HIGH VOLTAGE ENGINEERING

- Basic Knowledge of High Voltage

Bachelor’s Level
Eighth Semester
Nepal Engineering Collage

Mohan Neupane
Visiting Faculty

Marks Weightage

Final Exam - 50

Sessional -50

- **Attendance -5**
- **Assignment -10 [2]**
- **Class Test -5 [2]**
- **Presentation -10 [2]**
- **Internal Assessment -10[1]**
- **Interaction /Viva -10**

Course Book -

S. K. Singh, *"Fundamentals of High Voltage Engineering"*, Dhantpat Rai & Co., 2012

Reference Books:

R. D. Begamudre, *Extra High Voltage AC Transmission Engineering*, New Age International Publishers, 2006.

M. S. Naidu and V. Kamaraju, *High Voltage Engineering*, Tata McGraw-Hill, 2009.

E. Kuffel, W. S. Zaengl and J. Kuffel, *High Voltage Engineering*, Newnes, 2000.

J. R. Lucas, *High Voltage Engineering*, 2001.

DEVELOPMENT HIGH VOLTAGE SYSTEM

Transmission System

High Voltage System

Low Voltage

Generation of High Voltages and Currents

Course Chapter Details

Objectives:-

- **Generation**, **Measurement** and **Testing** of High Voltages and Currents
- **Power Cables** and **Protection** used in **High Voltages**
- **Over Voltage** Phenomena and **Insulation Co-ordination**

Course Chapter Details

Generation of High Voltages and Currents **(10 Hours)**

Generation of High DC Voltages
Rectifier and Voltage Doubler Circuits
Voltage Multiplier Circuits: Cascaded Rectifier Unit with Pulse Generator, Cockroft- Walton-circuit

Generation of High AC Voltages
Cascaded-Transformer Connection, Resonant Transformers
High Frequency AC Voltages and Advantages of High-Frequency Transformers

Generation of Impulse Voltages
Standard Impulse wave shapes
Types of Impulse Generator Circuits and their analysis
Effect of Circuit Parameters on Impulse Generator Circuits
Wave shaping Circuit and Control
Multistage Impulse Generator: Marx Circuit
Van de-Graff Generator

Generation of Impulse Currents
Impulse Current Waveforms
Circuit for Producing Impulse Current Waves

Measurement of High Voltages and Currents **(8 Hours)**

Various Techniques for Measuring High Voltages and Currents Direct Measurement
Electrostatic Voltmeters
Sphere Gaps and Rod-Gaps

Transformer and Potential Divider Methods
Transformer ratio method
Resistive and Capacitive Divider Method, Resistive Capacitive Divider Method

Measurement of Impulse Voltage and Currents
Impulse Voltage Measurement: Cathode Ray Oscilloscope (CRO), Klydonograph and its application, Peak Voltmeters
Impulse Current Measurement: Magnetic Potentiometers or Rogowski Coil, Magnetic Links

Introduction to High Voltage Testing (8 Hours)

Standard Testing Procedures, Type and Routine Tests General Tests Carried Out on High Voltage Equipment:
Sustained low-frequency Tests, High Voltage Direct Current Tests, High Frequency Tests, Surge or Impulse Tests, Flashover Tests

Testing of Cables, Line Insulators, Bushings, Isolators, Circuit Breakers and Surge Arrestors Non-destructive Insulation Test Techniques
Measurement of Dielectric Constant and loss factor, Partial Discharge Measurement and Test Circuits

High Voltage Power Cables (7 Hours)

Classification of Cables

Typical Construction and Cross-Sections of Cables

Dependence of Power Rating of Cable in Different Environments

Electrical Characteristics of EHV Cables

Belted Cables and its Capacitance Measurement

Super Tension Cables: H-type, Separate Lead (S.L) type and H.S.L type cables

Pressurized High Voltage Cables

Oil-pressure cables, Gas-pressure cables(External and Internal Pressure cables)

Materials used for Insulation in HV cables: Oil filled, XLPE

Methods for Laying Underground Cables

Over Voltage Phenomena and Insulation Co-ordination (6 Hours)

Overvoltage due to Lighting and Switching Surges

Power Frequency Overvoltage

Insulation Co-ordination

Necessity of Insulation Co-ordination

Equipment Insulation level

Insulation Co-ordination and volt-time characteristics

Standards for Insulation Co-ordination: IEC 71

Insulation Co-ordination in EHV and UHV systems

Surge arrestor sizing

Protection Against High Voltage Surge **(6 Hours)**

Protection of Lines

Application of Ground Rods and Counter Poise

Ground Wire

Lightning Arrestors and their characteristics: Gap type SiC Arrestors, Metal Oxide Arrestors, Thyrite type for EHV

