslightlylessthanthatofG_2 and soon.Ifisalso necessarythattheaxesofthegaps$G$beinthesameverticalplanesothattheultravioletradiationsdue tosparkinthefirstgap$G$,willirradiatetheothergaps.Thisensuresasupplyofelectronsreleasedfrom the gapelectronstoinitiatebreakdownduringtheshortperiodwhenthegapsaresubjectedto overvoltages.

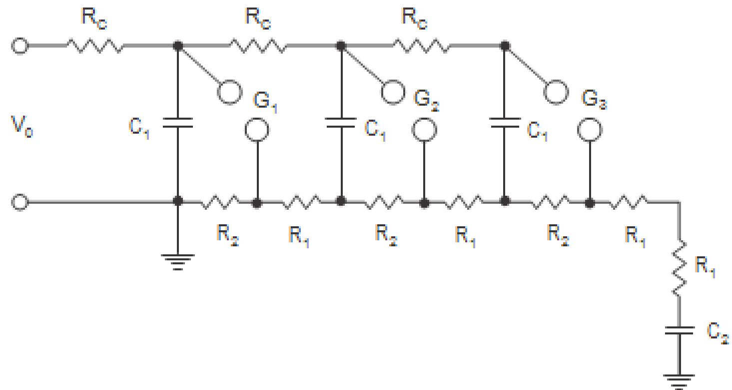


Fig. 5.7 A 3-stage Marx impulse generator in circuit 'b' connections.

Thewavefrontcontrolresistancecanhavethreepossiblelocations(*i*)entirelywithinthegenerator (*ii*)entirelyoutsidethegenerator(*iii*)partlywithinandpartlyoutsidethegenerator.

Thefirstarrangementisunsatisfactoryastheinductanceandcapacitanceoftheexternalleads andtheloadformanoscillatorycircuitwhichrequirestobedampedbyanexternalresistance.The secondarrangementisalsounsatisfactoryasasingleexternalfrontresistancewillhavetowithstand, eventhoughforaveryshorttime,thefullratedvoltageandtherefore,willturnouttobeinconveniently long and would occupy much space. A compromise between the two is the third arrangement as shown inFig.5.7andthusboththe"spaceeconomy"anddampingofoscillationsaretakencareof.

ItcanbeseenthatFig.5.7canbereducedtothesinglestageimpulsegeneratorofFig.5.4 (*b*). Afterthegeneratorhasfired,thetotaldischargecapacitanceC_1 maybegivenas

$$\frac{1}{C_1} \sum^{n} \frac{1}{C_1'}$$

theequivalentfrontresistance

$$R_1 = \sum^{n} R_1' + R_1''$$

andtheequivalenttailcontrolresistance

$$R_2 = \sum^{n} R_2'$$

where*n*isthenumberofstages.

Goodlethassuggestedanothercircuitshowninfig.5.8,forgenerationofimpulsevoltage wheretheloadisearthedduringthechargingperiod,withoutthenecessityforanisolatinggap.The impulseoutputvoltagehasthesamepolarityasthechargingvoltageiscaseofMarxcircuit,itis reversedincaseofGoodletcircuit.Also,ondischarge,bothsidesofthefirstsparkgapareraisedtothe chargingvoltageintheMarxcircuitbutincaseofGoodletcircuittheyattainearthpotential.

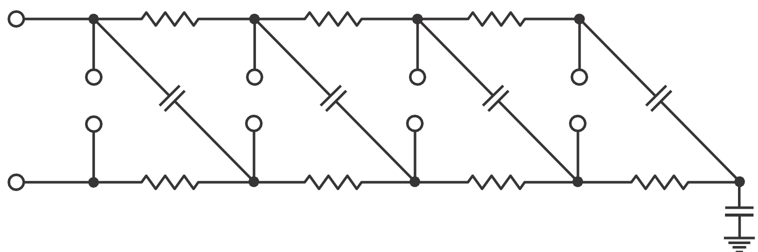


Fig.5.8 Basicgoodletcircuit

TRIGGERINGANDSYNCHRONISATIONOFTHEIMPULSEGENERATOR

Impulsegeneratorsarenormallyoperatedinconjunctionwithcathoderayoscillographsformeasureme nt andforstudyingtheeffectofimpulsewavesontheperformanceoftheinsulationsoftheequipments. Sincetheimpulsewavesareofshorterduration,itisnecessarythattheoperationofthegeneratorand theoscillograph should be synchronized accurately and if the wave front of the wave is to be recorded accurately,thetimesweepcircuitoftheoscillographshouldbeinitiatedatatimeslightlybeforethe impulsewavereachesthedeflectingplates.

If theimpulsegeneratoritselfinitiatesthesweepcircuitoftheoscillograph,itisthennecessary toconnect a delay cable between the generator or the potential divider and the deflecting plates of the oscilloscope so that the impulse wave reaches the plates at a controlled time after the sweep has been tripped. However, the use of delay cable leads to inaccuracies in measurement. For this reason, some trippingcircuitshavebeendevelopedwherethesweepcircuitisoperatedfirstandthenafteratimeof

about0.1to0.5μsec.thegeneratoristriggered.

Oneofthemethodsinvolvestheuseofathree-spheregapinthefirststageofthegeneratoras shown in Fig. 5.10. The spacing between the spheres is so adjusted that the two series gaps are able to withstandthechargingvoltageoftheimpulsegenerator.Ahighresistanceisconnectedbetweenthe outerspheresanditscentrepointisconnectedtothecontrolspheresothatthevoltagebetweenthe outerspheresisequallydividedbetweenthetwogaps.Ifthegeneratorisnowchargedtoavoltage slightly less than the breakdown voltage of the gaps, the breakdown can be achieved at any instant by applyinganimpulseofeitherpolarityandofapeakvoltagenotlessthanonefifthofthecharging voltagetothecontrolsphere.

Theoperationisexplainedasfollows.Theswitch*S*isclosedwhichinitiatesthesweepcircuitof the oscillograph. The same impulse is applied to the grid of the thyratron tube. The inherent time delay ofthethyratronensuresthatthesweepcircuitbeginstooperatebeforethestartofthehighvoltageimpulse.

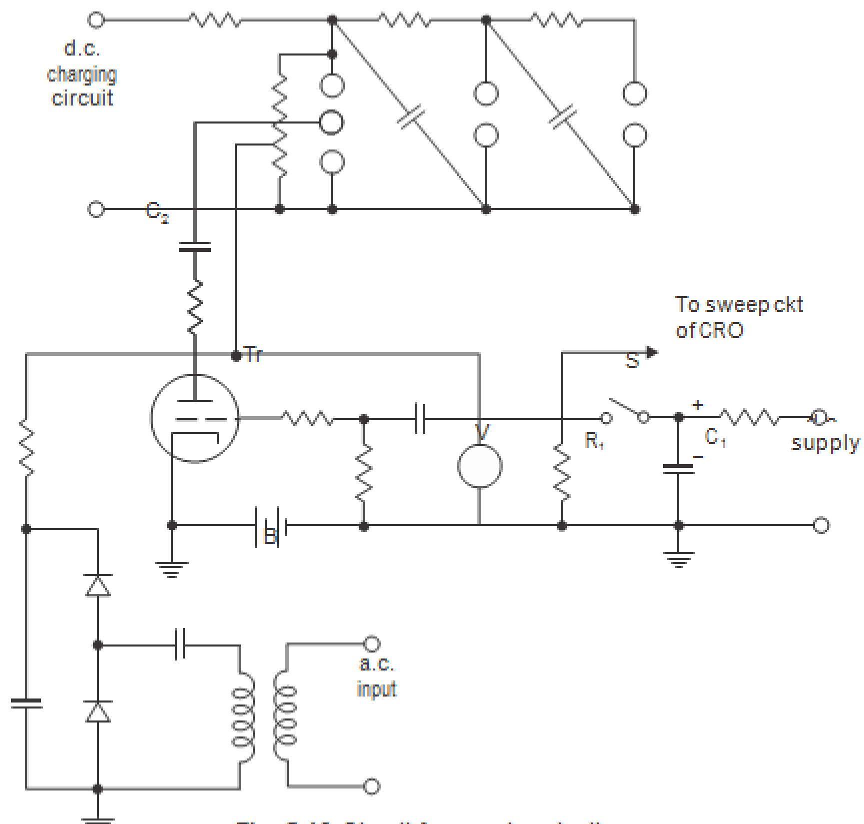


Fig. 5.10 Circuit for synchronisation

Afurtherdelaycanbeintroducedifrequiredbymeansofacapacitance-resistancecircuitR_1C_4.The trippingimpulseisappliedthroughthecapacitorC_4.Duringthechargnigperiodofthegeneratorthe anodeofthethyratrontubeisheldatapositivepotentialofabout20kV.Thegridisheldatnegativepotentialwithth ehelpofbattery*B*sothatitdoesnotconductduringthechargingperiod.Astheswitch *S*isclosed,thetriggerpulseisappliedtothegridofthethyratrontubewhichconductsandanegative impulseof20kVisappliedtothecentralspherewhichtriggerstheimpulsegenerator.

Fig.5.11showsatrigatrongapwhichisusedasthefirstgapoftheimpulsegeneratorand consistsessentiallyofathree-electrodegap.Thehighvoltageelectrodeisaspherearndtheearthed electrode may be a sphere, a semi-sphere or any other configuration which gives homogeneous electric field.Asmallholeisdrilledintotheearthedelectrodeintowhichametalrodprojects.Theannulargap betweentherodandthesurroundinghemisphereisabout1mm.Aglasstubeisfittedovertherod electrodeandissurroundedbyametalfoilwhichisconnectedtotheearthedhemisphere.Themetal rodortriggerelectrodeformsthethirdelectrode,beingessentiallyatthesamepotentialasthedrilled electrode, as it is connected to it through a high resistance, so that the control or tripping pulse can be appliedbetweenthesetwoelectrodes.Whenatrippingpulseisappliedtotherod,thefieldisdistorted inthemaingapandthelatterbreaksdownatavoltageappreciablylowerthanthatrequiredtocauseits breakdown in the absence of the tripping pulse. The function of the glass tube is to promote corona discharge round the rod as this causes photoionisation in the annular gap and the main gap and consequentlyfacilitatestheirrapidbreakdown.

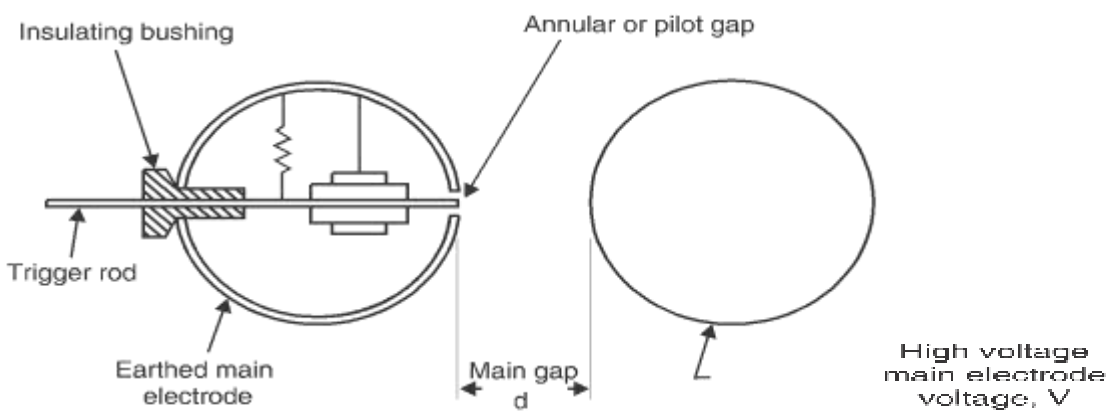


Fig.5.11 Thetrigatronsparkgap

For single stage or multi-stage impulse generators the trigatron gaps have been found quite satisfactoryandtheserequireatrippingvoltageofabout5kVofeitherpolarity.Thetrippingcircuits usedtodayarecommerciallyavailableandprovideingeneraltwoorthreetrippingpulsesoflower amplitudes.Fig.5.12showsatypicaltrippingcircuit.Thecapacitor C_1 ischargedthroughahigh resistanceR_4.Astheremotelycontrolledswitch$S$isclosed,apulseisappliedtothesweepcircuitofthe oscillographthroughthecapacitorC_5.AtthesametimethecapacitorC_2 ischargedupandatriggeringpulseisappliedtothetriggerelectrodeofthetrigatron.Therequisitedelayintriggeri ngthegenerator

canbeprovidedbysuitablyadjustingthevaluesofR_2andC_4.TheresidualchargeonC_2canbedischarged throughahighresistanceR_5.Thesedayslasersarealsousedfortrippingthesparkgap.

Thetrigatronalsohasaphaseshiftingcircuitassociatedwithitsoastosynchronisetheinitiation timewithanexternalalternatingvoltage.Thus,itispossibletocombinehighalternatingvoltagetests withasuperimposedimpulsewaveofadjustablephaseangle.

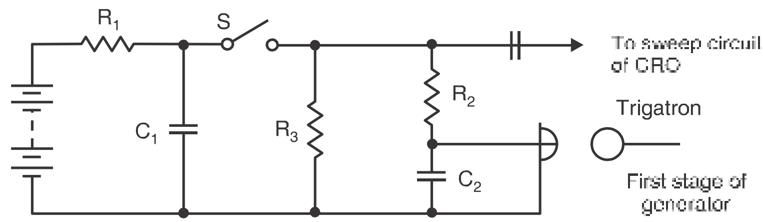


Fig.5.12 Atypicaltrippingcircuitofatrigatron

Thetrigatronisdesignedsoastopreventtheoverchargingoftheimpulsecapacitorsincaseof anaccidentalfailureoftriggering.Anindicatingdeviceshowswhetherthegeneratorisgoingtofire correctlyornot.Anadditionalfeedbackcircuitprovidesforasafewavechoppingandoscillograph release,independentoftheemittedcontrolpulse.

IMPULSECURRENTGENERATION

Theimpulsecurrentwaveisspecifiedonthesimilarlinesasanimpulsevoltagewave.Atypicalimpulse currentwaveisshowninFig.5.15.

High currentimpulsegeneratorsusually consist of a large number of capacitors connected in parallel to the common discharge path.Atypicalimpulsecurrentgeneratorcircuit isshowninFig.5.14.

Theequivalentcircuitofthegenerator isshowninFig.5.15andapproximatestothat ofacapacitance$C$chargedtoavoltageV_0whichcan be consideredtodischargethroughan inductance$L$andaresistance$R$.Inpracticeboth L and Raretheeffectiveinductanceand resistance of the leads, capacitors and the test objects.

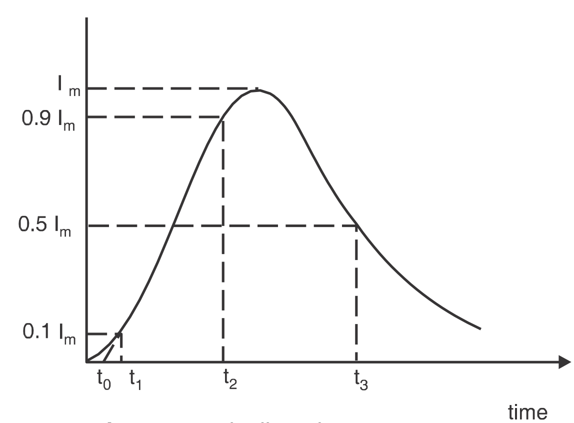


Fig.5.13 Atypicalimpulsecurrentwave

AnalysisofImpulseCurrentGeneratorRefertoFig.5.15

AfterthegapSistriggered,theLaplacetransformcurrentisgivenas

$$I(s) = \frac{V_0}{s} \frac{1}{R + sL + 1/Cs}$$

$$= \frac{V}{L} \cdot \frac{1}{s^2 + R/Ls + 1/LC}$$

$$= \frac{V}{L} \cdot \frac{1}{(s+\alpha)^2 + \omega^2}$$

where $\alpha = \frac{R}{2L}$ and $\omega = \left[\frac{1}{LC} - \frac{R^2}{4L^2}\right]^{1/2}$

or $\omega = \frac{1}{\sqrt{LC}}\left[1 - \frac{R^2C}{4L}\right]^{1/2} = \frac{1}{\sqrt{LC}}(1 - \nu^2)^{1/2}$

where $\nu = \frac{R}{2}\sqrt{\frac{C}{L}}$

TakingtheinverseLaplacewehavethecurrent

$$i(t) = \frac{V}{\omega L} e^{-\alpha t} \sin \omega t \qquad (5.25)$$

Forcurrent$i(t)$tobemaximum $\frac{di(t)}{dt} = 0$

$$\frac{di(t)}{dt} = \frac{V}{\omega L}\left[\omega e^{-\alpha t} \cos \omega t - \alpha e^{-\alpha t} \sin \omega t\right] = 0$$

$$= \frac{V}{\omega L} e^{-\alpha t}\left[\omega \cos \omega t - \alpha \sin \omega t\right] = 0$$

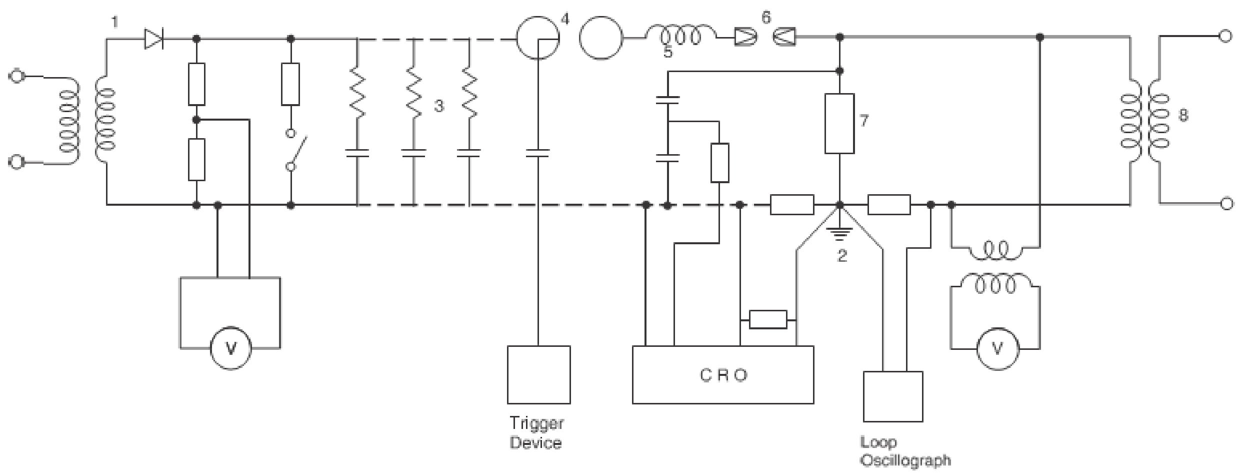


Fig. 5.14 A typical impulse current generator circuit. 4. Charging unit 4. Earthing device 5. Capacitors with damping resistors 4. Firing sphere gap. 5. Reactor coil 6. Protective sphere gap 7. Test specimen (LA) 8. Test transformer for power frequency.

1.Definetheterms(*i*)Impulsevoltages;(*ii*)Choppedwave;(*iii*)Impulseflashovervoltage;(*iv*)Impulse puncturevoltage;(*v*)Impulseratioforflashover;(*vi*)Impulseratioforpuncture.

2.DrawaneatexactequivalentcircuitofanImpulseGeneratorandindicatethesignificanceofeachparameter beingused.

3.Drawandcomparethetwosimplifiedequivalentcircuitsoftheimpulsegeneratorcircuits(*a*)and(*b*).

4. Givecompleteanalysisofcircuit‘*a*’ andshowthatthewavefrontandwavetailresistancesarephysically realisableonlyundercertaincondition.Derivethecondition.

5. Givecompleteanalysisofcircuit‘*b*’andderivetheconditionforphysicalrealisationofwavefrontand wavetailresistances.

6. Deriveanexpressionforvoltageefficiencyofasinglestageimpulsegenerator

7. Describetheconstruction,principleofoperationandapplicationofamultistageMarx'sSurgeGenerator.

8. ExplaintheGoodletcircuitofimpulsevoltagegenerationandcompareitsperformancewiththatofMarx’x Circuit.

9. Describetheconstructionofvariouscomponentsusedinthedevelopmentofanimpulsegenerator.

10. ExplainwithneatdiagramtriggeringandsynchronisationoftheimpulsegeneratorwiththeCRO.

11.Drawatypicalimpulsecurrentgeneratorcircuitandexplainitsoperationandapplication.

12.Drawaneatdiagramofahighcurrentgeneratorcircuit(equivalentcircuit)andthroughanalysisofthe circuitshowhowthewaveformcanbecontrolled.

UNIT- 6

MEASUREMENT OF HIGH VOLTAGES: Electrostatic voltmeter-principle, construction and limitation. Chubb and Fortescue method for HV AC measurement. Generating voltmeter-Principle, construction. Series resistance micro ammeter for HV DC measurements. Standard sphere gap measurements of HV AC, HV DC, and impulse voltages; Factors affecting the measurements. Potential dividers-resistance dividers capacitance dividers mixed RC potential dividers.Measurement of high impulse currents-Rogogowsky coil and Magnetic Links

10Hours

INTRODUCTION

Transientmeasurementshavemuchincommonwithmeasurementsofsteadystatequantitiesbutthe short-livednatureofthetransientswhichwearetryingtorecordintroducesspecialproblems.Frequently the transient quantity to be measured is not recorded directly because of its large magnitudes*e.g.* when ashuntisusedtomeasurecurrent,wereallymeasurethevoltageacrosstheshuntandthenweassume thatthevoltageisproportionaltothecurrent,afactwhichshouldnotbetakenforgrantedwithtransient currents.Oftenthevoltageappearingacrosstheshuntmaybeinsufficienttodrivethemeasuringdevice; itrequiresamplification.Ontheotherhand,ifthevoltagetobemeasuredistoolargetobemeasured withtheusualmeters,itmustbeattenuated.Thissuggestsanideaofameasuringsystemratherthana measuringdevice.

Measurements ofhighvoltagesandcurrentsinvolvesmuchmorecomplexproblemswhicha specialist,incommonelectricalmeasurement,doesnothavetoface.Thehighvoltageequipments havelargestraycapacitanceswithrespecttothegroundedstructuresandhencelargevoltagegradients aresetup.Apersonhandlingtheseequipmentsandthemeasuringdevicesmustbeprotectedagainst theseovervoltages.Forthis,largestructuresarerequiredtocontroltheelectricalfieldsandtoavoid flashover betweentheequipmentandthegroundedstructures.Sometimes,thesestructuresarere-quiredtocontrolheatdissipationwithinthecircuits.Therefore,thelocationandlayoutoftheequipments is very important to avoid these problems. Electromagnetic fields create problems in the measurements ofimpulsevoltagesandcurrentsandshouldbeminimized.

Thechapterisdevotedtodescribingvariousdevicesandcircuitsformeasurementofhighvoltages andcurrents.Theapplicationofthedevicetothetypeofvoltagesandcurrentsisalsodiscussed.

ELECTROSTATICVOLTMETER

The electricfieldaccordingtoCoulombisthefieldofforces.Theelectricfieldisproducedbyvoltage and,therefore,ifthefieldforcecouldbemeasured,thevoltagecanalsobemeasured.Whenevera voltageisappliedtoaparallelplateelectrodearrangement,anelectricfieldissetupbetweentheplates. Itispossibletohaveuniformelectricfieldbetweentheplateswithsuitablearrangementoftheplates. Thefieldisuniform,normaltothetwoplatesanddirectedtowardsthenegativeplate.If*A*istheareaoftheplateand *E*istheelectricfieldintensitybetweentheplatesϵthepermittivityofthemediumbetweentheplates,weknowthattheenergydensityoftheelectricfieldbetweentheplatesisgivenas,

$$W_d = \frac{1}{2} \epsilon E^2$$

Consideradifferentialvolumebetweentheplatesandparalleltotheplateswitharea *A*and thickness*dx*,theenergycontentinthisdifferentialvolume*Adx*is

Electrostaticvoltmetersmeasuretheforcebasedontheaboveequationsandarearrangedsuch thatoneoftheplatesisrigidlyfixedwhereastheotherisallowedtomove.Withthistheelectricfield getsdisturbed.Forthisreason,themovableelectrodeisallowedtomovebynotmorethanafractionof amillimetretoafewmillimetresevenforhighvoltagessothatthechangeinelectricfieldisnegligibly small.AstheforceisproportionaltosquareofV_{rms},themetercanbeusedbothfora.c.andd.c.voltage measurement.

The forcedevelopedbetweentheplatesissufficienttobeusedtomeasurethevoltage.Various designsofthevoltmeterhavebeendevelopedwhichdifferintheconstructionofelectrodearrangement andintheuseofdifferentmethodsofrestoringforcesrequiredtobalancetheelectrostaticforceof attraction.Someofthemethodsare

(*i*)Suspensionofmovingelectrodeononearmofabalance.

(*ii*)Suspensionofthemovingelectrodeonaspring.

(*iii*)Pendulоussuspensionofthemovingelectrode.

(*iv*)Torsionalsuspensionofmovingelectrode.

Thesmallmovementisgenerallytransmittedandamplifiedbyelectricaloropticalmethods.If theelectrodemovementisminimisedandthefielddistributioncanexactlybecalculated,themetercan beusedforabsolutevoltagemeasurementasthecalibrationcanbemadeintermsofthefundamental quantitiesoflengthandforce.