Protector Tube and Surge Absorber

Protection of Insulators: Arcing Horns, Corono and Grading Rings

Introduction High Voltage :-

What :-

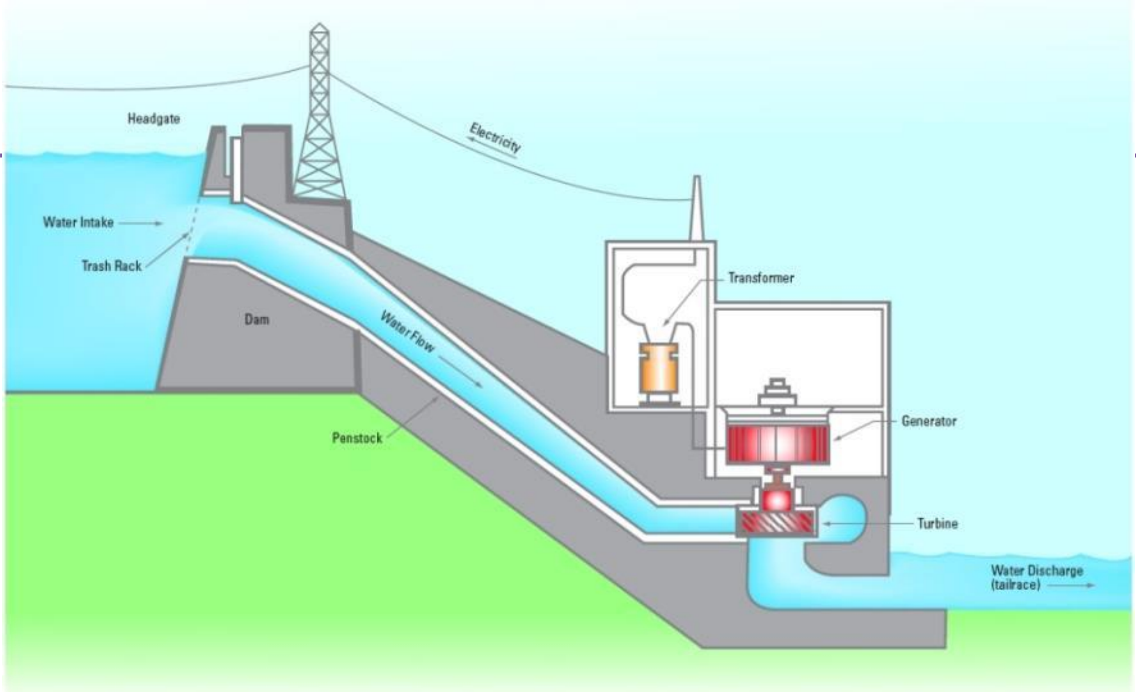
High voltage usually means electrical energy at voltages high enough to inflict harm on living organism.

- Two factors considered in classifying a voltage as "high voltage"
  - Spark in air,
  - The danger of electric shock by contact or proximity

•The International Electrotechnical Commission and its national counterparts (IET, IEEE, VDE, etc.) define high voltage as above 1000 V for AC, and at least 1500 V for DC — and distinguish it from low voltage (50–1000 V AC or 120–1500 V DC) and extra-low voltage (<50 V AC or <120 V DC) circuits.

•Different form of High Voltage :-

- **Natural Forms** of High Voltage [Transfer of +ve charge upward to the cloud for system's dynamic balance and controlled by thunderstorm activity]
- **Man-made** or Synthetic type



Potential benefits of Man made high voltages are –

- Reduce Line Loss [HV, Low Conductor R, Low Loss]
- High Voltage develop electro static force - Cathode ray tube, spray painting etc.
- Ionization in dielectric materials where energy is released in controlled quantities.
- For the testing problems of HV, EHV and UHV over head lines, cables

• 100kV at around 1910 and after then higher voltage system developed around the world.

Development History of High voltages :–

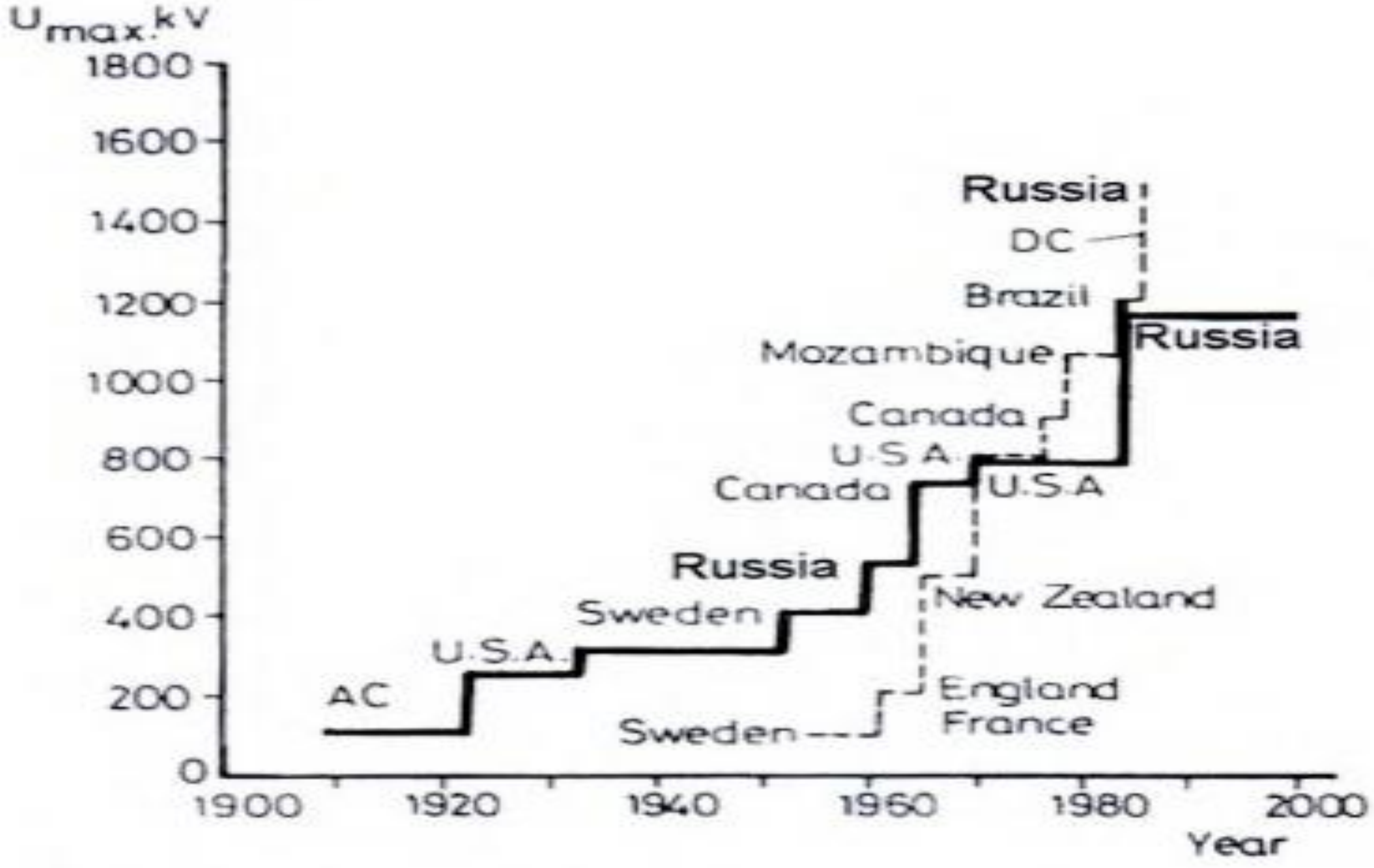


Figure 1.3 Historical development of transmission AC and DC voltages.