Fromtheexpressionfortheforce,itisclearthatforagivenvoltagetobemeasured,thehigher theforce,thegreateristheprecisionthatcanbeobtainedwiththemeter.Inordertoachievehigher forceforagivenvoltage,theareaoftheplatesshouldbelarge,thespacingbetweentheplates(*d*) shouldbesmallandsomedielectricmediumotherthanairshouldbeusedinbetweentheplates.If uniformityofelectricfieldistobemaintainedanincreaseinarea*A*mustbeaccompaniedbyanincrease intheareaofthesurroundingguardringandoftheopposingplateandtheelectrodemay,therefore, becomeundulylargespeciallyforhighervoltages.Similarlythegaplengthcannotbemadeverysmall asthisislimitedbythebreakdownstrengthofthedielectricmediumbetweentheplates.Ifairisusedas themedium,gradientsupto5kV/cmhavebeenfoundsatisfactory.ForhighergradientsvacuumorSF$_6$ gashasbeenused.

The greatestadvantageoftheelectrostaticvoltmeterisitsextremelylowloadingeffectasonly electricfieldsarerequiredtobesetup.Becauseofhighresistanceofthemediumbetweentheplates, theactivepowerlossisnegligiblysmall.Thevoltagesourceloadingis,therefore,limitedonlytothe reactivepowerrequiredtochargetheinstrumentcapacitancewhichcanbeaslowasafewpicofarads forlowvoltagevoltmeters.

The measuringsystemassuchdoesnotputanyupperlimitonthefrequencyofsupplytobe measured.However,astheloadinductanceandthemeasuringsystemcapacitanceformaseries resonance circuit,alimitisimposedonthefrequencyrange.Forlowrangevoltmeters,theupperfrequencyis generallylimitedtoafewMHz.

Fig.6.7showsaschematicdiagramofanabsoluteelectrostaticvoltmeter.Thehemispherical metaldome*D*enclosesasensitivebalance*B*whichmeasurestheforceofattractionbetweenthemovable discwhichhangsfromoneofitsarmsandthelowerplate*P*.Themovableelectrode*M*hangswitha clearanceofabove0.01cm,inacentralopeningintheupperplatewhichservesasaguard ring. The diameterofeachoftheplatesis1metre.Lightreflectedfromamirrorcarriedbythebalancebeam serves to magnify its motion and to indicate to the operator at a safe distance when a condition of equilibriumisreached.Asthespacingbetweenthetwoelectrodesislarge(about100cmsforavoltage ofabout300kV),theuniformityoftheelectricfieldismaintainedbytheguardrings*G*whichsurround thespacebetweenthediscs*M*and*P*.Theguardrings*G* aremaintainedataconstantpotentialinspace byacapacitancedividerensuringauniformspatialpotentialdistribution.Whenvoltagesintherange 10to100kVaremeasured,theaccuracyisoftheorderof0.01percent.

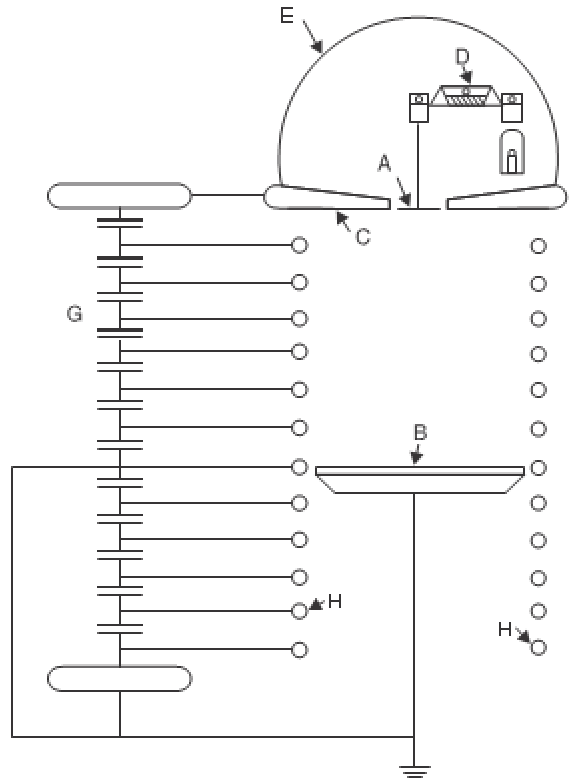


Fig. 6.7 Schematic diagram of electrostatic voltmeter

Hueterhasusedapairofspharesof100cmsdiameterforthemeasurementofhighvoltages utilisingtheelectrostaticattractiveforcebetweenthem.Thespheresarearrangedwithaverticalaxis andataspacingslightlygreaterthanthesparkingdistancefortheparticularvoltagetobemeasured. The upperhighvoltagesphereissupportedonaspringandtheextensionofspringcausedbythe electrostaticforceismagnifiedbyalamp-mirrorscalearrangement.Anaccuracyof0.5percenthas beenachievedbythearrangement.

Electrostaticvoltmetersusingcompressedgasastheinsulatingmediumhavebeendeveloped. Hereforagivenvoltagetheshortergaplengthenablestherequireduniformityofthefieldtobe maintainedwithelectrodesofsmallersizeandamorecompactsystemcanbeevolved.

Onesuch voltmeter using SF_6gashasbeenusedwhichcanmeasurevoltagesupto1000kVand accuracyisoftheorderof0.1%.Thehighvoltageelectrodeandearthedplaneprovideuniformelectric fieldwithintheregionofa5cmdiameterdiscsetina65cmdiameterguardplane.Aweighingbalanc arrangementisusedtoallowalargedampingmass.Thegaplengthcanbevariedbetween4.5,5and10cmsanddu etomaximumworkingelectricstressof100kV/cm,thevoltagerangescanbeselected to250kV,500kVand100kV.With100kV/cmasgradient,theaverageforceonthediscisfoundtobe0.8681Nequ ivalentto88.52gmwt.Thediscmovementsarekeptassmallas1μmbytheweighingbalancearrangement.

Thevoltmetersareusedforthemeasurementofhigha.c.andd.c.voltages.Themeasurementof voltageslowerthanabout50voltis,however,notpossible,astheforcesbecometoosmall.

GENERATINGVOLTMETER

Wheneverthesourceloadingisnotpermittedorwhendirectconnectiontothehighvoltagesourceisto beavoided,thegeneratingprincipleisemployedforthemeasurementofhighvoltages,Agenerating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to thevoltagetobemeasured.Similartoelectrostaticvoltmeterthegeneratingvoltmeterprovidesloss freemeasurementofd.c.anda.c.voltages.Thedeviceisdrivenbyanexternalconstantspeedmotor anddoesnotabsorbpowerorenergyfromthevoltagemeasuringsource.Theprincipleofoperationis explainedwiththehelpofFig.6.8.*H*isahighvoltageelectrodeandtheearthedelectrodeissubdivided intoasensingorpickupelectrode*P*,aguardelectrode*G*andamovableelectrode*M*,allofwhichare atthesamepotential.Thehighvoltageelectrode*H*developsanelectricfieldbetweenitselfandthe electrodes*P*,*G*and*M*.ThefieldlinesareshowninFig.6.8.Theelectricfielddensityσisalsoshown.

Ifelectrode*M*isfixedandthevoltage*V*ischanged,thefielddensityσwouldchangeandthusacurrent *i*(*t*)wouldflowbetween*P*andtheground.

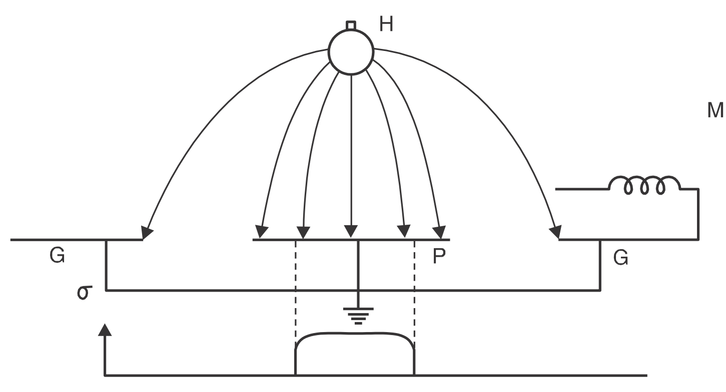


Fig.6.8 Principleofgeneratingvoltmeter

$\int \sigma(a)da$ Fig.6.10showsaschematicdiagramofageneratingvoltmeterwhichemploysrotatingvanes forvariationofcapacitance.ThehighvoltageelectrodeisconnectedtoadiscelectrodeD_3 whichis keptatafixeddistanceontheaxisoftheotherlowvoltageelectrodesD_2,D_1,andD_0.Therotor$D_0$is drivenataconstantspeedbyasynchronousmotoratasuitablespeed.TherotorvanesofD_0cause periodicchangeincapacitancebetweentheinsulateddiscD_2andthehighvoltageelectrodeD_5.The numberandshapeofvanesaresodesignedthatasuitablevariationofcapacitance(sinusodialorlinear) isachieved.Thea.c.currentisrectifiedandismeasuredusingmovingcoilmeters.Ifthecurrentis smallanamplifiermaybeusedbeforethecurrentismeasured.

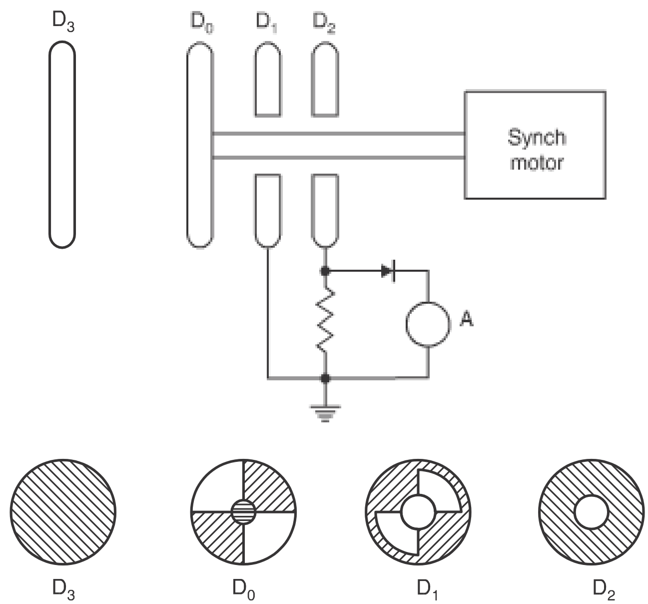


Fig.6.10 Schematicdiagramofgeneratingvoltmeter

Generatingvoltmetersarelinearscaleinstrumentsandapplicableoverawiderangeofvoltages. Thesensitivitycanbeincreasedbyincreasingtheareaofthepickupelectrodeandbyusingamplifier circuits.

Themainadvantagesofgeneratingvoltmetersare(*i*)scaleislinearandcanbeextrapolated (*ii*)sourceloadingispracticallyzero(*iii*)nodirectconnectiontothehighvoltageelectrode.

However,theyrequirecalibrationandconstructionisquitecumbersome.

Thebreakdownofinsulatingmaterialsdependsuponthemagnitudeofvoltageappliedandthe timeofapplicationofvoltage.However,ifthepeakvalueofvoltageislargeascomparedtobreakdown strength of the insulating material, the disruptive discharge phenomenon is in general caused by the instantaneousmaximumfieldgradientstressingthematerial.Variousmethodsdiscussedsofarcan measurepeakvoltagesbutbecauseofcomplexcalibrationproceduresandlimitedaccuracycallformoreconven ientandmoreaccuratemethods.Amoreconvenientthoughlessaccuratemethodwould betheuseofatestingtransformerwhereintheoutputvoltageismeasuredandrecordedandtheinput voltageisobtainedbymultiplyingtheoutputvoltagebythetransformationratio.However,herethe outputvoltagedependsupontheloadingofthesecondarywindingandwaveshapevariationiscaused bythetransformerimpedancesandhencethismethodisunacceptableforpeakvoltagemeasurements.

THECHUBB-FORTESCUEMETHOD

ChubbandFortescuesuggestedasimpleandaccuratemethodofmeasuringpeakvalueofa.c.voltages. The basiccircuitconsistsofastandardcapacitor,twodiodesandacurrentintegratingammeter (MCammeter)asshowninFig.6.11(*a*).

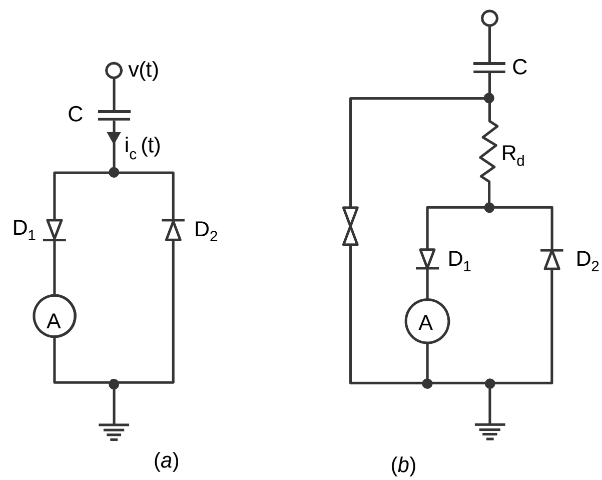


Fig.6.11(a)Basiccircuit(b)Modifiedcircuit

Thedisplacementcurrent$i_c(t)$,Fig.6.12isgivenbytherateofchangeofthechargeandhence thevoltage$V(t)$tobemeasuredflowsthroughthehighvoltagecapacitor$C$andissubdividedinto positive and negative components by the back to back connected diodes. The voltage drop across these diodescanbeneglected(1$V$for*Si*diodes)ascomparedwiththevoltagetobemeasured.Themeasuring instrument(M.C.ammeter)isincludedinoneofthebranches.Theammeterreadsthemeanvalueof thecurrent.

$$I = \frac{1}{T}\int_{t_1}^{t_2} C\frac{dv(t)}{dt}\,dt = \frac{C}{T}.2V = 2VfC \text{ or } V = \frac{I}{2fC}$$

Therelationissimilartotheoneobtainedincaseofgeneratingvoltmeters.Anincreasedcurrent wouldbeobtainedifthecurrentreacheszeromorethanonceduringonehalfcycle.Thismeansthe waveshapesofthevoltagewouldcontainmorethanonemaximaperhalfcycle.Thestandarda.c. voltagesfortestingshouldnotcontainanyharmonicsand,therefore,therecouldbeveryshortand rapidvoltagescausedbytheheavypredischarges,withinthetestcircuitwhichcouldintroduceerrorsin measurements.Toeliminatethisproblemfilteringofa.c.voltageiscarriedoutbyintroducingadamping resistorinbetweenthecapacitorandthediodecircuit,Fig.6.11(*b*).

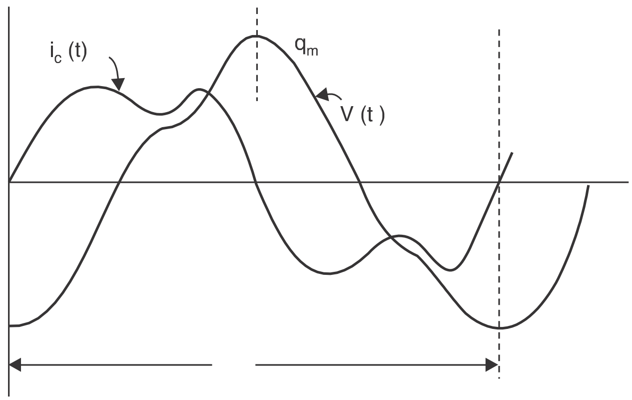
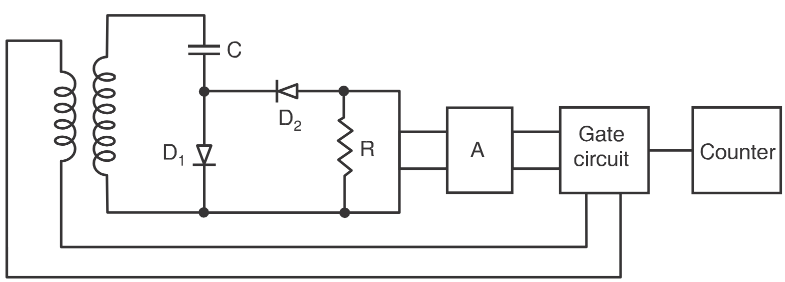


Fig.6.12

Also,iffullwaverectifierisusedinsteadofthehalfwaveasshowninFig.6.11,thefactor2in thedenominatoroftheaboveequationshouldbereplacedby6.Sincethefrequency*f*,thecapacitance *C*andcurrent*I*canbemeasuredaccurately,themeasurementofsymmetricala.c.voltagesusingChubb andFortescuemethodisquiteaccurateanditcanbeusedforcalibrationofotherpeakvoltagemeasuring devices.

Fig.6.13showsadigitalpeakvoltagemeasuringcircuit.Incontrasttothemethoddiscussedjust now,therectifiedcurrentisnotmeasureddirectly,insteadaproportionalanalogvoltagesignalisderived whichisthenconvertedintoaproportionalmediumfrequencyforusingavoltagetofrequencyconvertor (BlockAinFig.6.13).Thefrequencyratiof_m/fismeasuredwithagatecircuitcontrolledbythea.c.

powerfrequency(supplyfrequency*f*)andacounterthatopensforanadjustablenumberofperiod $\Delta t=p/f$.Thenumberofcycles*n*countedduringthisintervalis



$\frac{dq(t)}{} \quad \frac{d}{}\left[\quad\right]$

Where$\sigma(a)$istheelectricfielddensityorchargedensityalongsomepathandisassumedconstantover the differential area$da$of the pick up electrode. In this case$\sigma(a)$ is a function of time also and$\int da$ the areaofthepickupelectrode$P$exposedtotheelectricfield.

However,ifthevoltage$V$tobemeasuredisconstant(d.cvoltage),acurrent$i(t)$willflowonly ifitismoved*i.e.*now$\sigma(a)$willnotbefunctionoftimebutthecharge$q$ischangingbecausetheareaof thepickupelectrodeexposedtotheelectricfieldischanging.Thecurrent$i(t)$isgivenby

PeakVoltmeterswithPotentialDividers

Passivecircuitsarenotveryfrequentlyusedthesedaysformeasurementofthepeakvalueofa.c.or impulsevoltages.Thedevelopmentoffullyintegratedoperationalamplifiersandotherelectroniccircuits hasmadeitpossibletosampleandholdsuchvoltagesandthusmakemeasurementsand,therefore, havereplacedtheconventionalpassivecircuits.However,itistobenotedthatifthepassivecircuitsare designed properly,theyprovidesimplicityandadequateaccuracyandhenceasmalldescriptionof thesecircuitsisinorder.Passivecircuitsarecheap, reliable andhaveahighorderofelectromagnetic compatibility. However, in contrast, the most sophisticatedelectronicinstrumentsarecostlierand theirelectromagneticcompatibility(EMC)islow.

The passive circuits cannot measure high voltages directly and use potential dividers preferablyofthecapacitancetype.

Fig. 6.14 shows a simple peak voltmeter circuitconsistingofacapacitorvoltagedivider whichreducesthevoltage$V$tobemeasuredtoa lowvoltageV_m.

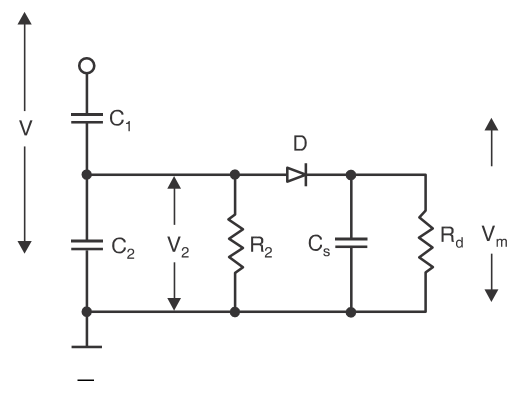


Fig.6.14 Peakvoltmeter

SupposeR_2 andR_d are notpresentandthesupplyvoltageis$V$.Thevoltageacrossthestorage capacitor$C_s$willbeequaltothepeakvalueofvoltageacrossC_2assumingvoltagedropacrossthediode tobenegligiblysmall.Thevoltagecouldbemeasuredbyanelectrostaticvoltmeterorothersuitable voltmeterswithveryhighinputimpedance.Ifthereversecurrentthroughthediodeisverysmalland thedischarge time constant of the storage capacitor very large, the storage capacitor will not discharge significantly for a long time and hence it will hold the voltage to its value for a long time. If now, $V$is decreased,thevoltageV_2decreasesproportionatelyandsincenowthevoltageacrossC_2issmallerthan thevoltageacross C_s towhichitisalreadycharged,therefore,thediodedoesnotconductandthe voltageacross$C_s$doesnotfollowthevoltageacrossC_4. Hence,adischargeresistorR_d mustbeintroduced intothecircuitsothatthevoltageacross$C_s$followsthevoltageacrossC_4. Frommeasurementpointof viewitisdesirablethatthequantitytobemeasuredshouldbeindicatedbythemeterwithinafew secondsandhence$R_d$issochosenthat $R_dC_s \approx 1$sec.Asaresultofthis,followingerrorsareintroduced. WiththeconnectionofR_d,thevoltageacross$C_s$willdecreasecontinuouslyevenwhentheinputvoltage iskeptconstant.Also,itwilldischargethecapacitorC_2andthemeanpotentialof$V_2(t)$willgaina negatived.c.component.HencealeakageresistorR_2mustbeinsertedinparallelwithC_2toequalise theseunipolardischargecurrents.Theseconderrorcorrespondstothevoltageshapeacrossthestorage capacitorwhichcontainsrippleandisduetothedischargeofthecapacitorC_s.Iftheinputimpedance ofthe measuring device is very high, the ripple is independent of the meter being used. The error is approximately proportional to the ripple factor and is thus frequency dependent as the discharge time-constantcannotbechanged.IfR_dC_s=1sec,thedischargeerroramountsto1%for50Hzand0.33%.

for150Hz.Thethirdsourceoferrorisrelatedtothisdischargeerror.Duringtheconductiontime (whenthevoltageacross$C_s$islowerthanthatacrossC_2 becauseofdischargeofC_s throughR_d)ofthe diodethestoragecapacitor$C_s$is rechargedtothepeakvalueandthus$C_s$becomesparallelwithC_4. If dischargeerrorise_d,rechargeerrore_r isgivenby

$$e_r = 2e_d \frac{C_s}{C_1 + C_2 + C_s}$$

HenceCsshouldbesmallascomparedwith C_2tokeepdowntherechargeerror.

Ithasalsobeenobservedthatinorderto keep the overall error to a low value, it is desirable tohaveahighvalueofR_4. Thesameeffectcanbe obtainedbyprovidinganequalisingarmtothelow voltagearmofthevoltagedividerasshownin Fig.6.15.Thisisaccomplishedbytheadditionof

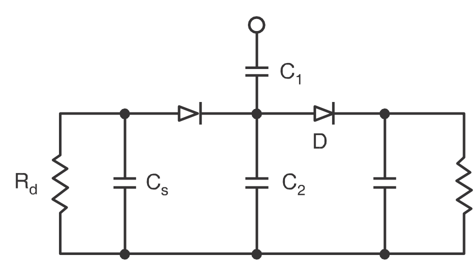


Fig.6.15 Modifiedpeakvoltmetercircuit

asecondnetworkcomprisingdiode,$C_s$and$R_d$fornegativepolaritycurrentstothecircuitshowninFig. 6.16.Withthis,thed.c.currentsinbothbranchesareoppositeinpolarityandequaliseeachother.The errorsduetoR_2 arethuseliminated.

RabusdevelopedanothercircuitshowninFig.6.16.toreduceerrorsduetoresistances.Two storagecapacitorsareconnectedbyaresistor$R_s$withineverybranchandbotharedischargedbyonly oneresistanceR_d.

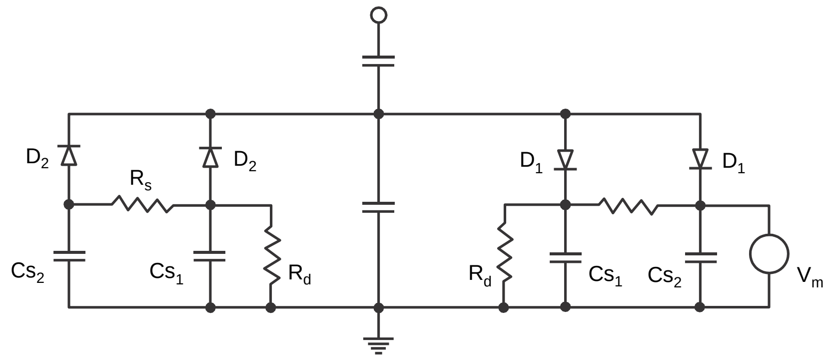


Fig.6.16 Two-wayboostercircuitdesignedbyRabus

HerebecauseofthepresenceofR_s,thedischargeofthestoragecapacitorC_{s2}isdelayedand hencetheinherentdischargeerror$e_d$isreduced.However,sincethesearetwostoragecapacitorswithin onebranch,theywoulddrawmorechargefromthecapacitorC_2andhencetherechargeerror$e_r$would increase.Itis,therefore,amatterofdesigningvariouselementsinthecircuitsothatthetotalsumofall theerrorsisaminimum.Ithasbeenobservedthatwiththecommonlyusedcircuitelementsinthe voltagedividers,theerrorcanbekepttowellwithinabout1%evenforfrequenciesbelow20Hz.

ThecapacitorC_1hastowithstandhighvoltagetobemeasuredandisalwaysplacedwithinthe testareawhereasthelowvoltagearmC_2includingthepeakcircuitandinstrumentformameasuring unitlocatedinthecontrolarea.Henceacoaxialcableisalwaysrequiredtoconnectthetwoareas.The cable capacitancecomesparallelwiththecapacitance C_2 whichisusuallychangedinstepsifthe voltage to be measured is changed. A change of the length of the cable would, thus, also require recalibrationofthesystem.Thesheathofthecoaxialcablepicksuptheelectrostaticfieldsandthus preventsthepenetrationofthisfieldtothecoreoftheconductor.Also,eventhoughtransientmagnetic fieldswillpenetrateintothecoreofthecable,noappreciablevoltage(extraneousofnoise)isinduced due to the symmetrical arrangement and hence a coaxial cable provides a good connection between the two areas.Whenever,adischargetakesplaceatthehighvoltageendofcapacitor C_1 tothecable connectionwherethecurrentlooksintoachangeinimpedanceahighvoltageofshortdurationmaybe builtupatthelowvoltageendofthecapacitorC_1 whichmustbelimitedbyusinganovervoltage protectiondevice(protectiongap).Thesedeviceswillalsopreventcompletedamageofthemeasuring circuitiftheinsulationofC_1fails.

SPHEREGAP

Spheregapisbynowconsideredasoneofthestandardmethodsforthemeasurementofpeakvalueof d.c.,a.c.andimpulsevoltagesandisusedforcheckingthevoltmetersandothervoltagemeasuring devicesusedinhighvoltagetestcircuits.Twoidenticalmetallicspheresseparatedbycertaindistance formaspheregap.Thespheregapcanbeusedformeasurementofimpulsevoltageofeitherpolarity providedthattheimpulseisofastandardwaveformandhaswavefronttimeatleast1microsec.and wavetailtimeof5microsec.Also,thegaplengthbetweenthesphereshouldnotexceedasphere radius.Iftheseconditionsaresatisfiedandthespecificationsregardingtheshape,mounting,clearancesofthesp heresaremet,theresultsobtainedbytheuseofspheregapsarereliabletowithin±3%.Ithas beensuggestedinstandardspecificationthatinplaceswheretheavailabilityofultravioletradiationis low,irradiationofthegapbyradioactiveorotherionizingmediashouldbeusedwhenvoltagesof magnitude less than 50 kV are being measured or where higher voltages with accurate results are to be obtained.

In ordertounderstandtheimportanceofirradiationofspheregapformeasurementofimpulse voltagesespeciallywhichareofshortduration,itisnecessarytounderstandthetime-laginvolvedin thedevelopmentofsparkprocess.Thistimelagconsistsoftwocomponents—(*i*)Thestatisticaltime-lagcausedbytheneedofanelectrontoappearinthegapduringtheapplicationofthevoltage.(*ii*)The formativetimelagwhichisthetimerequiredforthebreakdowntodeveloponceinitiated.

Thestatisticaltime-lagdependsontheirradiationlevelofthegap.Ifthegapissufficiently irradiatedsothatanelectronexistsinthegaptoinitiatethesparkprocessandifthegapissubjectedto animpulsevoltage,thebreakdownwilltakeplacewhenthepeakvoltageexceedsthed.c.breakdown value.However,iftheirradiationlevelislow,thevoltagemustbemaintainedabovethed.c.break-downvalueforalongerperiodbeforeanelectronappears.Variousmethodshavebeenusedforirradia- tion*e.g.* radioactivematerial,ultravioletilluminationassuppliedbymercuryarclampandcoronadischarges.

Ithasbeenobservedthatlargevariationcanoccurinthestatisticaltime-lagcharacteristicofa gap whenilluminatedbyaspecifiedlightsource,unlessthecathodeconditionsarealsopreciselyspecified.

Irradiation byradioactivematerialshastheadvantageinthattheycanformastablesourceof irradiationandthattheyproduceanamountofionisationinthegapwhichislargelyindependentofthe gap voltageandofthesurfaceconditionsoftheelectrode.Theradioactivematerialmaybeplaced insidehighvoltageelectrodeclosebehindthesparkingsurfaceortheradioactivematerialmayform thesparkingsurface.

Theinfluenceofthelightfromtheimpulsegeneratorsparkgapontheoperationofthesphere gapshasbeenstudied.Heretheilluminationisintenseandoccursattheexactinstantwhenitisre-quired,namely,attheinstantofapplicationofthevoltagewavetothespheregap.

Theformativetimelagdependsmainlyuponthemechanismofsparkgrowth.Incaseofsecond-aryelectronemission,itisthetransittimetakenbythepositiveiontotravelfromanodetocathodethat decidesthatformativetimelag.Theformativetime-lagdecreaseswiththeappliedovervoltageand increasewithgaplengthandfieldnon-uniformity.

SpecificationsonSpheresandAssociatedAccessories

Thespheresshouldbesomadethattheirsurfacesaresmoothandtheircurvaturesasuniformaspossible. Thecurvatureshouldbemeasuredbyaspherometeratvariouspositionsoveranareaenclosedbya circleofradius0.3*D*aboutthesparkingpointwhere *D*isthediameterofthesphereandsparking pointsonthetwospheresarethosewhichareatminimumdistancesfromeachother.

Forsmallersize,thespheresareplacedinhorizontalconfigurationwhereaslargesizes(diameters), thespheresaremountedwiththeaxisofthespheregapsverticalandthelowersphereisgrounded.In eithercase,itisimportantthatthespheresshouldbesoplacedthatthespacebetweenspheresisfree fromexternalelectricfieldsandfrombodieswhichmayaffectthefieldbetweenthespheres(Figs.6.1 and6.2).

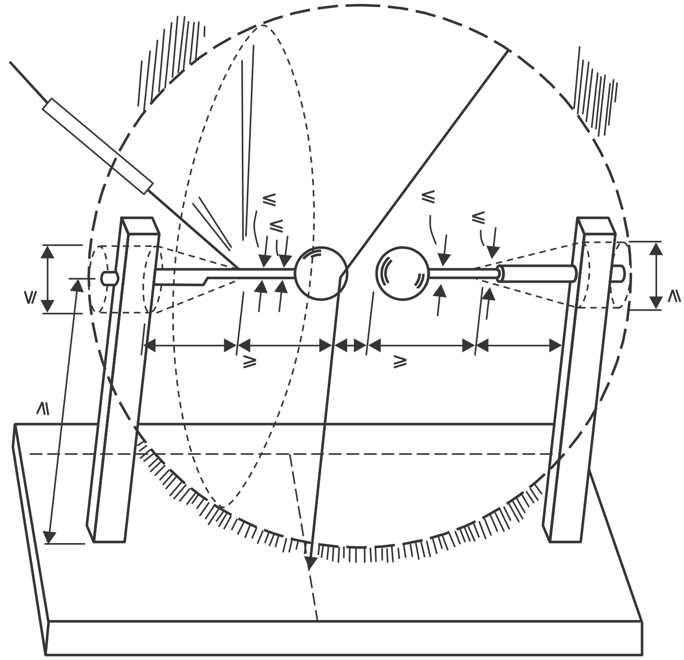


Fig.6.1

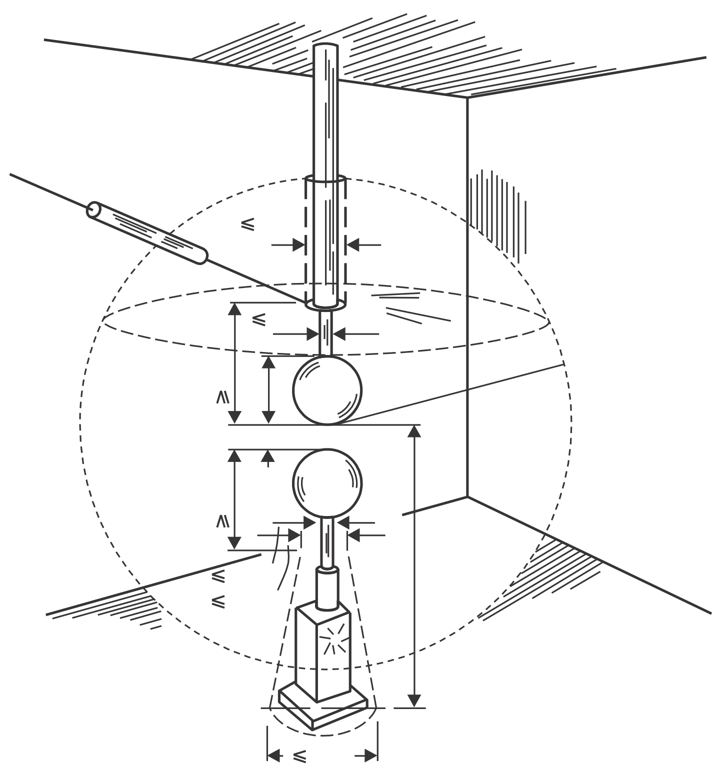


Fig.6.2

AccordingtoBSS358:1939,whenonesphereisgrounded,thedistancefromthesparking pointofthehighvoltagespheretotheequivalentearthplanetowhichtheearthedsphereisconnected shouldliewithinthelimitsasgiveninTable6.4.

Table6.1

Heightofsparkingpointofhighvoltagesphereabovetheequivalentearthplane.

***S*=Sparkingpointdistance**

SphereDiameter	*S<0.5D*		*S>0.5D*	
D	*Maxm. Height*	*Min. Height*	*Maxm. Height*	*Min. Height*
Upto 25cms.	7D	10S	7D	5D
50cms.	6D	8S	6D	4D
75cms.	6D	8S	6D	4D
100cms.	5D	7S	5D	5.5D
150cms.	4D	6S	4D	3D
200cms.	4D	6S	4D	3D

Inordertoavoidcoronadischarge,theshankssupportingthespheresshouldbefreefromsharp edgesandcorners.Thedistanceofthesparkingpointfromanyconductingsurfaceexcepttheshanks shouldbegreaterthan

$$\left(25+\frac{V}{3}\right)\text{cms}$$

where *V*is the peak voltage is kV to be measured. When large spheres are used for the measurement of lowvoltagesthelimitingdistanceshouldnotbelessthanaspherediameter.

Ithasbeenobservedthatthemetalofwhichthespheresaremadedoesnotaffecttheaccuracyof measurements MSS 358: 1939 states that the spheres may be made of brass, bronze, steel, copper, aluminiumorlightalloys.Theonlyrequirementisthatthesurfacesofthesespheresshouldbeclean, freefromgreasefilms,dustordepositedmoisture.Also,thegapbetweenthespheresshouldbekept freefromfloatingdustparticles,fibresetc.

Forpowerfrequencytests,aprotectiveresistancewithavalueof1Ω/*V*shouldbeconnectedin betweenthespheresandthetestequipmenttolimitthedischargecurrentandtopreventhighfrequency oscillations in the circuit which may otherwise result in excessive pitting of the spheres. For higher frequencies,thevoltagedropwouldincreaseanditisnecessarytohaveasmallervalueoftheresistance. Forimpulsevoltagetheprotectiveresistorsarenotrequired.Iftheconditionsofthespheresandits associatedaccessoriesasgivenabovearesatisfied,thesphereswillsparkatapeakvoltagewhichwill beclosetothenominalvalueshowninTable6.4.Thesecalibrationvaluesrelatetoatemperatureof 20°Candpressureof760mmHg.Fora.c.andimpulsevoltages,thetablesareconsideredtobeaccurate within±3%forgaplengthsupto0.5*D*.Thetablesarenotvalidforgaplengthslessthan0.05*D*and impulsevoltageslessthan10kV.Ifthegaplengthisgreaterthan0.5*D*,theresultsarelessaccurateand areshowninbrackets.

Table6.2

Spheregapwithonesphereearthed

Peakvalueofdisruptivedischargevoltages(50%forimpulsetests)arevalidfor(*i*)alternatingvoltages (*ii*)d.c.voltageofeitherpolarity(*iii*)negativelightningandswitchingimpulsevoltages

SphereGap Spacingmm	*VoltageKVPeak Spherediaincm.*						
	14.5	25	50	75	100	150	200
10	34.7						
20	59.0						
30	85	86					
40	108	112					
50	129	137	138	138	138	138	
75	167	195	202	203	203	203	203
100	(195)	244	263	265	266	266	266
125	(214)	282	320	327	330	330	330
150		(314)	373	387	390	390	390
175		(342)	420	443	443	450	450
200		(366)	460	492	510	510	510
250		(400)	530	585	615	630	630
300			(585)	665	710	745	750
350			(630)	735	800	850	855
400			(670)	(800)	875	955	975
450			(700)	(850)	945	1050	1080
500			(730)	(895)	1010	1130	1180
600				(970)	(1110)	1280	1340
700				(1025)	(1200)	1390	1480
800					(1260)	1490	1600
900					(1320)	1580	1720
1000					(1360)	1660	1840
1100						1730	1940
1200						1800	2020
1300						1870	2100
1400						1920	2180
1500						1960	2250
1600							2320
1700							2370
1800							2410
1900							2460
2000							2490

Duetodustandfibrepresentintheair,themeasurementofd.c.voltagesisgenerallysubjectto largererrors.Heretheaccuracyiswithin±5%providedthespacingislessthan0.4*D*andexcessive dustisnotpresent.

Theprocedureforhighvoltagemeasurementusingspheregapsdependsuponthetypeofvoltage tobemeasured.

Table6.3

SphereGapwithonespheregrounded
Peakvaluesofdisruptivedischargevoltages(50%values).
Positivelightningandswitchingimpulsevoltages

SphereGap	*PeakVoltagekV* *Spherediaincms*						
Spacingmm	14.5	25	50	75	100	150	200
10	34.7						
20	59	59					
30	85.5	86					
40	110	112					
50	134	138	138	138	138	138	138
75	(181)	199	203	202	203	203	203
100	(215)	254	263	265	266	266	266
125	(239)	299	323	327	330	330	330
150		(337)	380	387	390	390	390
175		(368)	432	447	450	450	450
200		(395)	480	505	510	510	510
250		(433)	555	605	620	630	630
300			(620)	695	725	745	760
350			(670)	770	815	858	820
400			(715)	(835)	900	965	980
450			(745)	(890)	980	1060	1090
500			(775)	(940)	1040	1150	1190
600				(1020)	(1150)	(1310)	1380
700				(1070)	(1240)	(1430)	1550
750				(1090)	(1280)	(1480)	1620
800					(1310)	(1530)	1690
900					(1370)	(1630)	(1820)
1000					(1410)	(1720)	1930
1100						(1790)	(2030)
1200						(1860)	(2120)

Forthemeasurementofa.c.ord.c.voltage,areducedvoltageisappliedtobeginwithsothatthe switchingtransientdoesnotflashoverthespheregapandthenthevoltageisincreasedgraduallytillthe gapbreaksdown.Alternativelythevoltageisappliedacrossarelativelylargegapandthespacingis

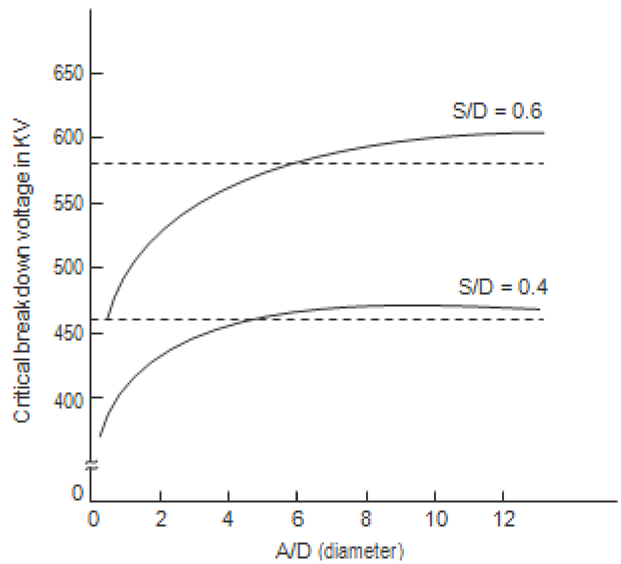


Fig. 6.3 Breakdown voltage as a function of A/D

WhereΔV= per cent reduction in voltage in the breakdown voltage from the value when the clearancewas14.6*D*,and*m*and*C*arethefactorsdependentontheratio*S/D*.

Fiegeland Keenhavestudiedtheinfluenceofnearbygroundplaneonimpulsebreakdown voltageofa50cmdiameterspheregapusing4.5/40microsec.negativepolarityimpulsewave.Fig.6.3 showsthebreakdownvoltageasafunctionof*A*/*D* forvariousvaluesof*S/D*.Thevoltagevalueswere correctedforrelativeairdensity.

It is observed that the voltage increases with increase in the ratio*A/D*. The results have been comparedwiththosegiveninTable6.2andrepresentedinFig.6.3bydashedlines.Theresultsalso agreewiththerecommendationregardingtheminimumandmaximumvaluesof*A/D*asgiveninTable 6.4.

InfluenceofHumidity

Kuffelhasstudiedtheeffectofthehumidityonthebreakdownvoltagebyusingspheresof2cmsto 25 cmsdiametersanduniformfieldelectrodes.Theeffectwasfoundtobemaximumintheregion0.4 mmHg.andthereafterthechangewasdecreased.Between4–17mmHg.therelationbetweenbreakdown voltageandhumiditywaspracticallylinearforspacinglessthanthatwhichgavethemaximumhumidity effect.Fig.6.4showstheeffectofhumidityonthebreakdownvoltageofa25cmdiameterspherewith spacingof1cmwhena.c.andd.cvoltagesareapplied.Itcanbeseenthat

(*i*)Thea.c.breakdownvoltageisslightlylessthand.c.voltage.

(*ii*)Thebreakdownvoltageincreaseswiththepartialpressureofwatervapour.

Ithasalsobeenobservedthat

(*i*)Thehumidityeffectincreaseswiththesizeofspheresandislargestforuniformfieldelec- trodes.

(*ii*)Thevoltagechangeforagivenhumiditychangeincreasewithgaplength.

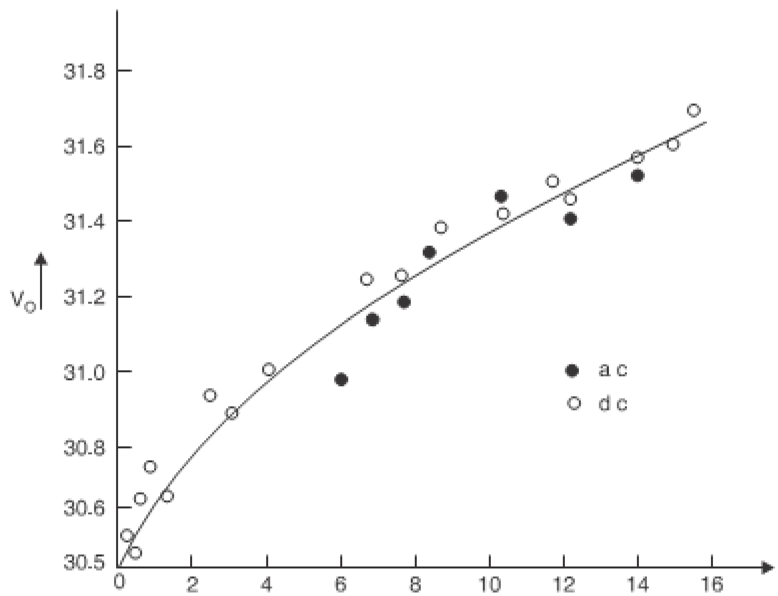


Fig. 6.4 Breakdown voltage humidity relation for a.c. and d.c. for 4.0 cm gap between 25 cms diameter spheres

Theincreaseinbreakdownvoltagewithincreaseinpartialpressureofwatervapourandthis increaseinvoltagewithincreaseingaplengthisduetotherelativevaluesofionisationandattachment coefficients in air. The water particles readily attach free electrons, forming negative ions. These ions thereforeslowdownandareunabletoioniseneutralmoleculesunderfieldconditionsinwhichelectrons will readilyionise.Ithas beenobservedthatwithinthehumidityrangeof4to17g/m^3 (relative humidityof25to95%for20°Ctemperature)therelativeincreaseofbreakdownvoltageisfoundtobe between0.2 to 0.35%pergm/m^3 forthelargestsphereofdiameter100cmsandgaplengthupto 50cms.

InfluenceofDustParticles

Whenadustparticleisfloatingbetweenthegapthisresultsintoerraticbreakdowninhomogeneousor slightlyinhomogenouselectrodeconfigurations.Whenthedustparticlecomesincontactwithone electrode under the application of d.c. voltage, it gets charged to the polarity of the electrode and gets attracted by the opposite electrode due to the field forces and the breakdown is triggered shortly before arrival. Gaps subjected to a.c. voltages are also sensitive to dust particles but the probability of erratic breakdownisless.Underd.c.voltageserraticbreakdownsoccurwithinafewminutesevenforvoltages aslow as 80% of the nominal breakdown voltages. This is a major problem, with high d.c. voltage measurementswithspheregaps.

UNIFORMFIELDSPARKGAPS

Brucesuggestedtheuseofuniformfieldsparkgapsforthemeasurementsofa.c.,d.c.andimpulse voltages.Thesegapsprovideaccuracytowithin0.2%fora.c.voltagemeasurementsanappreciableimproveme ntascomparedwiththeequivalentspheregaparrangement.Fig.6.5showsahalf-contour ofoneelectrodehavingplanesparkingsurfaceswithedgesofgraduallyincreasingcurvature.

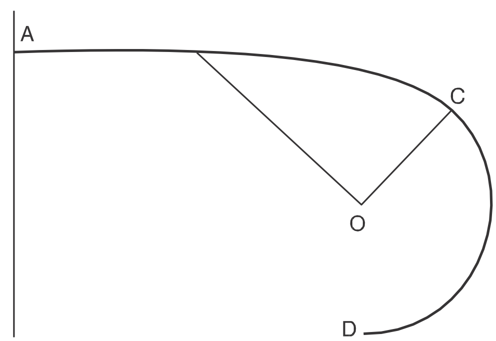


Fig.6.5 Halfcontourofuniformsparkgap

Theportion*AB*isflat,thetotaldiameteroftheflatportionbeinggreaterthanthemaximum spacingbetweentheelectrodes.Theportion*BC*consistsofasinecurvebasedontheaxes*OB*and*OC*andgivenby $XY = CO \sin(BX/BO.\pi/2)$.*CD*isanarcofacirclewithcentreat*O*.

Bruceshowedthatthebreakdownvoltage*V*ofagapoflength *S*cmsinairat20°Cand760mm Hg.pressureiswithin0.2percentofthevaluegivenbytheempiricalrelation.

$$V = 26.22S + 6.08\sqrt{S}$$

Thisequation,therefore,replacesTables6.2and6.3whicharenecessaryforspheregaps.This is a great advantage, that is, if the spacing between the spheres for breakdown is known the breakdown voltagecanbecalculated.

Theotheradvantagesofuniformfieldsparkgapsare

(*i*)Noinfluenceofnearbyearthedobjects

(*ii*)Nopolarityeffect.

However,thedisadvantagesare

(*i*)Veryaccuratemechanicalfinishoftheelectrodeisrequired.

(*ii*)Carefulparallelalignmentofthetwoelectrodes.

(*iii*)Influenceofdustbringsinerraticbreakdownofthegap.Thisismuchmoreseriousinthese gaps ascomparedwithspheregapsasthehighlystressedelectrodeareasbecomemuch larger.

Therefore,auniformfieldgapisnormallynotusedforvoltagemeasurements.

RODGAPS

Arodgapmaybeusedtomeasurethepeakvalueofpowerfrequencyandimpulsevoltages.Thegap usuallyconsistsoftwo4.27cmsquarerodelectrodessquareinsectionattheirendandaremountedon insulatingstandssothatalengthofrodequaltoorgreaterthanonehalfofthegapspacingoverhangs theinneredgeofthesupport.ThebreakdownvoltagesasfoundinAmericanstandardsfordifferent gaplengthsat25°C,760mmHg.pressureandwithwatervapourpressureof15.5mmHg.arereproducedhere

Gaplengthin Cms.	*BreakdownVoltageKV peak*	*GapLengthincms.*	*Breakdown VoltageKVpeak*
2	26	80	435
4	47	90	488
6	62	100	537
8	72	120	642
10	81	140	744
15	102	160	847
20	124	180	950
25	147	200	1054
30	172	220	1160
35	198		
40	225		
50	278		
60	332		
70	382		

The breakdown voltage is a rodgap increasesmoreorlesslinearlywithincreasingrelativeair densityoverthenormalvariationsinatmosphericpressure.Also,thebreakdownvoltageincreaseswith increasingrelativehumidity,thestandardhumiditybeingtakenas15.5mmHg.

Because ofthelargevariationinbreakdownvoltageforthesamespacingandtheuncertainties associatedwiththeinfluenceofhumidity,rodgapsarenolongerusedformeasurementofa.c.or impulse voltages. However, more recent investigations have shown that these rods can be used for d.c.measurementprovidedcertainregulationsregardingtheelectrodeconfigurationsareobserved.The arrangementconsistsoftwohemisphericallycappedrodsofabout20mmdiameterasshowninFig.6.6.

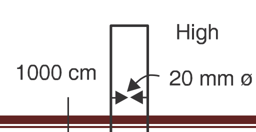


Fig.6.6 ElectrodearrangementforarodgaptomeasureHV

The earthedelectrodemustbelongenoughtoinitiatepositivebreakdownstreamersifthehigh voltagerodisthecathode.Withthisarrangement,thebreakdownvoltagewillalwaysbeinitiatedby positivestreamersforboththepolaritiesthusgivingaverysmallvariationandbeinghumiditydependent. Exceptforlowvoltages(lessthan120kV),wheretheaccuracyislow,thebreakdownvoltagecanbe givenbytheempiricalrelation.

$$V = \delta(A+BS)\ 4 \quad \sqrt{5.1\times10^{-2}(h+8.65)}\mathrm{kV}$$

where*h*istheabsolutehumidityingm/m^3 andvariesbetween4and20gm/m^3 intheaboverelation. The breakdown voltage is linearly related with thegap spacing and theslopeoftherelation *B*=5.1kV/cmandisfoundtobeindependentofthepolarityofvoltage.Howeverconstant*A*ispolarity dependentandhasthevalues

A=20kVforpositivepolarity

=15kVfornegativepolarityofthehighvoltageelectrode.