VOLTAGE CLASS:-

Below 11kV : Low voltage

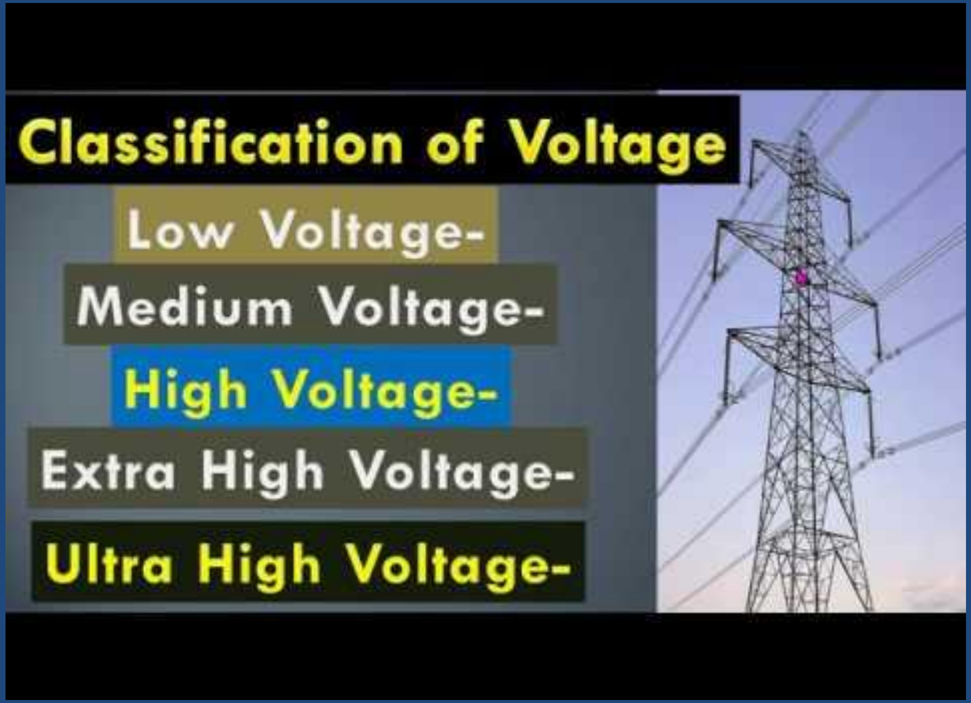
11kV – 100kV : HV (high Voltage)

100kV – 400kV : VHV (Very high voltage)

400kV and above : EHV (Extra high voltage)