Theaccuracyoftheaboverelationisbetterthan±20%and,therefore,providesbetteraccuracy evenascomparedtoaspheregap.

IMPULSEVOLTAGEMEASUREMENTSUSINGVOLTAGEDIVIDERS

Iftheamplitudesoftheimpulsevoltageisnothighandisintherangeofafewkilovolts,itispossible tomeasure them even when these are of short duration by using CROS. However, if the voltages to be measured are of high magnitude of the order of magavolts which normally is the case for testing and researchpurposes,variousproblemsarise.Thevoltagedividersrequiredareofspecialdesignandneed athoroughunderstandingoftheinteractionpresentinthesevoltagedividingsystems.Fig.6.17shows a layoutofavoltagetestingcircuitwithinahighvoltagetestingarea.Thevoltagegenerator*G*is connectedtoatestobject—*T*throughalead*L*.

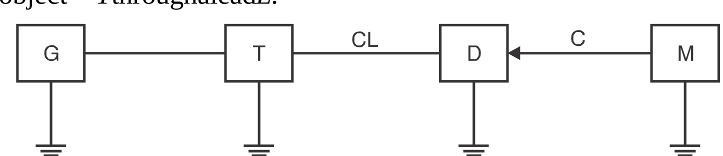


Fig.6.17 Basicvoltagetestingcircuit

Thesethreeelementsformavoltagegeneratingsystem.Thelead*L*consistsof aleadwireand aresistancetodamposcillationortolimitshort-circuitcurrentsifofthetestobjectfails.Themeasuring systemstartsattheterminalsofthetestobjectandconsistsofaconnectinglead*CL*tothevoltage divider*D*. The output of the divider is fed to the measuring instrument (CRO etc.)*M*. The appropriate groundreturnshouldassurelowvoltagedropsforevenhighlytransientphenomenaandkeeptheground potentialofzeroasfaraspossible.

Itis to be noted that the test object is a predominantly capacitive element and thus this forms an oscillatorycircuitwiththeinductanceoftheload.Theseoscillationsarelikelytobeexcitedbyany steep voltage rise from the generator output, but will only partly be detected by the voltage divider. A resistorinserieswiththeconnectingleadsdampsouttheseoscillations.Thevoltagedividershould always be connected outside the generator circuit towards the load circuit (Test object) for accurate measurement.Incaseitisconnectedwithinthegeneratorcircuit,andthetestobjectdischarges(chopped wave)thewholegeneratorincludingvoltagedividerwillbedischargedbythisshortcircuitatthetest objectandthusthevoltagedividerisloadedbythevoltagedropacrossthelead*L*.Asaresult,the voltagemeasurementwillbewrong.

Yetforanotherreason,thevoltagedividershouldbelocatedawayfromthegeneratorcircuit. Thedividerscannotbeshieldedagainstexternalfields.Allobjectsinthevicinityofthedividerwhich may acquiretransientpotentialsduringatestwilldisturbthefielddistributionandthusthedivider performance.Therefore,theconnectinglead*CL*isanintegralpartofthepotentialdividercircuit.

Inordertoavoidelectromagneticinterferencebetweenthemeasuringinstrument*M*and*C*the highvoltagetestarea,thelengthofthedelaycableshouldbeadequatelychosen.Veryshortlengthof thecablecanbeusedonlyifthemeasuringinstrumenthashighlevelofelectromagneticcompatibility (EMC). For any type of voltage to be measured, the cable should be co-axial type. The outer conductor providesashieldagainsttheelectrostaticfieldandthuspreventsthepenetrationofthisfieldtothe innerconductor.Eventhough,thetransientmagneticfieldswillpenetrateintothecable,noappreciable voltageisinducedduetothesymmetricalarrangement.Ordinarycoaxialcableswithbraidedshields maywellbeusedford.c.anda.c.voltages.However,forimpulsevoltagemeasurementdoubleshielded cableswithpredominentlytwoinsulatedbraidedshieldswillbeusedforbetteraccuracy.

Duringdisruptionoftestobject,veryheavytransientcurrentflowandhencethepotentialofthe groundmayrisetodangerouslyhighvaluesifproperearthingisnotprovided.Forthis,largemetal sheetsofhighlyconductingmaterialsuchascopperoraluminiumareused.Mostofthemodernhigh voltagelaboratoriesprovidesuchgroundreturnalongwithaFaradayCageforacompleteshieldingof thelaboratory.Expandedmetalsheetsgivesimilarperformance.Atleastmetaltapesoflargewidth shouldbeusedtoreducetheimpedance.

VoltageDivider

Voltagesdividersfora.c.,d.c.orimpulsevoltagesmayconsistofresistorsorcapacitorsoraconvenient combination of these elements. Inductors are normally not used as voltage dividing elements as pure inductances of proper magnitudes without stray capacitance cannot be built and also these inductances wouldotherwiseformoscillatorycircuitwiththeinherentcapacitanceofthetestobjectandthismay leadtoinaccuracyinmeasurementandhighvoltagesinthemeasuringcircuit.Theheightofavoltage dividerdependsupontheflashovervoltageandthisfollowsfromtheratedmaximumvoltageapplied. Now,thepotentialdistributionmaynotbeuniformandhencetheheightalsodependsuponthedesign ofthehighvoltageelectrode,thetopelectrode.Forvoltagesinthemegavoltrange,theheightofthe dividerbecomeslarge.Asathumbrulefollowingclearancesbetweentopelectrodeandgroundmaybe assumed.

4.5to3metres/MVford.c.voltages.
2to4.5m/MVforlightningimpulsevoltages.
Morethan5m/MVrmsfora.c.voltages.
Morethan4m/MVforswitchingimpulsevoltage.

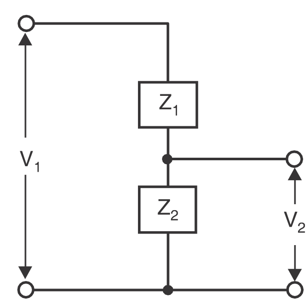


Fig.6.18 Basicdiagramofapoten-tialdividercircuit

Thepotentialdividerismostsimplyrepresentedbytwo impedancesZ_1 andZ_2 connectedinseriesandthesamplevoltage requiredformeasurementistakenfromacrossZ_2,Fig.6.18.

IfthevoltagetobemeasuredisV_1andsampledvoltageV_2, then

$$V_2 = \frac{Z_2}{Z_1 + Z_2} V_1$$

Iftheimpedancesarepureresistances

$$V_2 = \frac{R_2}{R_1 + R_2} V_1$$

The voltage V_2 isnormallyonlyafewhundredvoltsandhencethevalueof Z_2 issochosenthat V_2 acrossitgivessufficientdeflectiononaCRO.Therefore,mostofthevoltagedropisavailableacrosstheimpedance Z_1 andsincethevoltagetobemeasuredisinmegavoltthelengthof Z_1 islarge whichresultininaccuratemeasurementsbecauseofthestraycapacitancesassociatedwithlonglength voltagedividers(especiallywithimpulsevoltagemeasurements)unlessspecialprecautionsaretaken. Onthelowvoltagesideofthepotentialdividerswhereascreenedcableoffinitelengthhastobe employedforconnectiontotheoscillographothererrorsanddistortionofwaveshapecanalsooccur.

ResistancePotentialDividers

Theresistancepotentialdividersarethefirsttoappearbecauseoftheirsimplicityofconstruction,less spacerequirements,lessweightandeasyportability.Thesecanbeplacednearthetestobjectwhich mightnotalwaysbeconfinedtoonelocation.

Thelengthofthedividerdependsupontwoorthreefactors.Themaximumvoltagetobemeasured isthefirstandifheightisalimitation,thelengthcanbebasedonasurfaceflashovergradientinthe orderof3–4kV/cmirrespectiveofwhethertheresistance R_1 isofliquidorwirewoundconstruction. Thelengthalsodependsupontheresistancevaluebutthisisimplicitlyboundupwiththestraycapacitance oftheresistancecolumn,theproductofthetwo(RC)givingatimeconstantthevalueofwhichmust notexceedthedurationofthewavefrontitisrequiredtorecord.

Itistobenotedwithcautionthattheresistanceofthepotentialdividershouldbematchedtothe equivalentresistanceofagivengeneratortoobtainagivenwaveshape.

Fig.6.19(a)showsacommonformofresistancepotentialdividerusedfortestingpurposes wherethewavefronttimeofthewaveislessthan1microsec.

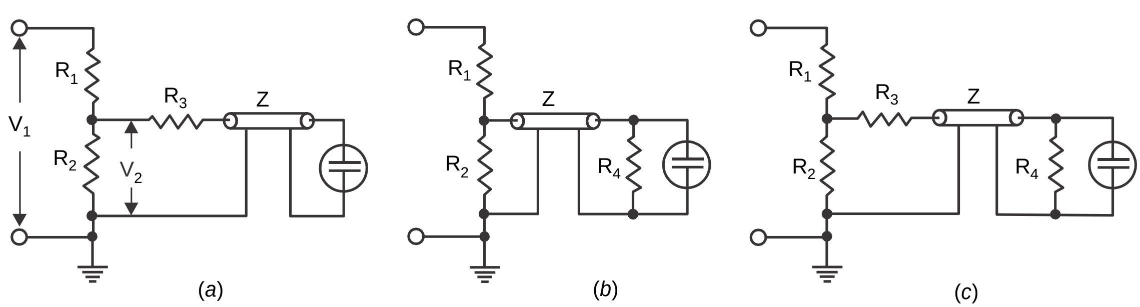


Fig.6.19 Variousformsofresistancepotentialdividersrecordingcircuits(a)Matchingatdividerend (b)MatchingatOscillographend(c)Matchingatbothendsofdelaycable

Here R_3, the resistance at the divider end of the delay cable is chosen such that $R_2 + R_3 = Z$ which puts an upper limit on R_2 *i.e.*, $R_2 < Z$. In fact, sometimes the condition for matching is given as

$$Z = R_3 + \frac{R_1 R_2}{R_1 + R_2}$$

But, since usually $R_1 >> R_2$, the above relation reduces to $Z = R_3 + R_4$. From Fig. 6.19(*a*), the voltage appearing across R_2 is

$V_2 =$

$$Z_1 \quad V$$

$$Z + R$$

whereZ_1 istheequivalentimpedanceofR_2 inparallelwith$(Z+R_3)$,thesurgeimpedanceofthecable beingrepresentedbyanimpedance$Z$toground.

Now $$Z_1 = \frac{(Z+R_3)R_2}{R_2+Z+R_3} = \frac{(Z+R_3)R_2}{2Z}$$

Therefore, $$V_2 = \frac{(Z+R_3)R_2}{2Z}\,\frac{V_1}{Z_1+R_1}$$

However,thevoltageenteringthedelaycableis

$$V_3 = \frac{V_2}{Z+R_3}Z = \frac{Z}{Z+R_3}\,\frac{(Z+R_3)R_2}{2Z}\cdot\frac{V_1}{Z_1+R_1} = V_1\frac{R_2}{2(Z_1+R_1)}$$

AsthisvoltagewavereachestheCROendofthedelaycable,itsuffersreflectionsasthe impedance offered by the CRO is infinite and as a result the voltage wave transmitted into the CRO is doubled.TheCRO,therefore,recordsavoltage

$$V_3' = \frac{R_2}{Z_1+R_1}V_1$$

Thereflectedwave,however,asitreachesthelowvoltagearmofthepotentialdividerdoesnot sufferanyreflectionas$Z = R_2+R_3$andistotallyabsorbedby(R_2+R_3).

SinceR_2issmallerthan$Z$andZ_1 isaparallelcombinationofR_2 and(R_3+Z),Z_1 isgoingtobe smallerthanR_2andsince$R_1 >> R_2$,R_1willbemuchgreaterthan$Z_1$and,thereforetoafirstapproximation $Z_1+R_1 \approx R_4$.

Therefore, $$V_3' = \frac{R_2}{R_1}V_1 \approx \frac{R_2}{R_1+R_2}V_1 \text{ as } R_2 << R_1$$

Fig. 6.19(b)and(c)arethevariantsofthepotentialdividercircuitofFig.6.19(a).Thecable matchingisdonebyapureohmicresistanceR_4 =Zattheendofthedelaycableand,therefore,the voltagereflectioncoefficientiszero*i.e.*thevoltageattheendofthecableistransmittedcompletely intoR_4andhenceappearsacrosstheCROplateswithoutbeingreflected.Astheinputimpedanceofthe delaycableisR_4 =Z,thisresistanceisaparalleltoR_2 andformsanintegralpartofthedivider’slow voltagearm.Thevoltageofsuchadivideris,therefore,calculatedasfollows:

Equivalentimpedance

$$= R_1 + \frac{R_2Z}{R_2+Z} = \frac{R_1(R_2+Z)+R_2Z}{(R_2+Z)}$$

Therefore,Current $$I = \frac{V_1(R_2+Z)}{}$$

$$R_1(R_2+Z)+R_2Z$$

1

and voltage $$V_2 = \frac{IR_2Z}{R_2+Z} = \frac{V_1(R_2+Z)}{R_1(R_2+Z)+R_2Z}\,\frac{R_2Z}{R_2+Z}$$

$$= \frac{R_2 Z}{R_1(R_2+Z)+R_2 Z} V_1$$

orvoltageratio $$\frac{V_2}{V_1} = \frac{R_2 Z}{R_1(R_2+Z)+R_2 Z}$$

DuetothematchingattheCROendofthedelaycable,thevoltagedoesnotsufferanyreflection atthatendandthevoltagerecordedbytheCROisgivenas

$$V_2 = \frac{R_2 Z V_1}{R_1(R_2+Z)+R_2 Z} = \frac{R_2 Z V_1}{(R_1+R_2)Z+R_1 R_2} = \frac{R_2 V_1}{(R_1+R_2)+\frac{R_1 R_2}{Z}}$$

Normallyforundistortedwaveshapethroughthecable

$$Z \approx R_2$$

Therefore,

$$V_2 = \frac{R_2}{2R_1+R_2} V_1$$

ForagivenappliedvoltageV_1thisarrangementwillproduceasmallerdeflectionontheCRO platesascomparedtotheoneinFig.6.19(*a*).

ThearrangementofFig.6.19(*c*)providesformatchingatbothendsofthedelaycableandisto berecommendedwhereitisfeltnecessarytoreducetotheminimumirregularitiesproducedinthe delaycablecircuit.SincematchingisprovidedattheCROendofthedelaycable,therefore,thereisno reflection ofthevoltageatthatendandthevoltagerecordedwillbehalfofthatrecordedinthe arrangementofFig.6.19(*a*)*viz*.

$$V_2 = \frac{R_2}{2(R_1+R_2)} V_1$$

Itisdesirabletoenclosethelowvoltageresistance(*s*)ofthepotentialdividersinametalscreening box.Steelsheetisasuitablematerialforthisboxwhichcouldbeprovidedwithadetachableclose fittinglidforeasyaccess.IftherearetwolowvoltageresistorsatthedividerpositionasinFig.6.19(*a*) and(*c*),theyshouldbecontainedinthescreeningbox,asclosetogetheraspossible,witharemovable metallicpartitionbetweenthem.Thepartitionservestwopurposes(*i*)itactsasanelectrostaticshield betweenthetworesistors(*ii*)itfacilitatesthechangingoftheresistors.Thelengthsoftheleadsshould beshortsothatpracticallynoinductanceiscontributedbytheseleads.Thescreeningboxshouldbe fitted with a large earthing terminal. Fig. 6.20 shows a sketched cross-section of possible layout for the lowvoltagearmofvoltagedivider.

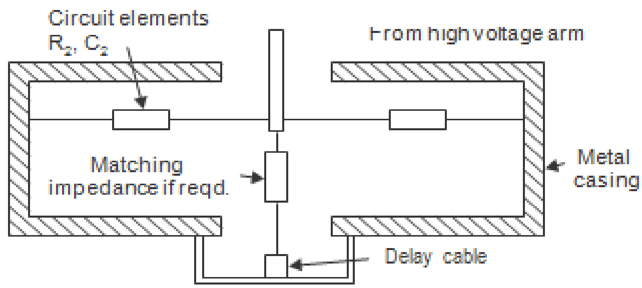


Fig. 6.20 Cross-section of low voltage arm of a voltage divider

CapacitancePotentialDividers

Capacitancepotentialdividersaremorecomplexthantheresistancetype.Formeasurementofimpulse voltagesnotexceeding1MVcapacitancedividerscanbebothportableandtransportable.Ingeneral, formeasurementof1MVandover,thecapacitancedividerisalaboratoryfixture.Thecapacitance dividersareusuallymadeofcapacitorunitsmountedoneabovetheotherandboltedtogether.Itisthis failurewhichmakesthesmalldividersportable.Ascreeningboxsimilartothatdescribedearliercan beusedforhousingboththelowvoltagecapacitorunitC_2 andthematchingresistorifrequired.

ThelowvoltagecapacitorC_2 shouldbenon-inductive.Aformofcapacitorwhichhasgiven excellentresults is of mica and tin foil plate, construction, each foil having connecting tags coming out at oppositecorners.Thisensuresthatthecurrentcannotpassfromthehighvoltagecircuittothedelay cablewithoutactuallygoingthroughthefoilelectrodes.Itisalsoimportantthatthecouplingbetween thehighandlowvoltagearmsofthedividerbepurelycapacitive.Hence,thelowvoltagearmshould containonecapacitoronly;twoormorecapacitorsinparallel mustbeavoidedbecauseofappreciable inductancethatwouldthusbeintroduced.Further, thetappingstothedelaycablemustbetakenoffas closeaspossibletotheterminalsofC_4.Fig.6.21showsvariantsofcapacitancepotentialdividers.

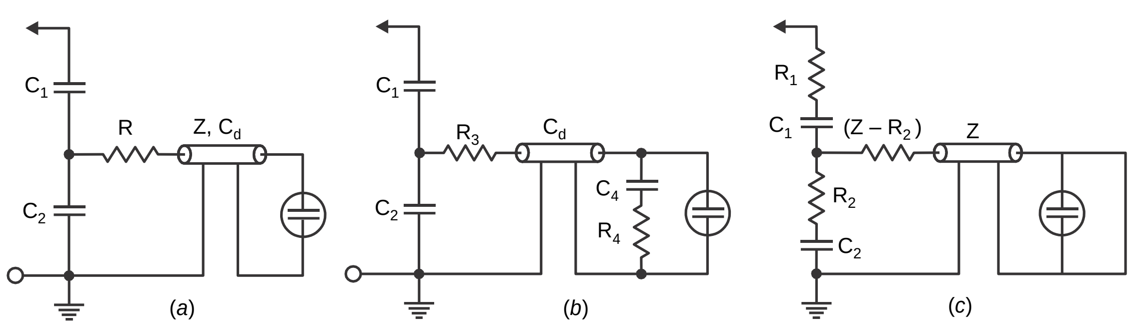


Fig.6.21 Capacitordividers(a)Simplematching(b)Compensatedmatching (c)Dampedcapacitordividersimplematching

ForvoltagedividersinFig.(*b*)and(*c*),thedelaycablecannotbematchedatitsend.Alow resistorinparalleltoC_2 wouldloadthelowvoltagearmofthedividertooheavilyanddecreasethe outputvoltagewithtime.Since$R$and$Z$formapotentialdividerand$R=Z$,thevoltageinputtothe cablewillbehalfofthevoltageacrossthecapacitorC_4. Thishalvedvoltagestravelstowardstheopen end of the cable (CRO end) and gets doubled after reflection. That is, the voltage recorded by the CRO isequaltothevoltageacrossthecapacitorC_4.Thereflectedwavechargesthecabletoitsfinalvoltage magnitudeandisabsorbedby$R$(*i.e.*reflectiontakesplaceat$R$andsince$R=Z$,thewaveiscompletely absorbedascoefficientofvoltagereflectioniszero)asthecapacitorC_2 actsasashortcircuitforhigh frequencywaves.Thetransformationratio,therefore,changesfromthevalue:

$$\frac{C_1+C_2}{C_1}$$

forveryhighfrequenciestothevalue

$$\frac{C_1+C_2+C_d}{C_1}$$

forlowfrequencies.

However,thecapacitanceofthedelaycableC_d isusuallysmallascomparedwithC_4.

Forcapacitivedivideranadditionaldampingresistanceisusuallyconnectedintheleadonthe highvoltagesideasshowninFig.6.21(*c*).Theperformanceofthedividercanbeimprovedifdamping resistorwhichcorrespondstotheaperiodiclimitingcaseisinsertedinserieswiththeindividualelement ofcapacitordivider.Thiskindofdampedcapacitivedivideractsforhighfrequenciesasaresistive dividerandforlowfrequenciesasacapacitivedivider.Itcan,therefore,beusedoverawiderangeof frequencies*i.e.*forimpulsevoltagesofverydifferentdurationandalsoforalternatingvoltages.

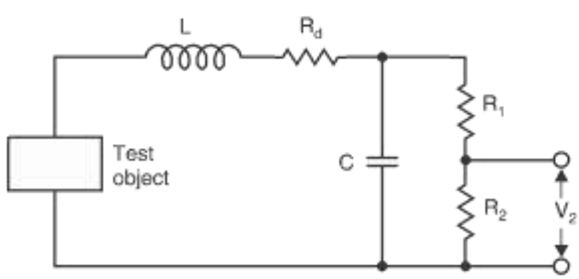


Fig.6.22 Simplifieddiagramofaresistancepotentialdivider

Fig. 6.22 shows a simplified diagram of a resistance potential divider after taking into considerationstheleadinconnectionastheinductanceandthestraycapacitanceaslumpedcapacitance. Here*L* representstheloopinductanceofthelead-inconnectionforthehighvoltagearm.Thedamping resistance$R_d$limitsthetransientovershootinthecircuitformedbytestobject,L,R_d and$C$.Itsvaluehas adecidedeffectontheperformanceofthedivider.Inordertoevaluatethevoltagetransformationofthe divider,thelowvoltagearmvoltageV_2resultingfromasquarewaveimpulseV_1onthe*hv*sidemustbe investigaged.ThevoltageV_2 followscurve2inFig.6.23(*a*)incaseofaperiodicdampingandcurve2 in Fig.6.23(*b*)incaseofsub-criticaldamping.Thetotalareabetweencurves1and2takinginto considerationthepolarity,isdescribedastheresponsetime.

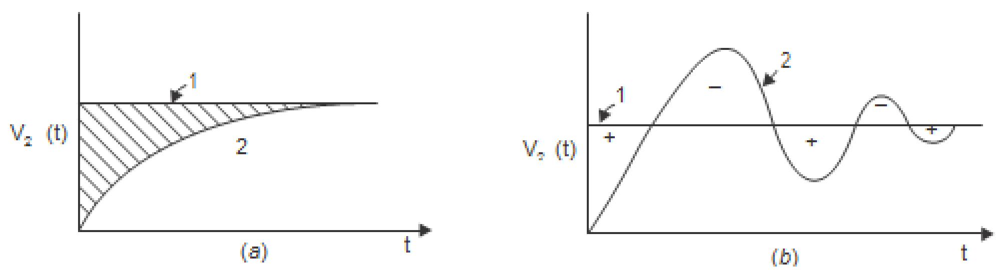


Fig. 6.23 The response of resistance voltage divider

Withsubcriticaldamping,eventhoughtheresponsetimeissmaller,thedampingshouldnotbe very small.Thisisbecauseanundesirableresonancemayoccurforacertainfrequencywithinthe passingfrequencybandofthedivider.Acompromisemustthereforeberealisedbetweentheshortrise timeandtherapidstabilizationofthemeasuringsystem.AccordingtoIECpublicationNo.60amaximum overshootof3%isallowedforthefullimpulsewave,5%foranimpulsewavechoppedonthefrontat timesshorterthan1microsec.Inordertofulfilltheserequirements,theresponsetimeofthedivider mustnotexceed0.2microsec.forfullimpulsewaves4.2/50or4.2/5orimpulsewaveschoppedonthe tail.Iftheimpulsewaveischoppedonthefrontattimesshorterthan1microsectheresponsetimemust benotgreaterthan5%ofthetimetochopping.

KlydonographorSurgeRecorder

Since lightningsurgesareinfrequentandrandominnature,itisnecessarytoinstalalargenumberof recordingdevicestoobtainareasonableamountofdataregardingthesesurgesproducedontransmission lines andotherequipments.Somefairlysimpledeviceshavebeendevelopedforthispurpose. Klydonograph is one such device which makes use of the patterns known as Litchenberg figures which areproducedonaphotographicfilmbysurfacecoronadischarges.

TheKlydonograph(Fig.6.24)consistsofaroundedelectroderestingupontheemulsionsideof aphotographicfilmorplatewhichiskeptonthesmoothsurfaceofaninsulatingmaterialplatebacked byaplateelectrode.Theminimumcriticalvoltagetoproduceafigureisabout2 kV and the maximum voltagethatcanberecordedisabout20kV,asathighervoltagessparkoversoccurswhichspoilsthe film.Thedevicecanbeusedwithapotentialdividertomeasurehighervoltagesandwitharesistance shunttomeasureimpulsecurrent.

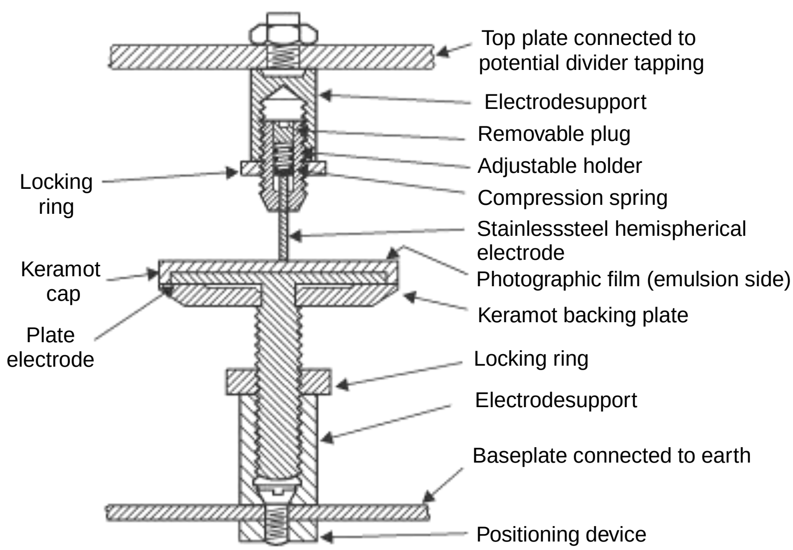


Fig. 6.24 Kiydonograph

There are characteristic differences between the figures for positive and negative voltages. However,foreitherpolaritytheradiusofthefigure(ifitissymmetrical)orthemaximumdistancefrom thecentreofthefiguretoitsoutsideedge(ifitisunsymmetrical)isafunctiononlyoftheapplied voltage.Theoscillatoryvoltagesproducesuperimposedeffectsforeachpartofthewave.Thusitis possibleto knowwhetherthewaveisunidirectionaloroscillatory.Sincethesizeofthefigurefor positivepolarityislarger,itispreferabletousepositivepolarityfigures.Thisisparticularlydesirable incaseofmeasurementofsurgesontransmissionlinesorothersuchequipmentwhichareordinarily operatingona.c.voltageandthealternatingvoltagegivesablackbandalongthecentreofthefilm causedbysuperpositionofpositiveandnegativefiguresproducedoneachhalfcycle.Foreachsurge voltageitispossibletoobtainbothpositiveandnegativepolarityfiguresbyconnectingpairsofelectrodes inparallel,onepairwithahighvoltagepointandanearthedplateandtheotherpairwithahighvoltage plateandanearthedpoint.

Klydonographbeingasimpleandinexpensivedevice,alargenumberofelementscanbeused formeasurement.Ithasbeenusedinthepastquiteextensivelyforprovidingstatisticaldataonmagnitude, polarityandfrequencyofvoltagesurgesontransmissionlineseventhoughitsaccuracyofmeasurement isonlyoftheorderof25percent.

Example 1.*Determinethebreakdownvoltageforairgapsof2mmand15mmlengthsunderuni-formfieldandstandardatmosphericconditions.Also,determinethevoltageiftheatmosphericpres-sureis750mmHgandtemperature35°C.*

Solution: Accordingtoempiricalformulawhichholdsgoodatstandardatmosphericconditions

$$V_b = 26.22S + 6.08\sqrt{S}$$

where*S*isthegaplengthincms.

(*i*)When $S = 0.2$ cm

$$V = 26.22 \times 0.2 + 6.08\sqrt{0.2} = 7.56 \text{ kV}$$ **Ans.**

(*ii*)When $S = 4.5$ cms

$$V_b = 26.22 \times 4.5 + 6.08\sqrt{4.5} = 36.33 + 7.446 = 45.776 \text{ kV}$$ **Ans.**

Theairdensitycorrectionfactor

$$= \frac{5.92b}{273+t}$$

$$= \frac{5.92 \times 75}{273+35} = 0.9545$$ **Ans.**

Therefore,voltagefor2mmgapwillbe7.216kVandfor15mmgapitwillbe44.78kV.

Example 3.*Anelectrostaticvoltmeterhastwoparallelplates.Themovableplateis10cmindiameter.With10kVbetweentheplatesthepullis5×10^{-3}N.Determinethechangeincapacitancefora movementof 1mmofmovableplate.*

Solution: $$5\times10^{-3} = \frac{1}{2} \cdot \frac{1}{36\pi} \times 10^{-9} \times \frac{10^8}{d^2} 25\pi \times 10^{-4}$$

or d=26.35mm.

Therefore,changeincapacitance

$$\frac{10^3}{36\pi} \times 10^{-9} \times 25\pi \times 10^{-4} \left[\frac{1}{26.35} - \frac{1}{27.35} \right]$$

=0.0959pF **Ans.**

Example5.*Apeakreadingvoltmeterisrequiredtomeasurevoltageupto150kV.Thepeakvoltmeter usesanRCcircuit,amicroammeterandacapacitancepotentialdivider.Thepotentialdividerhasa ratioof1200:1andthemicrometercanreadupto10μA.DeterminethevalueofRandCifthetime constantofRCcircuitis8secs.*

Solution: Thevoltageacrossthelowvoltagearmofthepotentialdivider,

$$= \frac{150 \times 1000}{1200} = 125\text{volts.}$$

Thesamevoltageappearsacrosstheresistance.

Therefore $$R = \frac{V}{I} = \frac{125}{10 \times 10^{-6}} = 14.5\,M\Omega$$

SincethetimeconstantoftheRCcircuitis8sec.

$$C = \frac{8}{14.5 \times 10^6}$$

=0.64μF **Ans.**

1. Whataretherequirementsofaspheregapformeasurementofhighvoltages?Discussthedisadvantages ofspheregapformeasurements.
2. Explainclearlytheprocedureformeasurementof(i)impulse;(ii)a.c.highvoltagesusingspheregap.
3. Discusstheeffectof(i)nearbyearthedobjects(ii)humidityand(iii)dustparticlesonthemeasurements

usingspheregaps.

4.Describetheconstructionofauniformfieldsparkgapanddiscussitsadvantagesanddisadvantagesfor highvoltagemeasurements.

5. Explainwithneatdiagramhowrodgapscanbeusedformeasurementofhighvoltages. Compareits performancewithaspheregap.

6. ExplainwithneatdiagramtheprincipleofoperationofanElectrostaticVoltmeter.Discussitsadvan tages andlimitationsforhighvoltagemeasurements.

7. Drawaneatschematicdiagramofageneratingvoltmeterandexplainitsprincipleofoperation.Disc uss itsapplicationandlimitations.

8. DrawChubb- FortescueCircuitformeasurementofpeakvalueofa.c.voltagesdiscussitsadvantagesover othermethods.

9. Discusstheproblemsassociatedwithpeakvoltmetercircuitsusingpassiveelements.Drawcircuit devel- opedbyRabusandexplainhowthiscircuitovercomestheseproblems.

10. Whataretheproblemsassociatedwithmeasurementofveryhighimpulsevoltages?Explainhowth ese canbetakencareofduringmeasurements.

11.Discuss and compare the performance of (*i*) resistance (*ii*) capacitance potential dividers for measurement ofimpulsevoltages.

12.Discussvariousresistancepotentialdividersandcomparetheirperformanceofmeasurementofimpul se voltages.

13.Discussvariouscapacitance,potentialdividersandcomparetheirperformanceformeasurementofim - pulsevoltages.

14.Drawasimplifiedequivalentcircuitofaresistancepotentialdivideranddiscussitsstepresponse.

15. Discussvariousmethodsofmeasuringhighd.c.anda.c.currents.

16. Discussvariousmethodsofmeasuringhighimpulsecurrents.

17. WhatisRogowskiCoil?Explainwithaneatdiagramitsprincipleofoperationformeasurementofhi

gh impulsecurrents.

UNIT -7

NON-DESTRUCTIVE INSULATION TESTING TECHNIQUES: Dielectric loss and loss angle measurements using Schering Bridge, Transformer ratio Arms Bridge. Need for discharge detection and PD measurements aspects. Factor affecting the discharge detection. Discharge detection methods-straight and balanced methods.

6 Hours

Allelectrical appliances are insulated with gaseous or liquid or solid or a suitable combination of these materials. The insulation is provided between live parts or between live part and grounded part of the appliance.Thematerialsmaybesubjectedtovaryingdegreesofvoltages,temperaturesandfrequen-ciesanditisexpectedofthesematerialstoworksatisfactorilyovertheserangeswhichmayoccur occasionallyinthesystem.Thedielectriclossesmustbelowandtheinsulationresistancehighinorder topreventthermalbreakdownofthesematerials.Thevoidformationwithintheinsulatingmaterials mustbeavoidedasthesedeterioratethedielectricmaterials.

Oneofthepossibletestingprocedureistoover-stressinsulationwithhigha.c.and/ord.c.or surge voltages. However, the disadvantage of the technique is that during the process of testing the equipmentmaybedamagediftheinsulationisfaulty.Forthisreason,followingnon-destructivetesting methodsthatpermitearlydetectionforinsulationfaultsareused:

(*i*)Measurementoftheinsulationresistanceunderd.c.voltages.

(*ii*)Determinationoflossfactortanδandthecapacitance*C*.

(*iii*)Measurementofpartialdischarges.

MEASUREMENTOFDIELECTRICCONSTANTANDLOSSFACTOR

Dielectriclossandequivalentcircuit

Incaseoftimevaryingelectricfields,thecurrentdensity$J_c$usingAmpereslawisgivenby

$$J_c = \sigma E + \frac{\partial D}{\partial t} = \sigma E + \epsilon \frac{\partial E}{\partial t}$$

Forharmonicallyvaryingfields

$$E = E_m e^{j\omega t}$$

$$\frac{\partial E}{\partial t} = jE_m \omega e^{j\omega t} = j\omega E$$

I_r I

Therefore, $J_c = \sigma E + j\omega\epsilon E$

$=(\sigma+j\omega\epsilon)E$

Ingeneral, in addition to conduction losses, ionization andpolarizationlossesalsooccurand,therefore,thedielec- tricconstant$\epsilon=\epsilon_0\,\epsilon_r$ is nolongerarealquantityratheritisa

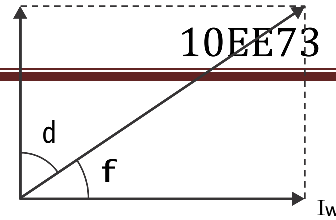


Fig.7.3 Phasordiagramforareal dielectricmaterial

complexquantity.Bydefinition,thedissipationfactortanδistheratioofrealcomponentofcurrentI_ω tothereactivecomponentI_r (Fig.7.3).

$$\tan\delta=\frac{I_\omega}{I_r}=\frac{p_{\text{did}}}{P_r}$$

Hereδistheanglebetweenthereactivecomponentofcurrentandthetotalcurrentflowing throughthedielectricatfundamentalfrequency.Whenδisverysmalltanδ =δ whenδisexpressedin radiansandtanδ=sinδ=sin(90–ϕ)=cosϕ*i.e.*,tanδthenequalsthepowerfactorofthedielectric material.

Asmentionedearlier,thedielectriclossconsistsofthreecomponentscorrespondingtothethree lossmechanism.

$$P_{\text{diel}}=P_c+P_p+P_i$$

andforeachoftheseanindividualdissipationfactorcanbegivensuchthat

$$\tan\delta=\tan\delta_c+\tan\delta_p+\tan\delta_i$$

Ifonlyconductionlossesoccurthen

$$P_{\text{diel}}=P_c=\sigma E^2 Ad=V^2\omega C\tan\delta=\frac{V^2\omega\epsilon_0\,\epsilon_r A}{d}\tan\delta$$

or $$\sigma E^2=\frac{V^2}{d^2}\omega\epsilon_0\epsilon_r\tan\delta=E^2\,\omega\epsilon_0\epsilon_r\tan\delta$$

or $$\tan\delta=\frac{\sigma\omega}{\epsilon_0\,\epsilon_r}$$

Thisshowsthatthedissipationfactorduetoconductionlossaloneisinverselyproportionalto thefrequencyandcan,therefore,beneglectedathigherfrequencies.However,forsupplyfrequency eachlosscomponentwillhaveconsiderablemagnitude.

Inordertoincludealllosses,itiscustomarytorefertheexistenceofalosscurrentinadditionto thechargingcurrentbyintroducingcomplexpermittivity.

$$\epsilon^*=\epsilon'-j\epsilon''$$

andthetotalcurrent$I$isexpressedas

$$I=(j\omega\epsilon'+\omega\epsilon'')\frac{C_0}{\epsilon_0}V$$

whereC_0isthecapacitancewithoutdielectricmaterial. or

$$I=j\omega C_0\epsilon_r^*.V$$

where $$\epsilon_r^*=\frac{(\epsilon'-j\epsilon'')}{\epsilon_0}$$

$= \epsilon'_r - j\epsilon''_r$

ϵ_r^* iscalledthecomplexrelativepermittivityorcomplexdielectricconstant, ϵ' and ϵ_r' arecalled thepermittivityandrelativepermittivityand ϵ'' and ϵ_r'' arecalledthelossfactorandrelativelossfactor respectively.Thelosstangent

$$\tan\delta = \frac{\epsilon''}{\epsilon'} = \frac{\epsilon_r''}{\epsilon_r'}$$

Theproductoftheangularfrequencyand ϵ'' isequivalenttothedielectricconductivity σ'' *i.e.*, $\sigma'' = \omega\epsilon''$.

Thedielectricconductivitytakesintoaccountallthethreepowerdissipativeprocessesinclud- ing theonewhichisfrequencydependent.Fig.7.4showstwoequivalentcircuitsrepresentingtheelectricalbehaviourofinsulatingmaterialsundera.c.voltages,losseshavebeensimulatedbyresistances.

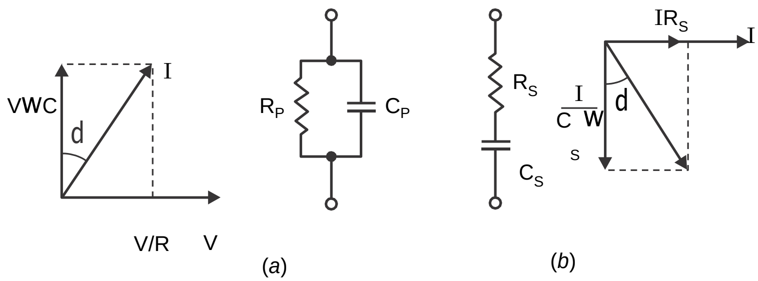


Fig.7.4 Equivalentcircuitsforaninsulatingmaterial

Normallytheanglebetween *V* andthetotalcurrentinapurecapacitoris90°.Duetolosses,this angleislessthan90°.Therefore, δ istheanglebywhichthevoltageandchargingcurrentfallshortof the90°displacement.

Fortheparallelcircuitthedissipationfactorisgivenby

$$\tan\delta = \frac{1}{\omega C_p R_p}$$

andfortheseriescircuit

$$\tan\delta = \omega C_s R_s$$

For afixedfrequency,boththeequivalentsholdgoodandonecanbeobtainedfromtheother. However,thefrequencydependenceisjusttheoppositeinthetwocasesandthisshowsthelimited validityoftheseequivalentcircuits.

Theinformationobtainedfromthemeasurementoftan δ andcomplexpermittivityisanindica- tionofthequalityoftheinsulatingmaterial.

(*i*)If tan δ variesandchangesabruptlywiththeapplicationofhighvoltage,itshowsinception ofinternalpartialdischarge.

(*ii*)Theeffecttoffrequencyonthedielectricpropertiescanbestudiedandthebandoffrequen- cies where dispersion occurs*i.e.*,wherethatpermittivityreduceswithriseinfrequencycan beobtained.

HIGHVOLTAGESCHERINGBRIDGE

Thebridge is widely used for capacity and dielectric loss measurement of all kinds of capacitances, for instance cables, insulators and liquid insulating materials. We know that most of the high voltage equipments have low capacitance and low loss factor. Typical values of these equipments are given in Chapter5.Thisbridgeisthenmoresuitableformeasurementofsuchsmallcapacitanceequipmentsas thebridgeuseseitherhighvoltageorhighfrequencysupply.Ifmeasurementsforsuchlowcapacity equipmentsiscarriedoutatlowvoltage,theresultssoobtainedarenotaccurate

Fig.7.5showsahighvoltagescheringbridgewherethespecimenhasbeenrepresentedbya parallelcombinationofR_p andC_p.

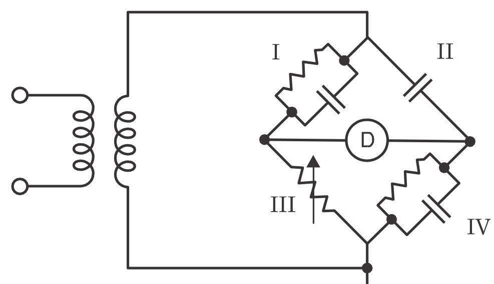


Fig.7.5 Basichighvoltagescheringbridge

Thespecialfeaturesofthebridgeare:

4.Highvoltagesupply,consistsofahighvoltagetransformerwithregulation,protectivecir- cuitry and special screening. The input voltage is 220 volt and output continuously variable between0and10kV.Themaximumcurrentis100mAanditisof1kVAcapacity.

4.ScreenedstandardcapacitorC_s of100*pF*±5%,10kVmaxanddissipationfactortanδ =10^{-5}.Itisagas-filledcapacitorhavingnegligiblelossfactoroverawiderangeoffrequency.

5.TheimpedancesofarmsIandIIareverylargeand,therefore,currentdrawnbythesearms issmallfromthesourceandasensitivedetectorisrequiredforobtainingbalance.Also, sincetheimpedanceofarmIandIIareverylargeascomparedtoIIIandIV,thedetectorand theimpedancesinarmIIIandIVareatapotentialofonlyafewvolts(10to20volts)above earthevenwhenthesupplyvoltageis10kV,exceptofcourse,incaseofbreakdownofone ofthecapacitorsofarmIorIIinwhichcasethepotentialwillbethatofsupplyvoltage. Sparkgapsare,therefore,providedtosparkoverwheneverthevoltageacrossarmIIIorIV exceeds100voltsoastoprovidepersonnelsafetyandsafetyforthenulldetector.

4.*NullDetector:* Anoscilloscopeisusedasanulldetector.The γ–platesaresuppliedwiththe bridgevoltageV_{ab}andthe*x*-plateswiththesupplyvoltage*V*.IfV_{ab}hasphasedifference withrespectto*V*,anellipsewillappearonthescreen(Fig.7.6).However,ifmagnitude balance is not reached, an inclined straight line will be observed on the screen. The information about the phase is obtained from the area of the eclipse and the one about the magnitude from the inclination angle. Fig. 7.6*a*shows that both magnitude and phase are balancedandthisrepresentsthenullpointcondition.Fig.(7.6*c*)and(*d*)showsthatonly phaseandamplituderespectivelyarebalanced.

(*a*) (*b*) (*c*) (*d*)

Fig.7.6 Indicationsonnulldetector

The handling of bridge keys allows to meet directly both the phase and the magnitude conditionsinasingleattempt.Atimeconsumingiterativeprocedurebeingusedearlieris thusavoidedandalsowiththisaveryhighorderofaccuracyinthemeasurementisachieved.

Thehighaccuracyisobtainedasthesenulloscilloscopesareequippedwithaγ–amplifier of automatically controlled gain. If the impedances are far away from the balance point, the wholescreenisused.Fornearlyobtainedbalance,itisstillalmostfullyused.AsV_{ab}becomes smaller,byapproachingthebalancepoint,thegainincreasesautomaticallyonlyfordeviations veryclosetobalance,theellipseareashrinkstoahorizontalline.

5.*AutomaticGuardPotentialRegulator:*Whilemeasuringcapacitanceandlossfactorsusing a.c.bridges,thedetrimentalstraycapacitancesbetweenbridgejunctionsandtheground adverselyaffectthemeasurementsandarethesourceoferror.Therefore,arrangements should be made to shield the measuring system so that these stray capacitances are either neutralised,balancedoreliminatedbypreciseandrigorouscalculations.Fig.7.7shows variousstraycapacitanceassociatedwithHighVoltageScheringBridge.

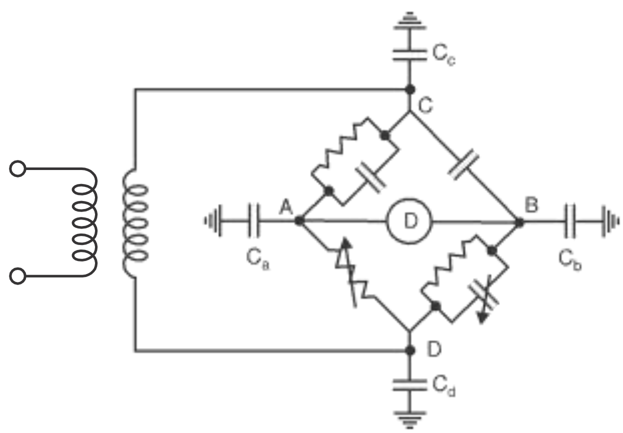


Fig.7.7 Scheringbridgewithstraycapacitances

C_a,C_b,$C_c$and$C_d$arethestraycapacitancesatthejunctions*A*,*B*,*C*and*D*ofthebridge.Ifpoint *D*isearthedduringmeasurementcapacitanceC_d isthuseliminated.SinceC_c comesacrossthepower supplyforearthedbridge,hasnoinfluenceonthemeasurement.Theeffectof otherstraycapacitances C_a andC_b canbeeliminatedbyuseofauxiliaryarms,eitherguardpotentialregulatororauxiliary branchassuggestedbyWagner.

Fig.7.8showsthebasicprincipleofWagnerearthtoeliminatetheeffectofstraycapacitances $C_a$andC_b.Inthisarrangementanadditionalarm*Z* isconnectedbetweenthelowvoltageterminalofthe four arm bridge and earth. The stray capacitance*C*between the high voltage terminal of the bridge and thegroundedshieldandtheimpedance*Z*togetherconstituteasixarmbridgeandadoublebalancing procedureisrequired.

Switch*S*isfirstconnectedtothebridgepoint*b*andbalanceisobtained.Atthispoint*a*and*b*are atthesamepotentialbutnotnecessarilyatthegroundpotential.Switch*S*isnowconnectedtopoint*C* andbyadjustingimpedance*Z*balanceisagainobtained.Underthisconditionpoint'*a*'mustbeatthe samepotentialasearthalthoughitisnotpermanentlyatearthpotential.Switch*S*isagainconnectedto point*b*andbalanceisobtainedbyadjustingbridgeparameters.Theprocedureisrepeatedtillallthe threepoints*a*,*b* and*c*areattheearthpotentialandthusC_a andC_b areeliminated.

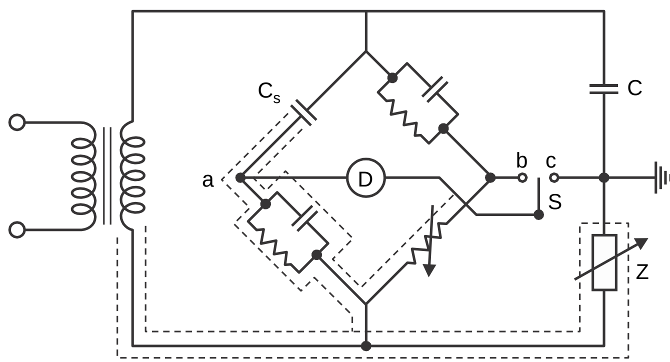


Fig.7.8 BridgeincorporatingWagnerearth

This method is, however, now rarely used.Insteadanauxiliaryarmusingautomatic guard potential regulator is used. The basic circuitisshowninFig.7.9.

Theguardpotentialregulatorkeepsthe shieldpotentialatthesamevalueasthatof thedetectordiagonalterminals*a*and*b*forthe bridge balance considered. Since potentials of *a*,*b*andshieldareheldatthesamevaluethe straycapacitancesareeliminated.Duringthe processofbalancingthebridgethepoints *a* and*b*attaindifferentvaluesofpotentialin

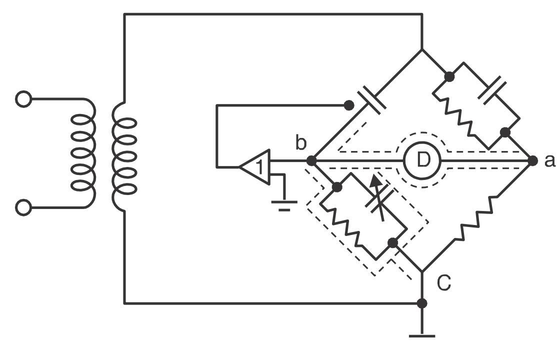


Fig.7.9 AutomaticWagnerearthorautomatic guardpotentialregulator

magnitudeandphasewithrespecttoground.Asaresult,theguardpotentialregulatorshouldbeableto adjust the voltage both in magnitude and phase. This is achieved with a voltage divider arrangement providedwithcoarseandfinecontrols,oneofthemfedwithin-phaseandtheotherquadraturecompo-nentofvoltage.Thecontrolvoltageisthentheresultantofbothcomponentswhichcanbeadjusted eitherinpositiveorinnegativepolarityasdesired.Thecomparisonbetweentheshieldingpotential adjustedbymeansoftheGuardpotentialregulatorandthebridgevoltageismadeinthenullindicator oscilloscopeasmentionedearlier.Modifyingthepotential,itiseasytobringthereadingofthenull detectortoahorizontalstraightlinewhichshowsabalancebetweenthetwovoltagesbothinmagni-tudeandphase.

The automaticguardpotentialregulatoradjustsautomaticallytheguardpotentialofthebridge makingthisequalinmagnitudeandphasetothepotentialofthepoint*a*or*b*withrespecttoground. Theregulatordoesnotuseanyexternalsourceofvoltagetoachievethisobjective.Itisrathercon-nectedtothebridgecornerpointbetween*a*or*b*and*c*andistakenasareferencevoltageandthisis thentransmittedtotheguardcircuitwithunitygainbothinmagnitudeandphase.Theshieldsofthe leadsto $C_s$andC_p arenotgroundedbutconnectedtotheoutputofthe regulatorwhich,infact,isan operationalamplifier.Theinputimpedanceoftheamplifierismorethan1000Megaohmsandthe outputimpedanceislessthan0.5ohm.Thehighinputimpedanceandverylowoutputimpedanceof theamplifierdoesnotloadthedetectorandkeepstheshieldpotentialatanyinstantatanartificial ground.