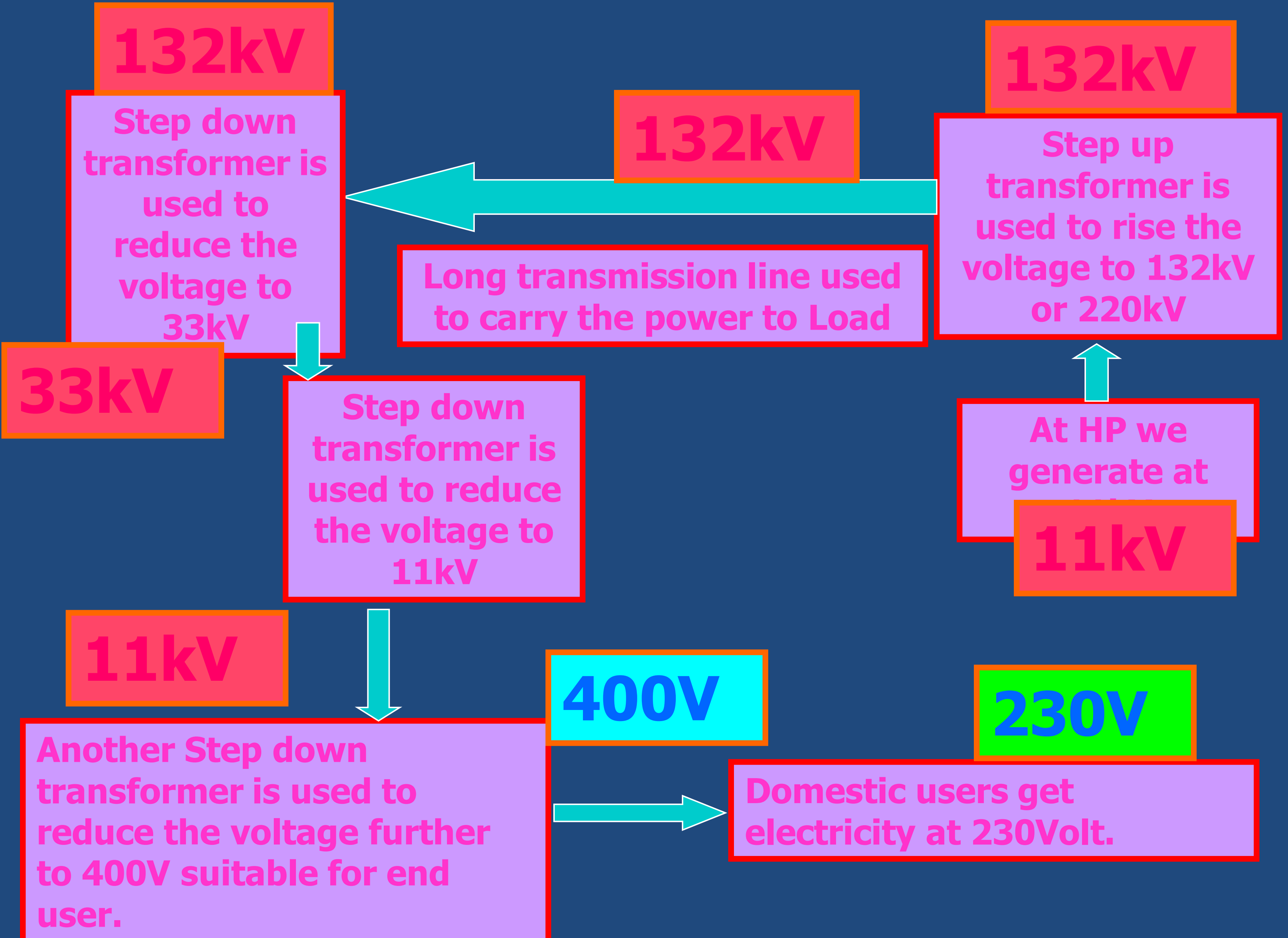
UHV : Ultra high voltage

- **Distribution and Transmission System In Nepal–**
  - **Distribution Voltages:-**
    - **3.3 KV /6.6KV/11KV/22KV/33KV – Variation 5%**
  - **Transmission Voltage:-**
    - **33KV/ 66KV/ 132KV/ 220KV/ 400KV – Variation 10%**
  - **Frequency :-50 Hz, Power Factor :- Distribution-0.8, Generation :-0.85-1**

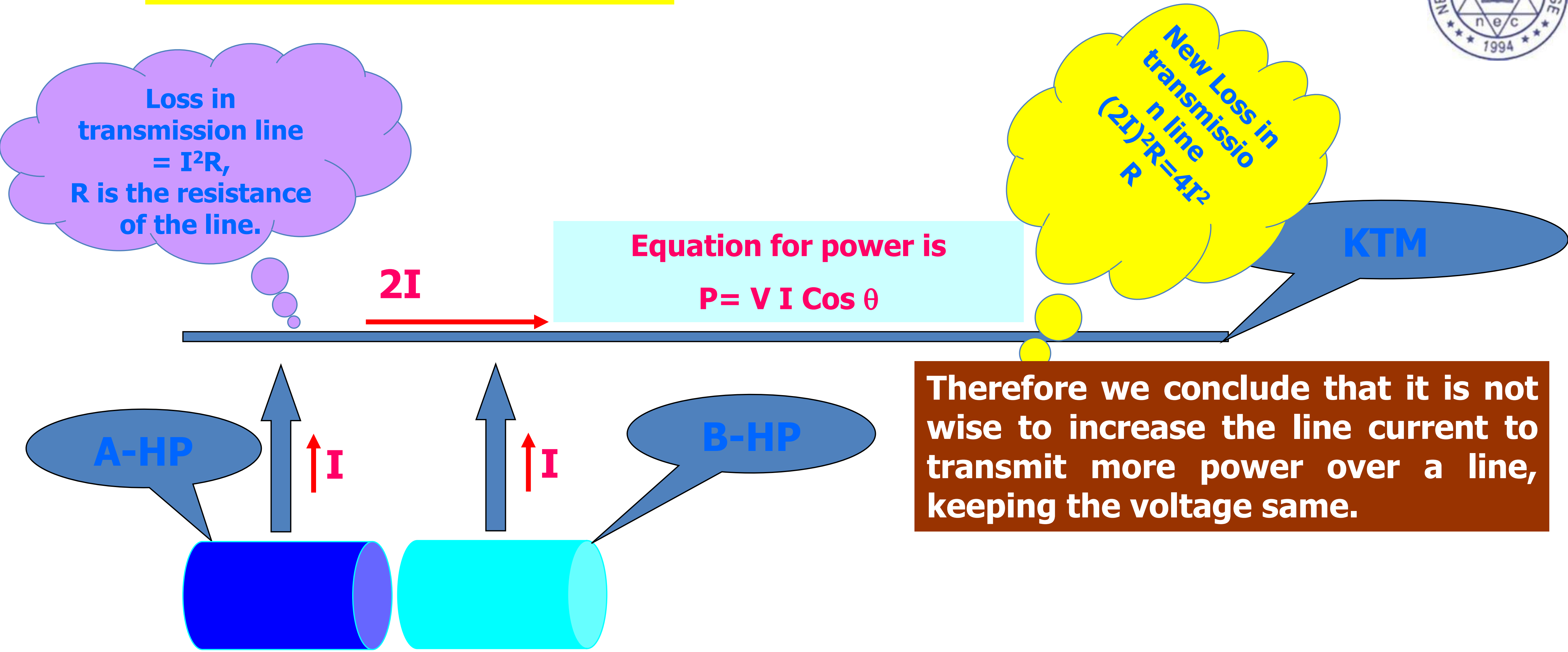


Name	Range
Low voltage	100 – 1000 V
Medium voltage	1 kV – 100 kV
High voltage	100 kV – 345 kV
Extra high voltage	345 kV – 765 kV
Ultra high voltage	> 765 kV

- High voltage is specially referred to electrical power system.