BalancingtheBridge

ForreadyreferenceFig.7.5isreproducedhereanditsphasordiagramunderbalancedcondition isdrawninFig.7.10(*b*)

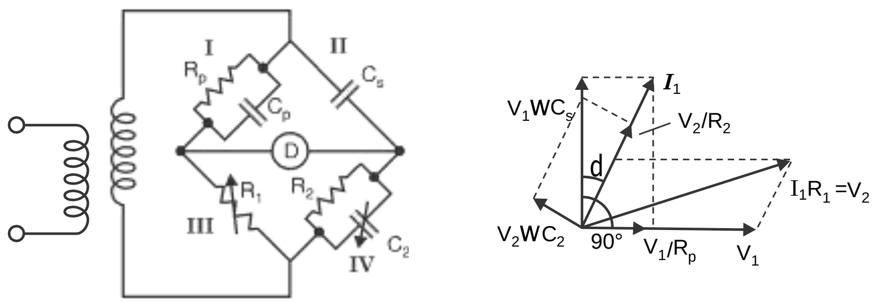


Fig.7.10(a)Scheringbridge(b)Phasordiagram

ThebridgeisbalancedbysuccessivevariationofR_1 andC_2 untilontheoscilloscope(Detector) ahorizontalstraightlineisobserved:

Atbalance $$\frac{Z_I}{Z_{II}} = \frac{Z_{III}}{Z_{IV}}$$

Now $$Z_I = \frac{R_p}{1+j\omega C_p R_p}$$

$$Z_{II} = \frac{1}{j\omega C_s}$$

$$Z_{III} = R_I \text{ and } Z_{IV} = \frac{R_2}{1+j\omega C_2 R_2}$$

Frombalanceequationwehave

$$\frac{R_p}{R_1(1+i\omega C_p R_p)} = \frac{1/j\omega C_s(1+j\omega C_2 R_2)}{R_2}$$

or $$\frac{R_p(1-j\omega C_p R_p)}{R_1[1+\omega^2 C_p^2 R_p^2]} = \frac{1+j\omega C_2 R_2}{j\omega C_s R_2}$$

TRANSFORMERRATIOARMBRIDGE

For measurementofvariousparameterslikeresistance,inductance,capacitance,usuallyfourarmbridgesareused. For high frequency measurements, the arm with high resistances leads to difficulties due to their residual inductance,capacitanceandskineffect.Alsoiflengthoftheleads islarge, shielding is difficult. Hence at high frequencies the transformerratioarmbridgewhicheliminatesatleasttwo arms, are preferred. These bridges provide more accurate resultsforsmallcapacitancemeasurements.Thereare two typesoftransformerratioarmbridges(*i*)Voltageratio;(*ii*)

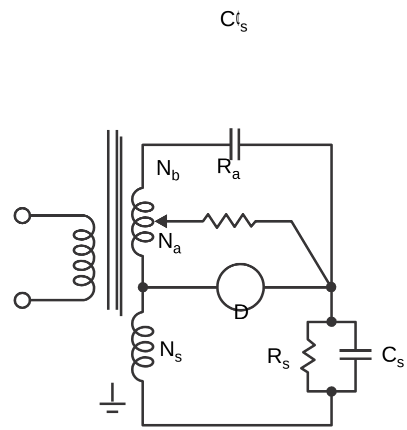


Fig.7.16 Transformervoltageratio armbridge

Current ratio. The voltage ratio type is used for high frequency low voltage application. Fig. 7.16 shows schematic diagramofavoltageratioarmbridge.Assumingidealtransformer,underbalancecondition:

However,inpracticalsituationduetothepresenceofmagnetisingcurrentandtheloadcurrents, thevoltageratioslightlydiffersfromtheturnsratioandtherefore,themethodinvolvescertainerrors. Theerrorsareclassifiedasratioerrorandloaderrorwhichcanbecalculatedbeforehandfora transformer. A typical bridge has a useful range from a fraction of a*pF*toabout100 μ*F*and is accurate over awide rangeoffrequencyfrom100Hzto100kHz,theaccuracybeingbetterthan±0.5%.

The currentratioarmbridgeisusedforhighvoltagelowfrequencyapplications.Themain advantage of the method is that the test specimen is subjected to full system voltage. Fig. 7.17 shows schematicdiagramofthebridge.Themaincomponentofthebridgeisathreewindingcurrenttransformerwithverylowlossesandleakage(coreofhighpermeability).Thetransformeriscarefully shieldedagainststraymagneticfieldsandprotectedagainstmechanicalvibrations.

NEED FOR PARTIALDISCHARGES

Partialdischargeisdefinedaslocaliseddischargeprocessinwhichthedistancebetweentwoelec- trodes is only partially bridged*i.e.,*the insulation between the electrodes is partially punctured. Partial dischargesmayoriginatedirectlyatoneoftheelectrodesoroccurinacavityinthedielectric.Someof thetypicalpartialdischargesare:(*i*)Coronaorgasdischarge.Theseoccurduetonon-uniformfieldon sharpedgesoftheconductorsubjectedtohighvoltageespeciallywhentheinsulationprovidedisairor gasorliquidFig.7.18(*a*).(*ii*)Surfacedischargesanddischargesinlaminatedmaterialsontheinter-facesofdifferentdielectricmaterialsuchasgas/solidinterfaceasgasgetsoverstressedϵ_r timesthestressonthesolidmaterial(whereϵ_r istherelativepermittivityofsolidmaterial)andionizationofgas resultsFig.7.18(*b*)and(*c*). (*iii*)Cavitydischarges:Whencavitiesareformedinsolidorliquidinsulat- ing materialsthegasinthecavityisoverstressedanddischargesareformedFig.7.18(*d*)(*iv*).TreeingChannels:Hi ghintensityfieldsareproducedinaninsulatingmaterialatitssharpedgesand thisdeterioratestheinsulatingmaterial.Thecontinuouspartialdischargessoproducedareknownas TreeingChannelsFig.7.18(*e*).

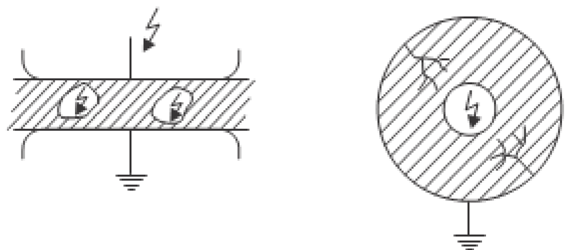
ExternalPartialDischarge

Externalpartial discharge is the process which occurs external to the equipment e.g. on overhead lines, onarmatureetc.

InternalPartialDischarge

Internal paratial discharge is a process of electrical discharge which occurs inside a closed system (discharge in voids, treeing etc). This kind of classification is essential for the PD measuring system as externaldischargescanbenicelydistinguishedfrominternaldischarges.Partialdischargemeasure-ment have been used to assess the life expectancy of insulating materials. Even though there is no well defined relationship, yet it gives sufficient idea of the insulating properties of the material. Partial discharges on insulation can be measured not only by electrical methods but by optical, acoustic and chemicalmethodalso.Themeasuringprinciplesarebasedonenergyconversionprocessassociated withelectricaldischargessuchasemissionofelectromagneticwaves,light,noiseorformationofchemical compounds.Theoldestandsimplestbutlesssensitiveisthemethodoflisteningtohissingsoundcomingoutofp artialdischarge.Ahighvalueoflossfactortanδisanindicationofoccurrenceofpartialdischargeinthematerial. Thisisalsonotareliablemeasurementastheadditionallossesgeneratedduetoapplicationofhighvoltageareloc alisedandcanbeverysmallincomparisontothevolume losses resulting from polarization process. Optical methods are used only for those materials which are transparentandthusnotapplicableforallmaterials.Acousticdetectionmethodsusingultrasonictransducersha ve,however,beenusedwithsomesuccess.Themostmodernandthemostaccuratemethods aretheelectricalmethods.ThemainobjectivehereistoseparateimpulsecurrentsassociatedwithPD fromanyotherphenomenon.

(a) (b) (c)



(d) (e)

Fig. 7.18 Various partial discharges

ThePartialDischargeEquivalentCircuit

If thereareanypartialdischargesinadielectricmaterial,thesecanbemeasuredonlyacrossits terminal.Fig.7.19showsasimplecapacitorarrangementinwhichagasfilledvoidispresent.The partialdischargeinthevoidwilltakeplaceastheelectricstressinthevoidis$\epsilon_r$timesthestressinthe restofthematerialwhere$\epsilon_r$istherelativepermittivityofthematerial.Duetogeometryofthematerial, variouscapacitancesareformedasshowninFig.7.19(*a*).Fluxlinesstartingfromelectrodeandtermi-natingatthevoidwillformonecapacitanceC_{b1}andsimilarlyC_{b2}betweenelectrode*B*andthecavity. $C_c$isthecapacitanceofthevoid.SimilarlyC_{a1}andC_{a2}arethecapacitanceofhealthyportionsofthe dielectriconthetwosidesofthevoid.Fig.7.19(*b*)showstheequivalentof7.19(*a*)where$C_a = C_{a1} + C_{a2}$,and$C_b = C_{b1}C_{b2}/(C_{b1}+C_{b2})$ andC_c isthecavitycapacitance.Ingeneral$C_a >> C_b >> C_c$.

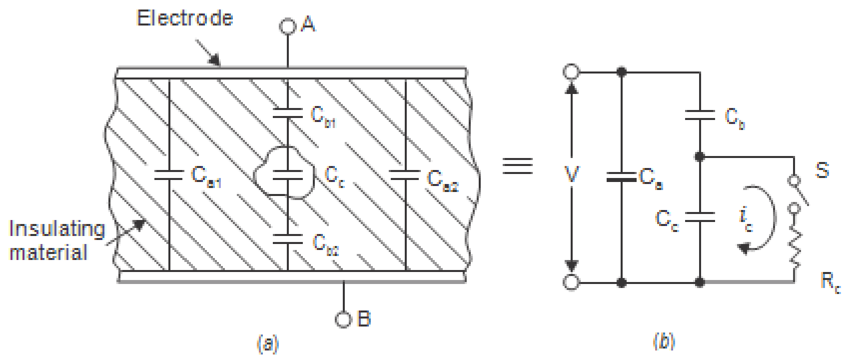


Fig. 7.19. (a) Dielectric material with a cavity (b) Equivalent circuit

Closingofswitch*S*isequivalenttosimulatingpartialdischargeinthevoidasthevoltageV_c acrossthevoidreachesbreakdownvoltage.Thedischargeresultsintoacurrent$i_c(t)$toflow.ResistorR_c simulatesthefinitevalueofcurrent$i_c(t)$.

Supposevoltage*V*isappliedacrosstheelectrode*A*and*B*andthesampleischargedtothis voltageandsourceisremoved.Thevoltage$V_c$across thevoidissufficienttobreakdownthevoid.Itis equivalenttoclosingswitch *S*inFig.7.19(*b*).Asaresult,thecurrent $i_c(t)$flowswhichreleasesa charge$\Delta q_c = \Delta V_c C_c$whichisdispersedinthedielectricmaterialacrossthecapacitanceC_b andC_a.Here ΔV_cisthedropinthevoltage $V_c$asaresultofdischarge.Theequivalentcircuitduringredistributionof chargeΔq_cisshowninFig.7.20

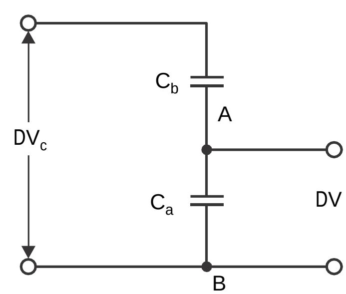


Fig.7.20 Equivalentof7.19(a)afterdischarge

ThevoltageasmeasuredacrossABwillbe

$$\Delta V = \frac{C_b}{C_a + C_b}\,\Delta V_c = \frac{C_b}{C_a + C_b}\,\frac{\Delta q_c}{C_c}$$

OrdinarilyΔV_cisinkVwhereasΔVisafewvoltssincetheratio C_b/C_a isoftheorderof$10^{-4}$to 10^{-5}.ThevoltagedropΔVeventhoughcanbemeasuredbutasC_b andC_c arenormallynotknown neitherΔV_cnorΔq_ccanbeobtained.Alsosince*V*isinkVandΔVisinvoltstheratio$\Delta V/V$isverysmall $\approx 10^{-3}$,thereforethedetectionof$\Delta V/V$isatedioustask.

Suppose,thatthetestobjectremainsconnectedtothevoltagesourceFig.7.24.Here$C_k$isthe couplingcapacitor.*Z*istheimpedance consistingeitheronlyoftheleadimpedanceoforleadimpe- danceand*PD*-freeinductororfilterwhichdecouplesthecouplingcapacitorandthetestobjectfrom thesourceduringdischargeperiodonly,whenveryhighfrequencycurrentpulse$i_c(t)$circulatebetween $C_k$andC_t.C_t isthetotalequipmentcapacitanceofthetestspecimen.

C_t

Fig.7.21

ItistobenotedthatZoffershighimpedancetocircularcurrent(impulsecurrents)and,there- fore,thesearelimitedonlytoC_k and C_t.However,supplyfrequencydisplacementcurrentscontinueto flowthrough$C_k$and$C_t$andwaveshapesofcurrentsthrough$C_k$and$C_t$areshowninFig.7.24.

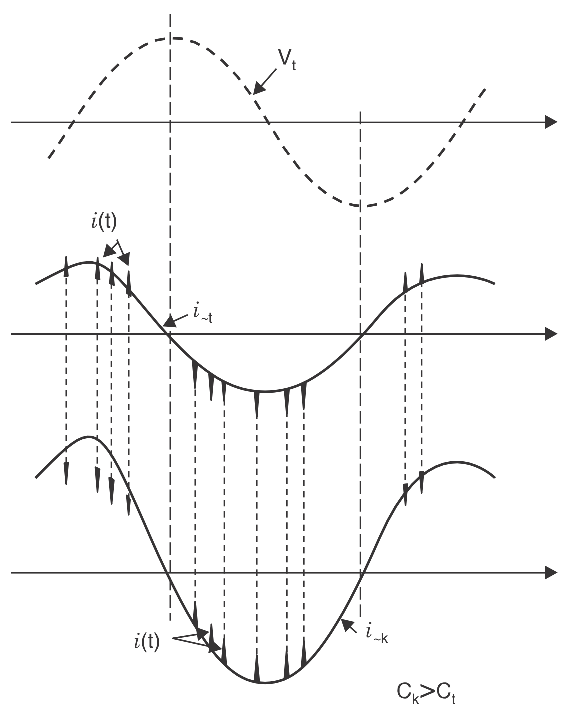


Fig.7.22 CurrentwaveformsinC_k andC_t.

It isinterestingtofindthatpulsecurrentsin$C_k$and$C_t$have exactlysamelocationbutopposite polarities and these are of the same magnitude. Therefore, one can say that these pulse currents are not suppliedbythesourcebutareduetolocalpartialdischarges.Theamplitudeofpulsesdependsuponthe voltageappliedandthenumberofpulsesdependsuponthenumberofvoids.Thelargerthenumberof faultsthehigherthenumberofpulsesoverahalfcycle.

Duringdischarge,thevoltageacrossthetestobjectC_t fallsbyanamountΔVandduringthis period$C_k$storestheenergyandreleasethechargebetweenC_k andC_t thuscompensatingthedropΔV. Theequivalentcapacitanceofthetestspecimenis$C_t \approx C_a + C_b$assuming$C_c$tobenegligiblysmall.If $C_k >> C_t$,thechargetransferisgivenby

$$q = \int i(t)dt \approx (C_a + C_b)\Delta V$$

Now $$\Delta V = \frac{C_b}{C_a + C_b} \Delta V_c$$

and $$\Delta V = \frac{q}{C_a + C_b}$$

Therefore, $$\frac{q}{C_a + C_b} = \frac{C_b}{C_a + C_b} \Delta V_c$$

or $$q = C_b \Delta V_C$$

Here$q$isknownasapparentchargeasitisnotequaltothechargelocallyinvolved*i.e.*$C_c \Delta V_c$. Thischarge$q$is,however,morerealisticthancalculatingΔV,as$q$isindependentofC_a whereasΔV dependsuponC_a.

Inpracticethecondition$C_k >> C_t$ isneversatisfiedastheC_k willoverloadthesupplyandalso itwillbeuneconomical.However,ifC_k isslightlygreaterthanC_t,thesensitivityofmeasurementis reducedasthecompensatingcurrent$i_c(t)$becomessmall.IfC_t is comparabletoC_k andΔVisthedrop involtageof C_t asaresultofdischarge,thetransferofchargebetween C_t andC_k willresultinto commonvoltage$\Delta V'$.

$$\Delta V' = \frac{C_t \Delta V + C_k.O}{C_t + C_k} = \frac{C_t \Delta V}{C_t + C_k} = \frac{q}{C_t + C_k}$$

$\Delta V'$isthenetriseinvoltageoftheparallelcombinationof$C_k$andC_t and,therefore,thecharge q_m transferredtoC_t fromC_k willbe

$$q_m = C_k \Delta V'$$

Thechargeq_m isknownasmeasurablecharge.Theratioofmeasurablechargetoapparent chargeis,therefore,givenas

$$\frac{q_m}{q} = \frac{C_k}{C_t + C_k}$$

Inordertohavehighsensitivityofmeasurements*i.e.*,highq_m/q itisclearthat$C_k$shouldbelarge compared toC_t.ButweknowthattherearedisadvantagesinhavinglargevalueofC_k.Therefore,this methodofmeasurementof*PD*haslimitedapplications.

ThemeasurementofPDcurrentpulsesprovidesimportantinformationconcerningthedischarge processesinatestspecimen.Thetimeresponseofanelectricdischargedependsmainlyonthenature of faultanddesignofinsulatingmaterial.Theshapeofthecircularcurrentisanindicationofthe physical discharge process at the fault location in the test object. The principle of measurement of*PD* currentisshowninFig.7.25.

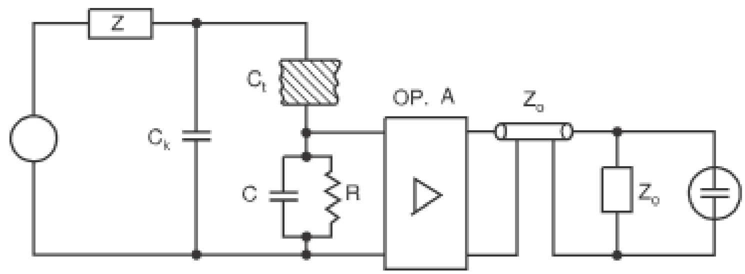


Fig.7.23 Principleofpulsecurrentmeasurement

Here*C*indicatesthestraycapacitancebetweentheleadof$C_t$andtheearth,theinputcapaci-

tanceoftheamplifierandotherstraycapacitances.Thefunctionofthehighpassamplifieristosup-

pressthepowerfrequencydisplacementcurrent$i_k(t)$and$I_c(t)$andtofurtheramplifytheshortduration

currentpulses.Thusthedelaycableiselectricallydisconnectedfromtheresistance*R*.Supposeduring

apartialdischargeashortdurationpulsecurrent$\delta(t)$isproducedandresultsinapparentcharge*q*onC_t

whichwillberedistributedbetweenC_t,*C*andC_k .ThecircuitforthesameisgiveninFig.7.24.

(*i*)*Pulseshapednoisesignals:*Thesearedueto impulsephenomenonsimilarto*PD*currents.

(*ii*)*Harmonicsignals:*Thesearemainlyduetopowersupplyandthyristorisedcontrollers.

Wearetakingapparentchargeastheindexlevelofthepartialdischargeswhichisintegrationof *PD*pulse currents. Therefore, continuous alternating current of any frequency would disturb the integrationprocessofthemeasuringcircuitandhenceitisimportantthatthesecurrents(otherthan*PD*

currents)mustbesuppressedbeforethemixtureofcurrentsispassedthroughtheintegratingcircuit. Thesolutiontotheproblemisobtainedbyusingfiltercircuitswhichmaybecompletelyindependentof integratingcircuits.

Fig.7.26showstwodifferentwaysinwhichthemeasuringimpedanceZ_m canbeconnectedin thecircuit.

Z

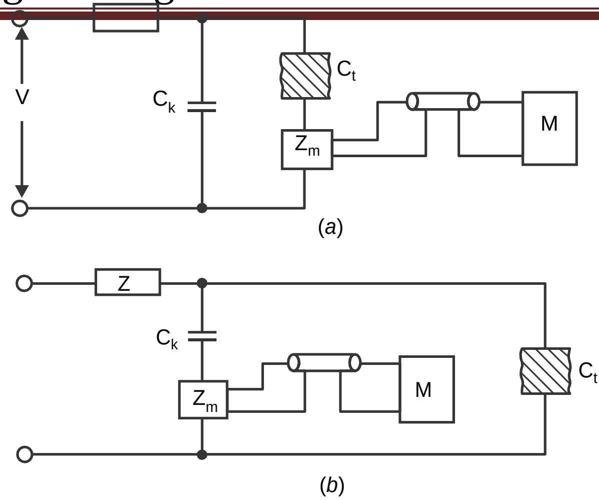


Fig.7.26

InFig.7.26(a)Z_m isconnectedinserieswith C_t andprovidesbettersensitivityasthePD currentsexcitedfrom$C_t$wouldbebetterpickedupbymeasuringcircuitZ_m. However,thedisadvantage isthatincaseofpunctureofthetestspecimenthemeasuringcircuitwouldalsobedamaged. Specifically forthisreason,thesecondarrangementinwhichZ_m isconnectedbetweenthegroundterminalofC_k andthegroundandisthecircuitmostcommonlyused.

Asismentionedearlier,accordingtointernationalstandardsthelevelofpartialdischargesis judged by quantity of apparent charge measured. The apparent charge is obtained by integration of the circularcurrent$i_c(t)$.ThisoperationiscarriedoutonthePDpulsesusing‘wideband’and‘narrow band’,measuringsystems.Thesearebasicallybandpassfilterswithamplifyingaction.Ifweexamine thefrequencyspectrumofthepulsecurrent,itwillbeclearwhybandpassfiltersaresuitablefor integratingPDpulsecurrents.

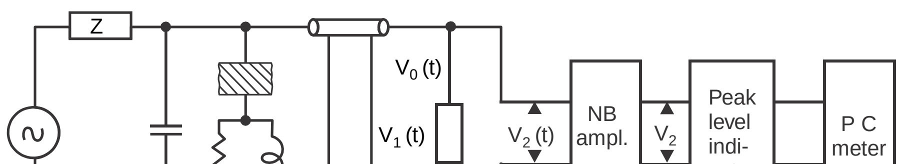
Weknowthatforanon-periodicpulsecurrent$i(t)$,thecomplexfrequencyspectrumofthe currentisgivenbyFouriertransformas

$$\int$$

NarrowBandPD-DetectionCircuit

AnarrowbandPDdetectioncircuitisbasicallyaverysensitivemeasurementreceivercircuitwitha continuouslyvariablemeasuringorcentrefrequencyf_m intherangeofapproximately50kHZtosev-eralMHz.Thenomenclaturetonarrow-bandisjustifiedasthebandwidthofthefilteramplifieris typicallyonly9kHz.However,ifspecialcircumstancesdemand,thebandwidthmaybeslightlymade widerornarrowerthan9kHz.

Fig.7.31showsanarrowbandPDmeasuringcircuit.ℑ



R L

Fig.7.31 BasicnarrowbandPDmeasuringcircuit

ParallelcombinationofRandLconstitutethemeasuringimpedance Z_m.Themeasuringimpe-danceactsasahighpassandhighfrequencyPDcurrentspulses $i(t)$ aredecoupledfromthetestcircuit. Whereasinwidebandcircuitsthemeasuringimpedance $Z_m(R\|L\|C)$ performsintegrationoperation ontheinputDiracdeltacurrent $i(t)$,nointegration iscarriedoutby Z_m inthenarrowbandcircuit.Alow resistanceratingofthemeasuringimpedance Z_m preventsthattheseriesconnectionof C_k and C_t at-tenuateshighfrequencycomponentsofPDsignals.Sincethedelaycableisterminatedwith Z_0 whichis thesurgeimpedanceofthecableitselfthecapacitance C_c ofthecabledoesnotplayanyrole.

AssumingthattheparallelcombinationofRandLissochosenthatLdoesnotperform integrating operation on the input signal $i(t) = I_0\,\delta(t)$,thevoltage $v_1(t)$ at the input of the narrow band amplifier is proportionaltothePDimpulsecurrent $i(t)$ *i.e.*,

$$v_1(t) = I_0\,\delta(t) R_m$$

Again,assumingthat $i(t) = I_0\,e^{-t/\tau}$ asinFig.7.27,wehave

$$v_1(t) = I_0 e^{-t/\tau} R_m$$

$$V_1(j\omega) = \frac{I_0\,\tau R_m}{1+j\omega\,\tau} = \frac{V_0\,\tau}{1+j\omega\,\tau}$$

where $$R_m = \frac{RZ_0}{R+Z_0}$$

Thetimeconstantofthecircuit $T = R_m C$

where $$C = \frac{C_t C_k}{C_t + C_k}$$

Let $$S_0 = V_0\,\tau$$

Thequantity S_0 containstheinformationconcerningtheindividualpulsecharge q andisreferred toastheintegralsignalamplitudeandisrepresentedinFig.7.34.