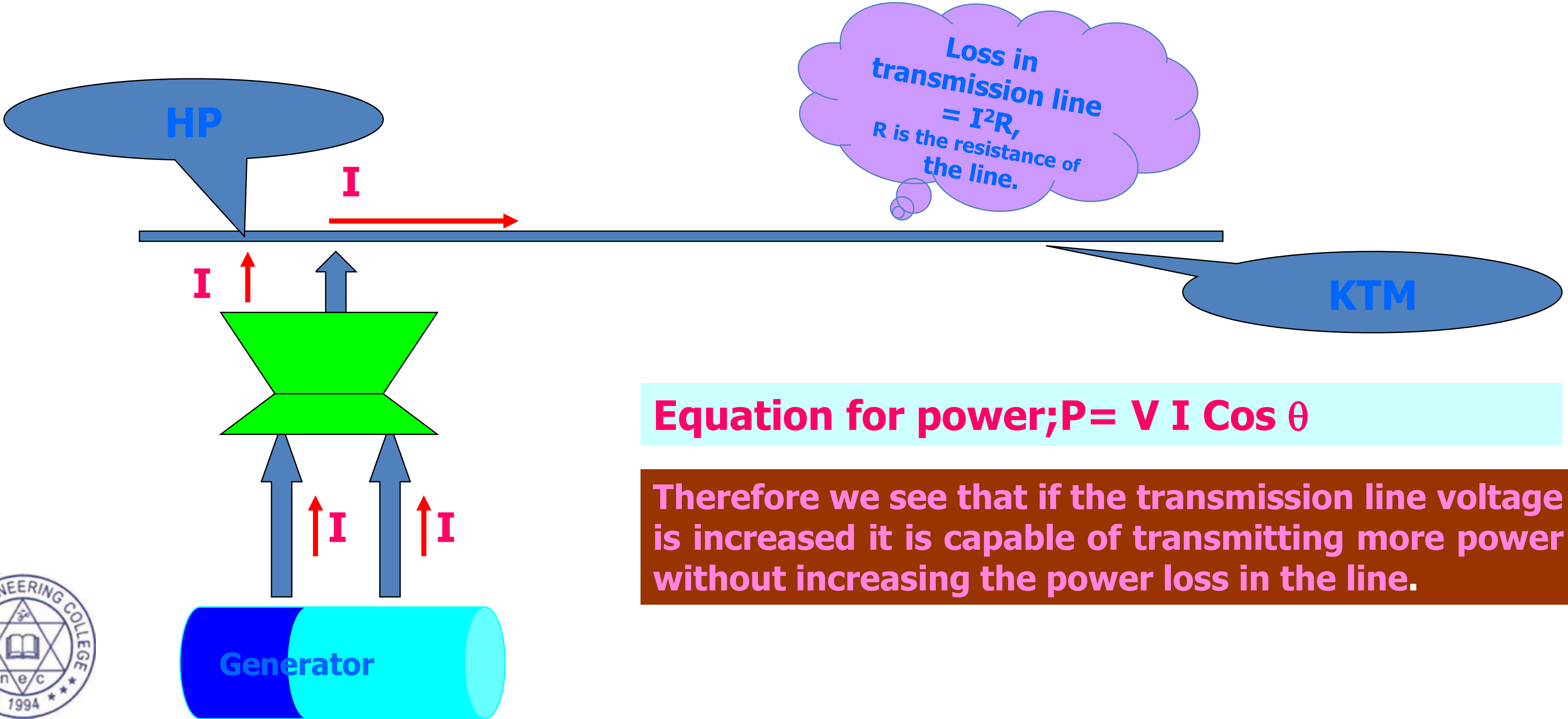


WHY HIGH VOLTAGE :-



Therefore we conclude that it is not wise to increase the line current to transmit more power over a line, keeping the voltage same.