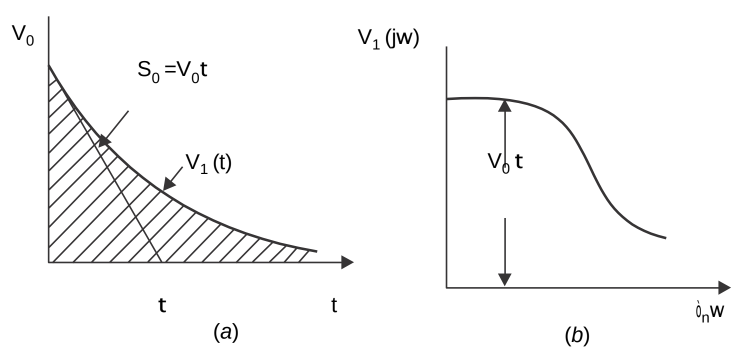


Fig.7.32 (a)Approximatevoltageimpulse(b)Itsfrequencyresponse

Table7.1

ComparisonbetweenwidebandandnarrowbandPDmeasuringcircuits

		WideBand	*NarrowBand*
4.	Bandwidth	$f_2 – f_1$ =150to200kHz	Δf=9kHz
4.	Centrefrequency	Fixedf_0 =80–150kHz	Variablef_m =50kHzto2MHz
5.	Pulseresolutiontime	Smallabout15μsec.	Largeabout220μsec.
4.	Pulsepolarity	Detectable	Notdetectable
5.	Noisesusceptibility	Relativelyhighasno.of interferencesources increaseswithbandwidth	Lowduetoselectivemeasurements throughvariablecentrefrequency.
7.	MaximumadmissiblePD pulsewidth	Approx1μsec.	Dependsuponf_m in
7.	Indicationofmeasured value	DirectlyinpC	DirectlyinpC

Tableaboveshowsrelativemeritsanddemeritsofthetwocircuits.However,inpracticalsituations,asystemthatcanbeswitchedoverbetweenwidebandandnarrowbandshouldprovetobemore versatileanduseful.

OSCILLOSCOPEASPDMEASURINGDEVICE

Oscilloscopeisanintegralandindispensablecomponentofa PDmeasuringsystem.Anindicating metere.g.apCmeterandRIVmetercangivequantityofcharge,whetherthechargeisasaresultof partialdischargeorduetoexternalinterferences,cannotbeestimated.Thisproblemcanbesolvedonly iftheoutputwaveformisstudiedontheOscilloscope.Whethertheoriginofthedischargesisfrom withinthetestobjectornot,canfrequentlybedeterminedbasedonthetypicalpatterns.Ifitisascertainedfromthepatternsthatthedischargeisfromthetestobject,themagnitudeoftheapparentcharge shouldbemeasuredwithpCmetersorRIVmeters.Thepeakvalueoftheintegratedpulsecurrentisthe desiredapparentcharge$q$.Thesesignalsarenormallysuperposedonthea.c.testvoltageforobservationontheOscilloscope.Dependinguponthepreferenceeithersineorellipticalshapescanbeselected.Onecompleterotationoftheellipseoronecompletecycleofsinewaveequals20msec.of duration.Sincethedurationofthesecurrentpulsestobemeasuredisafewmicrosecond,thesepulses whenseenonthepowerfrequencywave,looklikeverticallinesofvaryingheightssuperimposedon thepowerfrequencywaves.

WhenevercalibrationfacilityexistsinthePDtestcircuit,thecalibrationcurveofknowncharge appearsonthescreen.Thecalibrationpulsecanbeshiftedentirelyalongtheellipseorsinecurveofthe powersupplyandthesignaltobemeasuredcanbecomparedwiththecalibrationpulse.

Example1:*A20kV,50HzScheringbridgehasastandardcapacitanceof106μF.Inatest ona bakelitesheetbalancewasobtainedwithacapacitanceof0.35μF inparallelwithanon-inductive resistanceof318ohms,thenon-inductiveresistanceintheremainingarmofthebridgebeing130 ohms.Determinetheequivalentseriesresistanceandcapacitanceandthep.f.ofthespecimen.*

Solution: HereC'_s=106μF,C_2 =0.35μF

$R_2 = 318$ ohms and $R_1 = 130$ ohms.

Since $R_s = R_1 \dfrac{C_2}{C'_s} = 106 \times \dfrac{318}{130} = 259\,\mu F$ **Ans.**

$= 130 \times$

0.35

106

$= 0.429$ ohm **Ans.**

and $C_s = C'_s \dfrac{R_2}{R_1}$

$$\tan\delta_s = \omega C_s R_s = 314 \times 259 \times 10^{-6} \times 0.429$$
$$= 5.5 \times 10^4 \times 10^{-6} = 0.035$$ **Ans.**

Since $\tan\delta = \sin\delta = \cos(90 - \delta)$
$= \cos\phi = 0.035$ **Ans.**

Example 2.*Determinep.f.andtheequivalentparallelresistanceandcapacitanceoftherestspeci-menofexample7.1*

Solution: Forparallelequivalent

$$C_p = C_s \frac{R_2}{R_1}$$

HereC_s isthestandardcapacitance

$$C_p = 106 \times \frac{318}{130} = 259 \mu F \qquad \textbf{Ans.}$$

$$R_p = \frac{R_1}{\omega^2 C_2 C_s R_2^2}$$

$$R_p = \frac{130}{314^2 \times 0.35 \times 106 \times 10^{-12} \times 318^2}$$

$$= 351 \text{ohms} \qquad \textbf{Ans.}$$

$$\tan\delta = \frac{1}{314 \times 351 \times 259 \times 10^{-6}}$$

$$= \frac{1}{28.54} = 0.035 \qquad \textbf{Ans.}$$

Example 3.*A 33 kV,50HzhighvoltageScheringbridgeisusedtotestasampleofinsulation.Thevariousarmshavethefollowingparametersonbalance.Thestandardcapacitance500pF,theresis-tivebranch800ohmandbranchwithparallelcombinationofresistanceandcapacitancehasvalues 180ohmsand0.15μF.Determinethevalueofthecapacitanceofthissampleitsparallelequivalent lossresistance,thep.f.andthepowerlossunderthesetestconditions.*

Solution: Given

C_s =500pF

R_1=800ohm

R_2 =180ohm

C_2 =0.15μF

Now

$$C_p = C_s \frac{R_2}{R_1} = 500 \times 10^{-12} \times \frac{180}{800} = 114.5 \text{pF}$$

$$R_p = \frac{R_1}{\omega^2 C_2 C_s R_2^2} = \frac{800}{314^2 \times 500 \times 10^{-12} \times 0.15 \times 10^{-6} \times 180^2}$$

$$= \frac{800}{4.3958\times10^{11}\times10^{18}} \quad = 335.9\times10^{7} = 3339\ \text{M}\Omega$$

$$\text{p.f.} = \tan\delta_p = \frac{1}{\omega C R_{pp}} = \frac{1}{314\times114.5\times10^{-12}\times3339\times10^{6}}$$

$$= \frac{1}{117.95}\ 0.008478 \quad \textbf{Ans.}$$

Powerloss $= \dfrac{V^2}{R} = \dfrac{33^2\times10^6}{3339\times10^6}$

$= 0.326$ watts **Ans.**

Example 4. *A length of cable is tested for insulation resistance by the loss of charge method. An electrostatic voltmeter of infinite resistance is connected between the cable conductor and earth forming therewith a joint capacitance of 600 pF. It is observed that after charging the voltage falls from 250 volts to 92 V in one min. Determine the insulation resistance of the cable.*

Solution: The voltage at any time t is given as

$$v = Ve^{-t/CR}$$

where V is the initial voltage

or $\dfrac{V}{v} = e^{t/CR}$

or $\ln\dfrac{V}{v} = \dfrac{t}{CR}$

or $R = \dfrac{t}{C\ln\dfrac{V}{v}} = \dfrac{60}{600\times10^{-12}\ln\dfrac{250}{92}}$

$$= \frac{60}{600\times10^{-12}\times1}$$

$= 100{,}000$ Mohms **Ans.**

Example 5. *Following measurements are made to determine the dielectric constant and complex permittivity of a test specimen:*

The air capacitance of the electrode system = 50 pF

The capacitance and loss angle of the electrodes with specimen = 190 pF and 0.0085 respectively.

Solution: The dielectric constant $\epsilon_r = \dfrac{190}{50} = 5.8$

Now complex permittivity $\epsilon = \epsilon' - j\epsilon''$

$$= \epsilon_0(\epsilon_r' - j\epsilon_r'')$$

$$\epsilon_r' = \epsilon_r = 5.8$$

$$\tan\delta = \frac{\epsilon_r''}{\epsilon_r'} = \frac{\epsilon_r''}{5.8} = 0.0085$$

or $\epsilon_r'' = 0.0323$

$$\epsilon = \epsilon_0 (5.8 - j0.0323)$$

$$= 8.854 \times 10^{-12}(5.8 - j0.0323)$$

$$= (5.36 - j0.0286) \times 10^{-11} \text{F/m} \quad \textbf{Ans.}$$

Example 6. *Determinethespecificheatgeneratedinthetestspecimenduetodielectriclossifthe dielectricconstantandlossangleofthespecimenare5.8and0.0085respectively.Theelectricfieldis 40kV/cmat50Hz.]*

Solution: Thespecificlossisgivenby

$$\sigma E^2 \text{ Watts/m}^3$$

where σ istheconductivityofthespecimenand E thestrengthofelectricfield.

Alsoweknowthat

$$\tan\delta = \frac{\sigma}{\omega\epsilon_0\epsilon_r}$$

or $\sigma = \omega\epsilon_0\epsilon_r \tan\delta$

Therefore,specificlossisgivenas

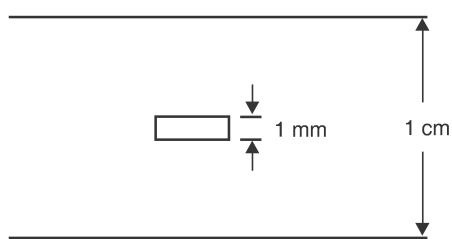
$$\sigma E^2 = \omega\epsilon_0\epsilon_r \tan\delta E^2$$

$$= 314 \times 8.854 \times 10^{-12} \times 5.8 \times 0.0085 \times 1600 \times 10^{10}$$

$$= 1436 \text{Watts/m}^3 \quad \textbf{Ans.}$$

Example7. *Asoliddielectricof1cmthicknessand $\epsilon_r = 5.8$ hasaninternalvoidof1mmthickness. If thevoidisfilledwithairwhichbreaksdownat21KV/cm,determinethevoltageatwhichaninternal dischargecanoccur.*

Solution: RefertoFig.Ex.7.7



Forinternaldischargetotakeplacethegradientinvoidshouldbe21kV/cm.Therefore,the gradientinthedielectricslabwillbe

$$\frac{21}{5.8} = 5.526 \text{kV/cm.}$$

Therefore,totalvoltagerequiredtoproducethesegradientwillbe

$$= 5.526 \times 0.9 + 21 \times 0.1$$

$$= 4.97 + 4.1$$

$$= 7.07 \text{kVrms} \quad \textbf{Ans.}$$

Questions

1.Whatisnon-destructivetestingofinsulatingmaterials?Giveverybrieflythecharacteristicsof thesemethods.

2.Startingfromfirstprinciples,developexpressiontoevolveequivalentcircuitofaninsulatingmaterial.

3.Drawaneatdiagramofahighvoltagescheringbridgeanddescribevariousfeaturesofthebridge.

4. Describethefunctionsof(*i*)Nulldetector(*ii*)Automaticguardpotentialregulatorusedinhighvoltage Scheringbridge.

5. DrawaneatdiagramofhighvoltageScheringbridgeandanalyseitforbalancedcondition. Drawits phasordiagram.Assume(*i*)Seriesequivalent(*ii*)Parallelequivalentrepresentationoftheinsulatingma- terial.

6.Whatmodificationsdoyousuggestinthebasic Scheringbridgewhilemeasuringlarge capacitances? Giveitsanalysis.Howtheexpressionsforcapacitanceandlossanglegetmodified?

7. Whatisaninvertedscheringbridge?Giveitsapplication.

8. Explain the operation of high voltage Schering bridge when the test specimen (*i*) is grounded (*ii*) has high lossfactor.

9. Discussvarioustypesoftransformerratioarmbridgesandgivetheirapplicationandadvantages.

10. Describewithaneatdiagramtheprincipleoftheoperationoftransformercurrentratioarmbridge.Ex- plainhowthisisusedformeasurementofcapacitanceandlossfactorofaninsulatingmaterial.

11.Whatarepartialdischarges?Differentiatebetweeninternalandexternaldischarges.

12.Developanddrawequivalentcircuitofinsulatingmaterialduringpartialdischarge.

13.What is apparent charge in relation to partial discharges? Show that the calculation of apparentchargeas ameasureofpartialdischargeseventhoughismorerealisticthancalculationofchangeinvoltageacross theelectrode,haslimitedapplicationforpartialdischargemeasurement.

14. Explainwithneatdiagrambasicprincipleofpulsecurrentmeasurementforestimationof partial dis- charges.

15. Writeshortnoteonthemeasuringimpedancecircuitforestimationofpartialdischarges.

16.Showsthatthed.c.contentofthefrequencyspectrumequalstheapparentchargeinthepulsecurrent.

17. Explainwithneatdiagramshowwidebandcircuitcanbeusedformeasuringpartialdischarge.

18. “Forpropermeasurementofpartialdischargetheresolutiontimeofthecircuitshouldbesmallerthanthe time- constantofthecurrentpulse”Why?Explain.

19. ExplainwithneatdiagramtheNarrow-BandPD-detectioncircuit.

20. Showthattheimpulseresponseofnarrow-bandpassreceiverisanOscilatoryandwithmainfrequencyfm andtheamplitudeisgivenbysignumfunction.Discussthelimitationofnarrowbandpassdetector.

21.Comparetheperformanceofnarrowbandandwideband*PD*measuringcircuits.

22.Explainwithneatdiagramabridgecircuitusedforsuppressinginterferencesignals.

23.WriteashortnoteontheuseofanOscilloscopeasa*PD*measuringdevice.

UNIT- 8

HIGH VOLTAGE TESTS ON ELECTRICAL APPARATUS: Definitions of terminologies, tests on isolators, circuit breakers, cables insulators and transformers

Theveryfastdevelopmentofsystemsisfollowed bystudies ofequipmentandtheserviceconditionstheyhavetofulfill.Theseconditionswillalso determinethevaluesfortestingatalternating,impulseandd.c.voltagesunderspecificconditions.

As wegoforhigherandhigheroperatingvoltages(sayabove1000kV)certainproblemsare associatedwiththetestingtechniques.Someoftheseare:

(*i*)Dimensionofhighvoltagetestlaboratories.

(*ii*)Characteristicsofequipmentforsuchlaboratories.

(*iii*)Somespecialaspectsofthetesttechniquesatextrahighvoltages.

Thedimensionsoflaboratoriesfortestequipmentsof750kVandabovearefixedbythefollowing mainconsiderations:

(*i*)Figures(values)oftestvoltagesunderdifferentconditions.

(*ii*)Sizesofthetestofequipmentsina.c.,d.c.andimpulsevoltages.

(*iii*) Distancesbetweentheobjectsunderhighvoltageduringthetestperiodandtheearthed surroundingssuchasfloors,wallsandroofsofthebuildings.Theproblemsassociatedwith thecharacteristicsoftheequipmentsusedfortestingaresummarisedhere.

Therearesomedifficultproblemswithimpulsetestingequipmentsalsoespeciallywhentesting largepowertransformersorlargereactorsorlargecablesoperating atveryhighvoltages.Theequiva-lentcapacitanceoftheimpulsegeneratorisusuallyabout40nanofaradsindependentoftheoperating voltagewhichgivesastoredenergyofabout$1/2 \times 40 \quad 10^{-9} \times 36 \times 10^{9}$ =720KJfor6MVgenerators which isrequiredfortestingequipmentsoperatingat150kV.Itisnotatalldifficulttopileupalarge numberofcapacitancestochargetheminparallelandthendischargeinseriestoobtainadesired impulsewave.Butthedifficultyexistsinreducingtheinternalreactanceofthecircuitsothatashort wavefrontwithminimumoscillationcanbeobtained.Forexamplefora4MVcircuittheinductanceof thecircuitisabout140 μHanditisimpossibletotestanequipmentwithacapacitanceof5000pFwith afronttimeof4.2μsec.andlessthan5%overshootonthewavefront.

Cascadedrectifiersareusedforhighvoltaged.c.testing.Acarefulconsiderationisnecessary whentestonpollutedinsulationistobeperformedwhichrequirescurrentsof50to200mAbutex- tremely predischarge streamer of 0.5 to 1 amp during milliseconds occur. The generator must have an internalreactanceinordertomaintainthetestvoltagewithouttoohighavoltagedrop.

TESTINGOFOVERHEADLINEINSULATORS

Varioustypesofoverheadlineinsulatorsare(*i*)Pintype(*ii*)Posttype(*iii*)Stringinsulatorunit (*iv*)Suspensioninsulatorstring(*v*)Tensioninsulator.

ArrangementofInsulatorsforTest

Stringinsulatorunitshouldbehungbyasuspensioneyefromanearthedmetalcrossarm.Thetest voltageisappliedbetweenthecrossarmandtheconductorhungverticallydownfromthemetalparton thelowersideoftheinsulatorunit.

Suspensionstringwithallitsaccessoriesasinserviceshouldbehungfromanearthedmetal crossarm.Thelengthofthecrossarmshouldbeatleast4.5timesthelengthofthestringbeingtested andshouldbeatleastequalto0.9moneithersideoftheaxisofthestring.Nootherearthedobject shouldbenearertotheinsulatorstringthen0.9mor4.5timesthelengthofthestringwhicheveris greater.Aconductorofactualsizetobeusedinserviceorofdiameternotlessthan1cmandlength4.5 timesthelengthofthestringissecuredinthesuspensionclampandshouldlieinahorizontalplane. Thetestvoltageisappliedbetweentheconductorandthecrossarmandconnectionfromtheimpulse generatorismadewithalengthofwiretooneendoftheconductor.Forhigheroperatingvoltages wherethelengthofthestringislarge,itisadvisabletosacrificethelengthoftheconductorasstipu-latedabove.Instead,itisdesirabletobendtheendsoftheconductoroverinalargeradius.

Fortensioninsulatorsthearrangementismoreorlesssameasinsuspensioninsulatorexcept thatitshouldbeheldinanapproximatelyhorizontalpositionunderasuitabletension(about1000Kg.).

Highvoltagetestingofelectricalequipmentrequirestwotypesoftests:(*i*) Typetests,and(*ii*) Routine test. Type tests involves quality testing of equipment at the design and development level*i.e.* samplesoftheproductaretakenandaretestedwhenanewproductisbeingdevelopedanddesignedor anoldproductistoberedesignedanddevelopedwhereastheroutinetestsaremeanttocheckthe quality of the individual test piece. This is carried out to ensure quality and reliability of individual test objects.

Highvoltagetestsinclude(*i*)Powerfrequencytestsand(*ii*)Impulsetests.Thesetestsarecar-riedoutonallinsulators.

(*i*)50%dryimpulseflashovertest.

(*ii*)Impulsewithstandtest.

(*iii*)Dryflashoveranddryoneminutetest.

(*iv*)Wetflashoverandoneminuteraintest.

(*v*)Temperaturecycletest.

(*vi*)Electro-mechanicaltest.

(*vii*)Mechanicaltest.

(*viii*)Porositytest.

(*ix*)Puncturetest.

(*x*)Mechanicalroutinetest.

Thetestsmentionedabovearebrieflydescribedhere.

(*i*) Thetestiscarriedoutonacleaninsulatormountedasinanormalworkingcondition.An impulse voltage of 1/50µ sec.waveshapeandofanamplitudewhichcancause50%flashoverofthe insulator,isapplied,*i.e.*oftheimpulsesapplied50%oftheimpulsesshouldcauseflashover.The polarityoftheimpulseisthenreversedandprocedurerepeated.Theremustbeatleast20applications oftheimpulseineachcaseandtheinsulatormustnotbedamaged.Themagnitudeoftheimpulse voltageshouldnotbelessthanthatspecifiedinstandardspecifications.

(*ii*)Theinsulatorissubjectedtostandardimpulseof1/50µsec.waveofspecifiedvalueunder dryconditionswithbothpositiveandnegativepolarities.Iffiveconsecutiveapplicationsdonotcause anyflashoverorpuncture,theinsulatorisdeemedtohavepassedtheimpulsewithstandtest.Ifoutof five,twoapplicationscauseflashover,theinsulatorisdeemedtohavefiledthetest.

(*iii*)Powerfrequencyvoltageisappliedtotheinsulatorandthevoltageincreasedtothespeci- fied valueandmaintainedforoneminute.Thevoltageisthenincreasedgraduallyuntilflashover occurs.Theinsulatoristhenflashedoveratleastfourmoretimes,thevoltageisraisedgraduallyto reachflashoverinabout10seconds.Themeanofatleastfiveconsecutiveflashovervoltagesmustnot belessthanthevaluespecifiedinspecifications.

(*iv*)If the test is carried out under artificial rain, it is called wet flash over test. The insulator is subjectedtosprayofwateroffollowingcharacteristics:

Precipitationrate	3±10%mm/min. Direction 45°tothevertical
Conductivityofwater	100microsiemens±10%
TemperatureofwaterAmbient+15°C	

Theinsulatorwith50%oftheone-min.raintestvoltageappliedtoit,isthensprayedfortwo minutes,thevoltageraisedtotheoneminutetestvoltageinapproximately10sec.andmaintainedthere foroneminute.Thevoltageisthenincreasedgraduallytillflashoveroccursandtheinsulatoristhen flashedatleastfourmoretimes,thetimetakentoreachflashovervoltagebeingineachcaseabout 10sec.Theflashovervoltagemustnotbelessthanthevaluespecifiedinspecifications.

(*v*)Theinsulatorisimmersedinahotwaterbathwhosetemperatureis70°higherthannormal waterbathfor*T*minutes.Itisthentakenoutandimmediatelyimmersedinnormalwaterbathfor*T* minutes. After*T* minutestheinsulatorisagainimmersedinhotwaterbathfor*T* minutes.Thecycleis repeatedthreetimesanditisexpectedthattheinsulatorshouldwithstandthetestwithoutdamagetothe insulatororglaze.Here$T$=(15+W/4.36)where$W$istheweightoftheinsulatorinkgs.

(*vi*)Thetestiscarriedoutonlyonsuspensionortensiontypeofinsulator.Theinsulatoris subjected to a 2½ times the specified maximum working tension maintained for one minute. Also, simultaneously75%ofthedryflashovervoltageisapplied.Theinsulatorshouldwithstandthistest withoutanydamage.

(*vii*)Thisisabendingtestapplicable topintypeandline-postinsulators.Theinsulatorissub- jected to a load three times the specified maximum breaking load for one minute. There should be no damage to the insulator and in case of post insulator the permanent set must be less than 1%. However, incaseofpostinsulator,theloadisthenraisedtothreetimesandthereshouldnotbeanydamagetothe insulatoranditspin.

(*viii*)Theinsulatorisbrokenandimmersedina0.5%alcoholsolutionoffuchsinunderapres- sureof13800kN/m^2 for24hours.Thebrokeninsulatoristakenoutandfurtherbroken.Itshouldnot showanysignofimpregnation.

(*ix*)Animpulseovervoltageisappliedbetweenthepinandtheleadfoilboundoverthetopand sidegroovesincaseofpintypeandpostinsulatorandbetweenthemetalfittingsincaseofsuspension typeinsulators.Thevoltageis1/50 μsec.wavewithamplitudetwicethe50%impulseflashover voltageandnegativepolarity.Twentysuchapplicationsareapplied.Theprocedureisrepeatedfor4.5, 3,5.5timesthe50%impulseflashovervoltageandcontinuedtilltheinsulatorispunctured.The insulatormustnotpunctureifthevoltageappliedisequaltotheonespecifiedinthespecification.

(*x*)Thestringininsulatorissuspendedverticallyorhorizontallyandatensileload20%in excessofthemaximumspecifiedworkingloadisappliedforoneminuteandnodamagetothestring shouldoccur.

TESTINGOFCABLES

Highvoltage power cables have proved quite useful especially in case of HV d.c. transmission. Under-grounddistributionusingcablesnotonlyaddstotheaestheticlooksofametropolitancitybutitpro-videsbetterenvironmentsandmorereliablesupplytotheconsumers.

PreparationofCableSample

Thecablesamplehastobecarefullypreparedforperformingvarioustestsespeciallyelectricaltests. Thisisessentialtoavoidanyexcessiveleakageorendflashoverswhichotherwisemayoccurduring testingandhencemaygivewronginformationregardingthequalityofcables.Thelengthofthesample cablevariesbetween50cmsto10m.Theterminationsareusuallymadebyshieldingtheendsofthe cablewithstressshieldssoastorelievetheendsfromexcessivehighelectricalstresses.

Acableissubjectedtofollowingtests:

(*i*)Bendingtests.

(*ii*)Loadingcycletest.

(*iii*)Thermalstabilitytest.

(*iv*)Dielectricthermalresistancetest.

(*v*)Lifeexpectancytest.

(*vi*)Dielectricpowerfactortest.

(*vii*)Powerfrequencywithstandvoltagetest.

(*viii*)Impulsewithstandvoltagetest.

(*ix*)Partialdischargetest.

(*i*)Itistobenotedthatavoltagetestshouldbemadebeforeandafterabendingtest.Thecable is bentroundacylinderofspecifieddiametertomakeonecompleteturn.Itisthenunwoundand rewoundintheoppositedirection.Thecycleistoberepeatedthreetimes.

(*ii*)Atestloop,consistingofcableanditsaccessoriesissubjectedto20loadcycleswitha minimumconductortemperature5°Cinexcessofthedesignvalueandthecableisenergizedto 4.5timestheworkingvoltage.Thecableshouldnotshowanysignofdamage.