WHY HIGH VOLTAGE :-



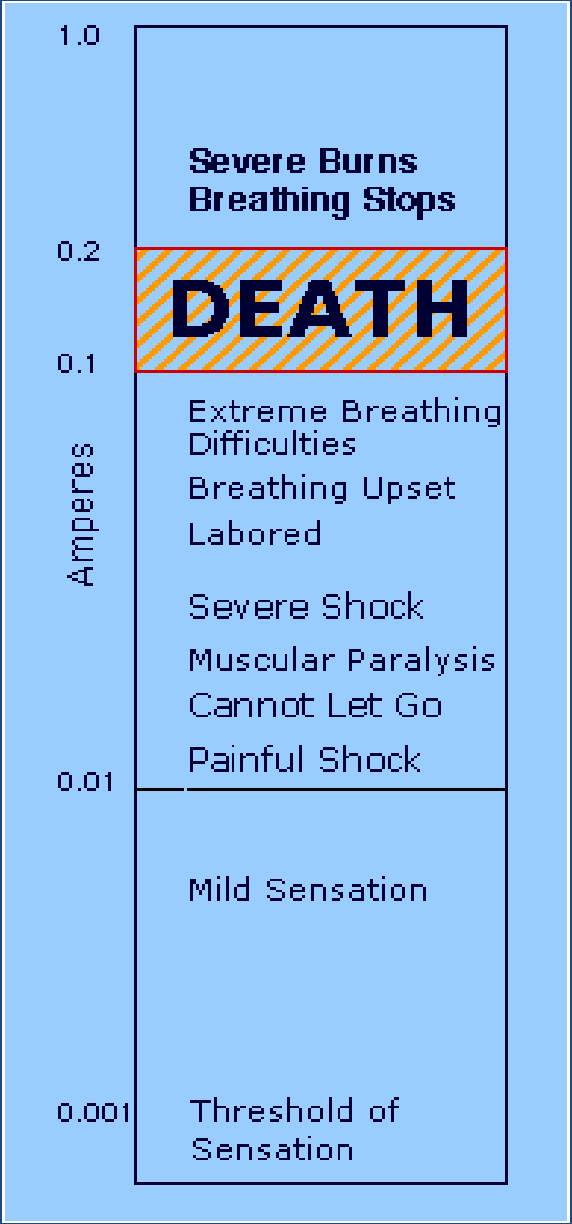
Equation for power;P= V I Cos θ

Therefore we see that if the transmission line voltage is increased it is capable of transmitting more power without increasing the power loss in the line.

Fields of Applications of HV

- Power system Engineering
- Research Laboratories
- Industries
- Nuclear Research, Particle accelerators
- Electrostatic precipitators
- Automobile ignition coils
- Medical applications like X-ray machine