(*iii*)After test as at (*ii*), the cable is energized with a voltage 4.5 times the working voltage for a cableof132kVrating(themultiplyingfactordecreaseswithincreasesinoperatingvoltage)andthe loadingcurrentissoadjustedthatthetemperatureofthecoreofthecableis5°Chigherthanitsspeci-fiedpermissibletemperature.Thecurrentshouldbemaintainedatthisvalueforsixhours.

(*iv*)Theratioofthetemperaturedifferencebetweenthecoreandsheathofthecableandthe heat flow from the cable gives the thermal resistance of the sample of the cable. It should be within the limitsspecifiedinthespecifications.

(*v*)Inordertoestimatelifeofacable,anacceleratedlifetestiscarriedoutbysubjectingthe cabletoavoltagestresshigherthanthenormalworkingstress.Ithasbeenobservedthattherelation betweentheexpectedlifeofthecableinhoursandthevoltagestressisgivenby

$$g = \frac{K}{n\sqrt{t}}$$

where$K$isaconstantwhichdependsonmaterialand$n$isthelifeindexdependingagainonthe material.

(*vi*)HighVoltageScheringBridgeisusedtoperformdielectricpowerfactortestonthecable sample.Thepowerfactorismeasuredfordifferentvaluesofvoltages*e.g.*0.5,4.0,4.5and4.0timesthe ratedoperatingvoltages.Themaximumvalueofpowerfactoratnormalworkingvoltagedoesnot exceed aspecifiedvalue(usually0.01)ataseriesoftemperaturesrangingfrom15°Cto65°C.The differenceinthepowerfactorbetweenratedvoltageand4.5timestheratedvoltageandtherated voltage and twice the rated voltage does not exceed a specified value. Sometimes the source is not able to supply charging current required by the test cable, a suitable choke in series with the test cable helps intidingoverthesituation.

(*vii*)Cablesaretestedforpowerfrequencya.c.andd.c.voltages.Duringmanufacturetheentire cableispassedthroughahighervoltagetestandtheratedvoltagetocheckthecontinuityofthecable. Asaroutinetestthecableissubjectedtoavoltage4.5timestheworkingvoltagefor10minwithout damagingtheinsulationofthecable.HVd.c.of4.8timestheratedd.c.voltageofnegativepolarityfor 30min.isappliedandthecableissaidtohavewithstoodthetestifnoinsulationfailuretakesplace.

(*viii*)Thetestcableissubjectedto10positiveand10negativeimpulsevoltageofmagnitudeas specifiedinspecification,thecableshouldwithstand5applicationswithoutanydamage.Usually,after theimpulse test, the power frequency dielectric power factor test is carried out to ensure that no failure occurredduringtheimpulsetest.

(*ix*)Partialdischargemeasurementofcablesisveryimportantasitgivesanindicationofex-pectedlifeofthecableanditgiveslocationoffault,ifany,inthecable.

Whenacableissubjectedtohighvoltageandifthereisavoidinthecable,thevoidbreaks downandadischargetakesplace.Asaresult,thereisasuddendipinvoltageintheformofanimpulse. ThisimpulsetravelsalongthecableasexplainedindetailinChapterVI.Thedurationbetweenthe normalpulseandthedischargepulseismeasuredontheoscilloscopeandthisdistancegivesthelocation ofthevoidfromthetestendofthecable.However,theshapeofthepulsegivesthenatureand intensityofthedischarge.

In ordertoscantheentirelengthofthecableagainstvoidsorotherimperfections,itispassed through a tube of insulating material filled with distilled water. Four electrodes, two at the end and two inthemiddleofthetubearearranged.Themiddleelectrodesarelocatedatastipulateddistanceand theseareenergizedwithhighvoltage.Thetwoendelectrodesandcableconductoraregrounded.As thecableispassedbetweenthemiddleelectrode,ifadischargeisseenontheoscilloscope,adefectin this part of the cable is stipulated and hence this part of the cable is removed from the rest of the cable.

TESTINGOFPOWERTRANSFORMERS

Transformerisoneofthemostexpensiveandimportantequipmentinpowersystem.Ifitisnotsuitably designeditsfailuremaycausealengthyandcostlyoutage.Therefore,itisveryimportanttobecautious while designing its insulation, so that it can withstand transient over voltage both due to switching and lightning.Thehighvoltagetestingoftransformersis,therefore,veryimportantandwouldbediscussed here. Other tests like temperature rise, short circuit, open circuit etc. are not considered here. However, thesecanbefoundintherelevantstandardspecification.

PartialDischargeTest

The testiscarriedoutonthewindingsofthetransformertoassessthemagnitudeofdischarges.The transformerisconnectedasatestspecimensimilartoanyotherequipmentasdiscussedinChapter-VI andthedischargemeasurementsaremade.Thelocationandseverityoffaultisascertainedusingthe travellingwavetheorytechniqueasexplainedinChapterVI.Themeasurementsaretobemadeatall theterminals of the transformer and it is estimated that if the apparent measured charge exceeds 10^4 picocoulombs,thedischargemagnitudeisconsideredtobesevereandthetransformerinsulationshould besodesignedthatthedischargemeasurementshouldbemuchbelowthevalueof10^4pico-coulombs.

ImpulseTestingofTransformer

The impulselevelofatransformerisdeterminedbythebreakdownvoltageofitsminorinsulation (Insulation between turn and between windings), breakdown voltage of its major insulation (insulation between windings and tank) and the flash over voltage of its bushings or a combination of these. The impulse characteristics of internal insulation in a transformer differs from flash over in air in two main respects.Firstlytheimpulseratioofthetransformerinsulationishigher(variesfrom4.1to4.2)than that of bushing (4.5forbushings,insulatorsetc.).Secondly,theimpulsebreakdownoftransformer

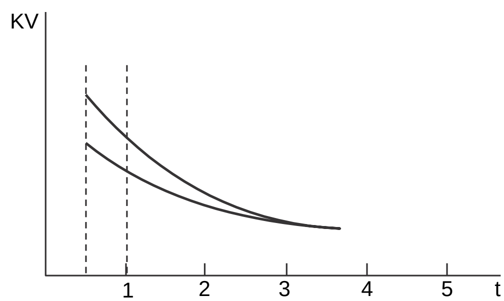


Fig.8.1 Volttimecurveoftypicalmajorinsulationintransformer

insulation inpracticallyconstantandisindependentoftimeofapplicationofimpulsevoltage.Fig.8.1 shows that after three micro seconds the flash over voltage is substantially constant. The voltage stress betweentheturnsofthesamewindingandbetweendifferentwindingsofthetransformerdepends uponthesteepnessofthesurgewavefront.Thevoltagestressmayfurthergetaggravatedbythepiling upactionofthewaveifthelengthofthesurgewaveislarge.Infact,duetohighsteepnessofthesurge waves,thefirstfewturnsofthewindingareoverstressedandthatiswhythemodernpracticeisto provideextrainsulationtothefirstfewturnsofthewinding.Fig.8.2showstheequivalentcircuitofa transformerwindingforimpulsevoltage.

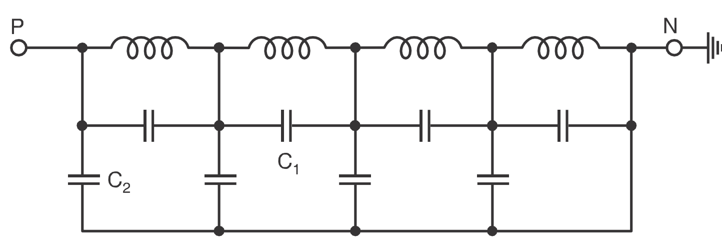


Fig.8.2 Equivalentcircuitofatransformerforimpulsevoltage

HereC_1 represents inter-turncapacitanceandC_2 capacitance betweenwindingandtheground (tank). In order that the minor insulation will be able to withstand the impulse voltage, the winding is subjected to chopped impulse wave of higher peak voltage than the full wave. This chopped wave is producedbyflashoverofarodgaporbushinginparallelwiththetransformerinsulation.Thechop-pingtimeisusually3to6microseconds.Whileimpulsevoltageisappliedbetweenonephaseand ground,highvoltageswouldbeinducedinthesecondaryofthetransformer.Toavoidthis,thesecond-arywindingsareshort-circuitedandfinallyconnectedtoground.Theshortcircuiting,however,de-creasestheimpedanceofthetransformerandhenceposesprobleminadjustingthewavefrontand wavetailtimingsofwave.Also,theminimumvalueoftheimpulsecapacitancerequiredisgivenby

where*P*=ratedMVAofthetransformerZ=percentimpedanceoftransformer.*V*=ratedvoltageof transformer.

Fig.8.3showsthearrangementofthetransformerforimpulsetesting.CROformsanintegral partofthetransformerimpulsetestingcircuit.Itisrequiredtorecordtowaveformsoftheapplied voltageandcurrentthroughthewindingundertest.

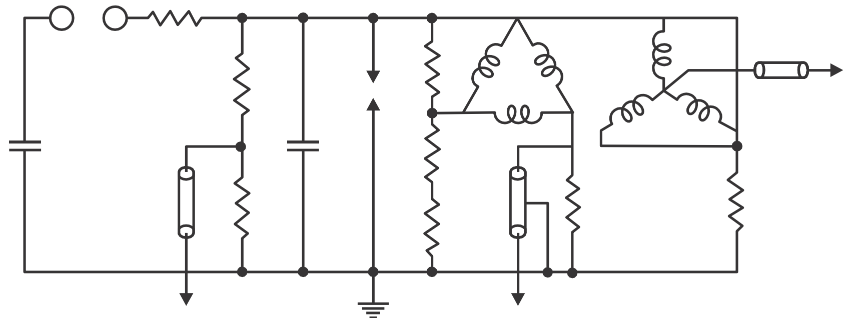


Fig.8.3 Arrangementforimpulsetestingoftransformer

Impulsetestingconsistsofthefollowingsteps:

(*i*)Applicationofimpulseofmagnitude75%oftheBasicImpulseLevel(BIL)ofthetransformer undertest.

(*ii*)Onefullwaveof100%ofBIL.

(*iii*)Twochoppedwaveof115%ofBIL.

(*iv*)Onefullwaveof100%BILand

(*v*)Onefullwaveof75%ofBIL.

During impulsetestingthefaultcanbelocatedbygeneralobservationlikenoiseinthetankor smokeorbubbleinthebreather.

If thereisafault,itappearsontheOscilloscopeasapartialofcompletecollapseoftheapplied voltage.

Study ofthewaveformoftheneutralcurrentalsoindicatedthetypeoffault.Ifanarcoccurs betweentheturnsorformturntotheground,atrainofhighfrequencypulsesareseenontheoscillo-scopeandwaveshapeofimpulsechanges.Ifitisapartialdischargeonly,highfrequencyoscillations areobservedbutnochangeinwaveshapeoccurs.

Thebushingformsanimportantandintegralpartoftransformerinsulation.Therefore,itsim-pulseflashovermustbecarefullyinvestigated.Theimpulsestrengthofthetransformerwindingis sameforeitherpolarityofwavewhereastheflashovervoltageforbushingisdifferentfordifferent polarity.Themanufacturer,however,whilespecifyingtheimpulsestrengthofthetransformertakes intoconsiderationtheoverallimpulsecharacteristicofthetransformer.

TESTINGOFCIRCUITBREAKERS

Anequipmentwhendesignedtocertainspecificationandisfabricated,needstestingforitsperform- ance.Thegeneraldesignistriedandtheresultsofsuchtestsconductedononeselectedbreakerandare thusapplicabletoallothersofidenticalconstruction.Thesetestsarecalledthetypetests.Thesetests areclassifiedasfollows:

4.Shortcircuittests:

(*i*)Makingcapacitytest.

(*ii*)Breakingcapacitytest.

(*iii*)Shorttimecurrenttest.

(*iv*)Operatingdutytes

4.Dielectrictests:

(*i*)Powerfrequencytest:

(*a*)Oneminutedrywithstandtest.

(*b*)Oneminutewetwithstandtest.

(*ii*)Impulsevoltagedrywithstandtest.

5.Thermaltest.

4.Mechanicaltest

Oncea particular design is found satisfactory, a large number of similar C.Bs. are manufactured formarketing.EverypieceofC.B.isthentestedbeforeputtingintoservice.Thesetestsareknownas routinetests.Withthesetestsitispossibletofindoutifincorrectassemblyorinferiorqualitymaterial hasbeen usedforaprovendesignequipment.Thesetestsareclassifiedas(*i*)operationtests,(*ii*)millivoltdroptests,(*iii*)powerfrequencyvoltagetestsatmanufacturer'spremises,and(*iv*)power frequencyvoltagetestsaftererectiononsite.

Wewilldiscussfirstthetypetests.Inthatalsowewilldiscusstheshortcircuittestsafterthe otherthreetests.

DielectricTests

Thegeneraldielectriccharacteristicsofanycircuitbreakerorswitchgearunitdependuponthebasic design*i.e.*clearances, bushing materials, etc. upon correctness and accuracy in assembly and upon the quality of materials used. For a C.B. these factors are checked from the viewpoint of their ability to withstand over voltages at the normal service voltage and abnormal voltages during lightning or other phenomenon.

Thetestvoltageisappliedforaperiodofoneminutebetween(*i*)phaseswiththebreakerclosed, (*ii*)phasesandearthwithC.B.open,and(*iii*)acrosstheterminalswithbreakeropen.Withthisthe breakermustnotflashoverorpuncture.Thesetestsarenormallymadeonindoorswitchgear.Forsuch C.Bstheimpulsetestsgenerallyareunnecessarybecauseitisnotexposedtoimpulsevoltageofavery highorder.Thehighfrequencyswitchingsurgesdooccurbuttheeffectoftheseincablesystemsused forindoorswitchgeararefoundtobesafelywithstoodbytheswitchgearifithaswithstoodthenormal frequencytest.

Sincetheoutdoorswitchgeariselectricallyexposed,theywillbesubjectedtoovervoltages causedbylightning.Theeffectofthesevoltagesismuchmoreseriousthanthepowerfrequencyvoltages inservice.Therefore,thisclassofswitchgearissubjectedinadditiontopowerfrequencytests,the impulsevoltagetests.

Thetestvoltageshouldbeastandard1/50µsecwave,thepeakvalueofwhichisspecified according to the rated voltage of the breaker. A higher impulse voltage is specified for non-effectively groundedsystemthanthoseforsolidlygroundedsystem.Thetestvoltagesareappliedbetween(*i*)each pole and earth in turn with the breaker closed and remaining phases earthed, and (*ii*) between all termi- nals on one side of the breaker and all the other terminals earthed, with the breaker open. The specified voltagesarewithstandvalues*i.e.*thebreakershouldnotflashoverfor10applicationsofthewave. Normallythistestiscarriedoutwithwavesofboththepolarities.

Thewetdielectrictestisusedforoutdoorswitchgear.Inthis,theexternalinsulationissprayed fortwominuteswhiletheratedservicevoltageisapplied;thetestovervoltageisthenmaintainedfor 30secondsduringwhichnoflashovershouldoccur.Theeffectofrainonexternalinsulationispartly beneficial,insofarasthesurfaceistherebycleaned,butisalsoharmfuliftheraincontainsimpurities.

ThermalTests

Thesetestsaremadetocheckthethermalbehaviourofthebreakers.Inthistesttheratedcurrent throughallthreephasesoftheswitchgearispassedcontinuouslyforaperiodlongenoughtoachieve steadystateconditions.Temperaturereadingsareobtainedbymeansofthermocoupleswhosehotjunc- tions areplacedinappropriatepositions.Thetemperatureriseaboveambient,ofconductors,must normallynotexceed40°Cwhentheratednormalcurrentislessthan800ampsand50°Cifitis800 ampsandabove.

Anadditionalrequirementinthetypetestisthemeasurementofthecontactresistancesbetween theisolatingcontactsandbetweenthemovingandfixedcontacts.Thesepointsaregenerallythemain sourcesofexcessiveheatgeneration.Thevoltagedropacrossthebreakerpoleismeasuredfordifferent valuesofd.c.currentwhichisameasureoftheresistanceofcurrentcarryingpartsandhencethatof contacts.

MechanicalTests

AC.B.mustopenandcloseatthecorrectspeedandperformsuchoperationswithoutmechanical failure. The breaker mechanism is, therefore, subjected to a mechanical endurance type test involving repeatedopeningandclosingofthebreaker.B.S.116:1952requires500suchoperationswithout failureandwithnoadjustmentofthemechanism.Somemanufacturefeelthatasmanyas20,000 operationsmaybereachedbeforeanyusefulinformationregardingthepossiblecausesoffailuremay beobtained.Aresultingchangeinthematerialordimensionsofaparticularcomponentmayconsider-ablyimprovethelifeandefficiencyofthemechanism.

ShortCircuitTests

Thesetestsarecarriedoutinshortcircuittestingstationstoprovetheratingsofthe C.Bs.Before discussingthetestsitispropertodiscussabouttheshortcircuittestingstations.

Therearetwotypesoftestingstations;(*i*)fieldtype,and(*ii*)laboratorytype.

In caseoffieldtypestationsthepowerrequiredfortestingisdirectlytakenfromalargepower system.Thebreakertobetestedisconnectedtothesystem.Whereasthismethodoftestingiseconomi-calforhighvoltageC.Bs.itsuffersfromthefollowingdrawbacks:

4.Thetestscannotberepeatedlycarriedoutforresearchanddevelopmentasitdisturbsthe wholenetwork.

4.Thepoweravailabledependsuponthelocationofthetestingstations,loadingconditions, installedcapacity,etc.

5.TestconditionslikethedesiredrecoveryvoltagetheRRRVetc.cannotbeachievedcon- veniently.

In caseoflaboratorytestingthepowerrequiredfortestingisprovidedbyspeciallydesigned generators.Thismethodhasthefollowingadvantages:

4.Testconditionssuchascurrent,voltage,powerfactor,restrikingvoltagescanbecontrolled accurately.

4.Severalindirecttestingmethodscanbeused.

5.Testscanberepeatedandhenceresearchanddevelopmentoverthedesignispossible.

Thelimitationsofthismethodarethecostandthelimitedpoweravailabilityfortestingthe breakers.

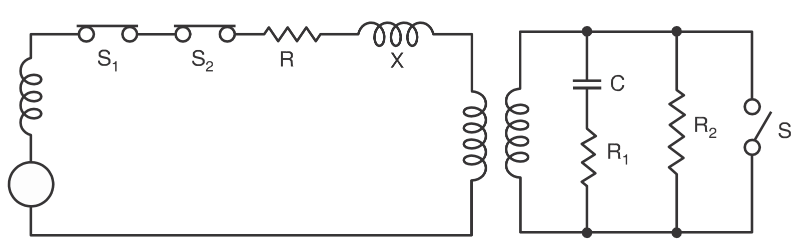


Fig.8.5 Circuitfordirecttesting

HereX_G=generatorreactance,S_1 andS_2aremasterandmakeswitchesrespectively.$R$and$X$are theresistanceandreactanceforlimitingthecurrentandcontrolofp.f.,Tisthetransformer,C,R_1 andR_2 isthecircuitforadjustingtherestrikingvoltage.

Fortesting,breakingcapacityofthebreakerundertest,masterandbreakerundertestareclosed first.Shortcircuitisappliedbyclosingthemakingswitch.Thebreakerundertestisopenedatthe desiredmomentandbreakingcurrentisdeterminedfromtheoscillographasexplainedearlier. Formakingcapacitytestthemasterandthemakeswitchesareclosedfirstandshortcircuitis applied by closing the breaker under test. The making current is determined from the oscillograph as explainedearlier.

Questions:

1. Explaintheprocedurefortestingstringinsulator.
2. Describethearrangementofinsulatorsforperformingvarioustests.
3. Listoutvarioustestsobecarriedoutoninsulatorandgiveabriefaccountofeachtest.
4. Writeashortnoteonthecablesamplepreparationbeforeitissubjectedtovarioustests.
5. Listoutvarioustestsobecarriedoutonacableandgiveabriefaccountofeachtest.
6. Explainbrieflyvarioustestsobecarriedoutonabushing.
7. Explain the function of discharge device used in a power capacitor and explain the test for efficacy of this device.
8. Explaintheprocedureforperforming(*i*)IRtest(*ii*)Stabilitytestand(*iii*)Partialdischargetest.
9. Explainbrieflyimpulsetestingofpowertransformer.
10. DescribevarioustestsobecarriedoutonC.B.

ShortCircuitTestPlants

The essentialcomponentsofatypicaltestplantarerepresentedinFig.8.4.Theshort-circuitpoweris supplied by specially designed short-circuit generators driven by induction motors. The magnitude of voltage can be varied by adjusting excitation of the generator or the transformer ratio. A plant master-breakerisavailabletointerruptthetestshortcircuitcurrentifthetestbreakershouldfail.Initiationof theshortcircuitmaybebythemasterbreaker,butisalwaysdonebyamakingswitchwhichisspecially designedforclosingonveryheavycurrentsbutnevercalledupontobreakcurrents.Thegenerator windingmaybearrangedforeitherstarordeltaconnectionaccordingtothevoltagerequired;by furtherdividingthewindingintotwosectionswhichmaybeconnectedinseriesorparallel,achoiceof fourvoltagesisavailable.Inadditiontothistheuseofresistorsandreactorsinseriesgivesawide rangeofcurrentandpowerfactors.Thegenerator,transformerandreactorsarehousedtogether,usu-allyinthebuildingaccommodatingthetestcells.

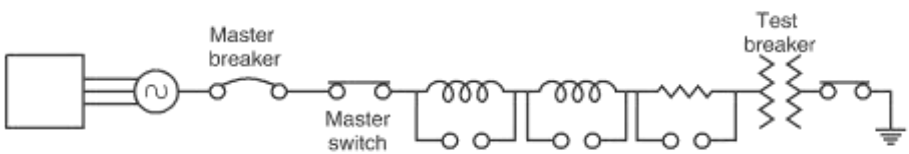


Fig.8.4 Schematicdiagramofatypicaltestplant

Generator

Theshortcircuitgeneratorisdifferentindesignfromtheconventionalpowerstation.Thecapacityof thesegeneratorsmaybeoftheorderof2000MVAandveryrigidbracingoftheconductorsandcoil endsisnecessaryinviewofthehighelectromagneticforcespossible.Thelimitingfactorforthemaxi-mumoutputcurrentistheelectromagneticforce.Sincetheoperationofthegeneratorisintermittent, thisneednotbeveryefficient.Thereductionofventilationenablesthemainfluxtobeincreasedand permitstheinclusionofextracoilendsupports.Themachinereactanceisreducedtoaminimum.

Immediatelybeforetheactualclosingofthemakingswitchthegeneratordrivingmotorisswitched outandtheshortcircuitenergyistakenfromthekineticenergyofthegeneratorset.Thisisdoneto avoidanydisturbancetothesystemduringshortcircuit.However,inthiscaseitisnecessarytocom-pensateforthedecrementinggeneratorvoltagecorrespondingtothediminishinggeneratorspeeddur-ingthetest.Thisis achievedbyadjustingthegeneratorfieldexcitationtoincreaseatasuitablerate duringtheshortcircuitperiod.

ResistorsandReactors

Theresistorsareusedtocontrolthep.f.ofthecurrentandtocontroltherateofdecayofd.c.component ofcurrent.Thereareanumberofcoilsperphaseandbycombinationsofseriesandparallelconnec-tions,desiredvalueofresistanceand/orreactancecanbeobtained.

Capacitors

Theseareusedforbreakinglinechargingcurrentsandforcontrollingtherateofre-strikingvoltage.

ShortCircuitTransformers

Theleakagereactanceofthetransformerislowsoastowithstandrepeatedshortcircuits.Sincethey areinuseintermittently,theydonotposeanycoolingproblem.Forvoltagehigherthanthegenerated voltages,usuallybanksofsinglephasetransformersareemployed.IntheshortcircuitstationatBhopal therearethreesinglephaseunitseachof11kV/76kV.Thenormalratingis30MVAbuttheirshort circuitcapacityis475MVA.

MasterC.Bs.

Thesebreakersareprovidedasbackupwhichwilloperate,shouldthebreakerundertestfailtooper- ate.Thisbreakerisnormallyairblasttypeandthecapacityismorethanthebreakerundertest.After everytest,itisolatesthetestbreakerfromthesupplyandcanhandlethefullshortcircuitofthetest circuit.

MakeSwitch

Themakeswitchisclosedafterotherswitchesareclosed.Theclosingoftheswitchisfast,sureand withoutchatter.Inordertoavoidbouncingandhenceweldingofcontacts,ahighairpressureismain- tainedinthechamber.Theclosingspeedishighsothatthecontactsarefullyclosedbeforetheshort circuitcurrentreachesitspeakvalue.

TestProcedure

Beforethetestisperformedallthecomponentsareadjustedtosuitablevaluessoastoobtaindesired valuesofvoltage,current,rateofriseofrestrikingvoltage,p.f.etc.Themeasuringcircuitsarecon- nectedandoscillographloopsarecalibrated.

Duringthetestseveraloperationsareperformedinasequenceinashorttimeoftheorderof 0.2sec. This is done with the help of a drum switch with several pairs of contacts which is rotated with amotor.Thisdrumwhenrotatedclosesandopensseveralcontrolcircuitsaccordingtoacertainse- quence.Inoneofthebreakingcapacityteststhefollowingsequencewasobserved:

(*i*)Afterrunningthemotortoaspeedthesupplyisswitchedoff.

(*ii*)Impulseexcitationisswitchedon.

(*iii*)MasterC.B.isclosed.

(*iv*)Oscillographisswitchedon.

(*v*)Makeswitchisclosed.

(*vi*)C.B.undertestisopened.

(*vii*)MasterC.B.isopened.

(*viii*)Excitercircuitisswitchedoff.