Danger Limit of Ampere

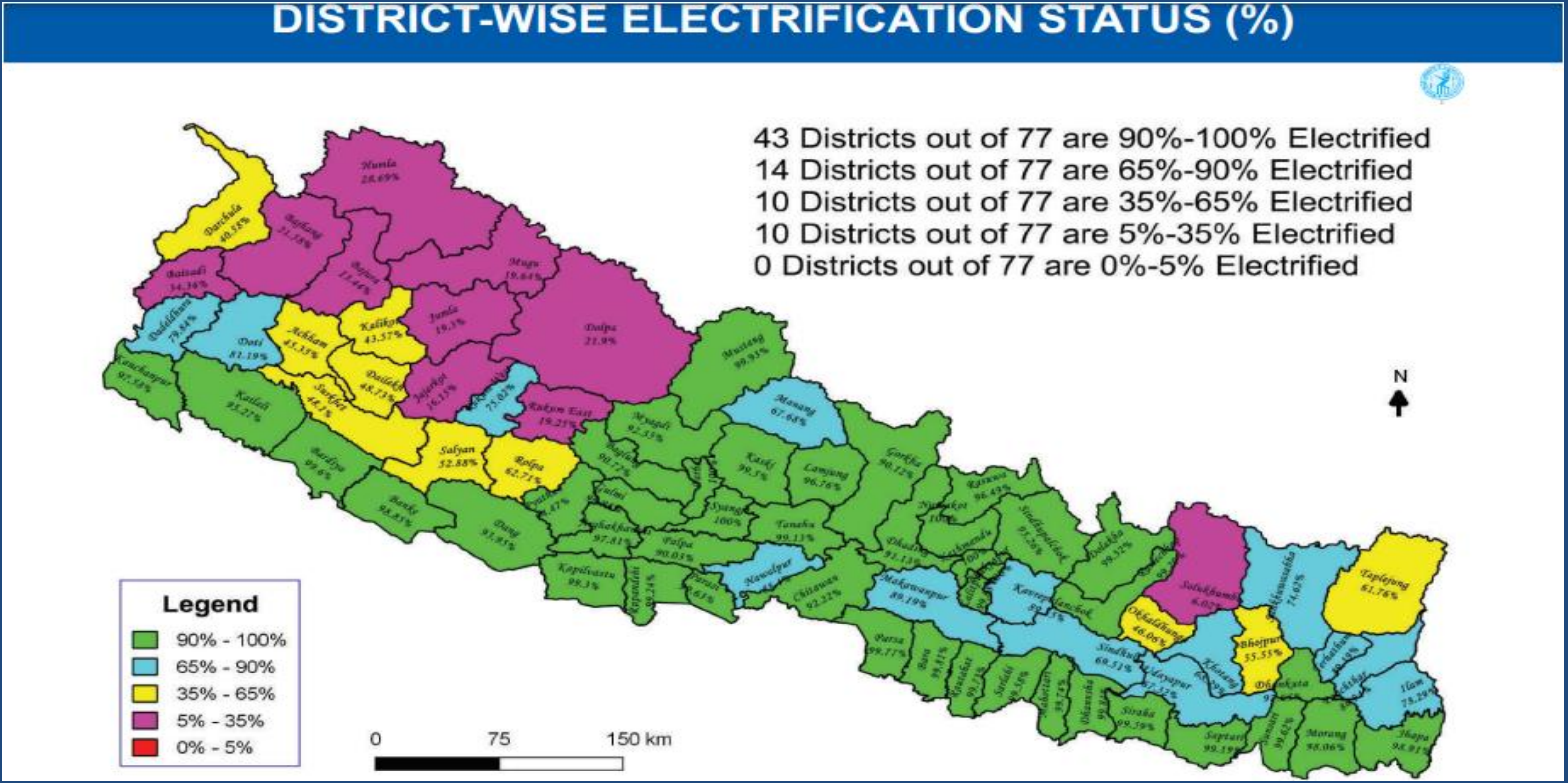


EFFECTS OF ELECTRICAL CURRENT IN THE HUMAN BODY	
Current	**Reaction**
Below 1 Milliampere	Generally not perceptible
1 Milliampere	Faint Tingle
5 Milliampere	Slight shock felt. Not painful but disturbing. Average individual can let go. Strong involuntary reactions can lead to other injuries.
6 to 25 Milliampere (women)	Painful shocks. Loss of muscle control.
9 to 30 Milliampere (men)	The freezing current or "let go" range. If extensor muscles are excited by shock, the person may be thrown away from the power source. Individuals cannot let go. Strong involuntary reactions can lead to other injuries.
50 to 150 Milliamperes	Extreme pain, respiratory arrest, severe muscle reactions. Death is possible.
1.0 to 4.3 Amperes	Rhythmic pumping action of the heart ceases. Muscular contraction and nerve damage occur; death is likely.
10 Amperes	Cardiac arrest, severe burns, death is probable.

Standards

- Voltages: ANSI C84.1- 1995 System Voltages
- Voltages: IEEE 1312 – 1987 AC Electrical Systems and Equipment Operating Voltages above 230kv
- BILs: ANSI 92 defines BILs for the equipment manufacturers to use
- IEEE std 4 – 1995 Standard Techniques for High Voltage Testing
- Circuit Breakers: ANSI C-37.06 1997
- Transformers: ANSI C57.12 – 1993 Liquid Immersed Distribution, Power and Regulating Power Transformers
- Switches: IEEE C37.34 Standard Test Code for High Voltage Switches
- Insulators: ANSI C29.8 & C29.9 Cap and Pin Type & Post Type Insulators
- Arresters: IEEE C62.11 Metal Oxide surge arresters for AC Power Circuits
- Arresters: IEEE C62.22 Guide for application of Metal Oxide surge arresters for Alternating Current Systems

Electricity Development



Generation of High DC Voltage

- High D.C. voltages - industries, research medical sciences etc.
- HVDC transmission (both overhead lines and underground cables) popular.
- HVDC is used for testing HVAC cables of long lengths due to 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 for electrostatic precipitation, communication systems etc. HV DC is also being used extensively in physics for particle acceleration and in medical Equipment (X-Rays).

- The most efficient method of generating high D.C. voltages - process of Rectification employing voltage multiplier circuits. Electrostatic generators have also been used for generating high D.C. voltages.
- According to IEEE standards 4-1978, the value of a direct test voltage is defined by its arithmetic mean value Vd and is expressed mathematically as

$$V_d = \frac{1}{T}\int_0^T v(t)\,dt$$

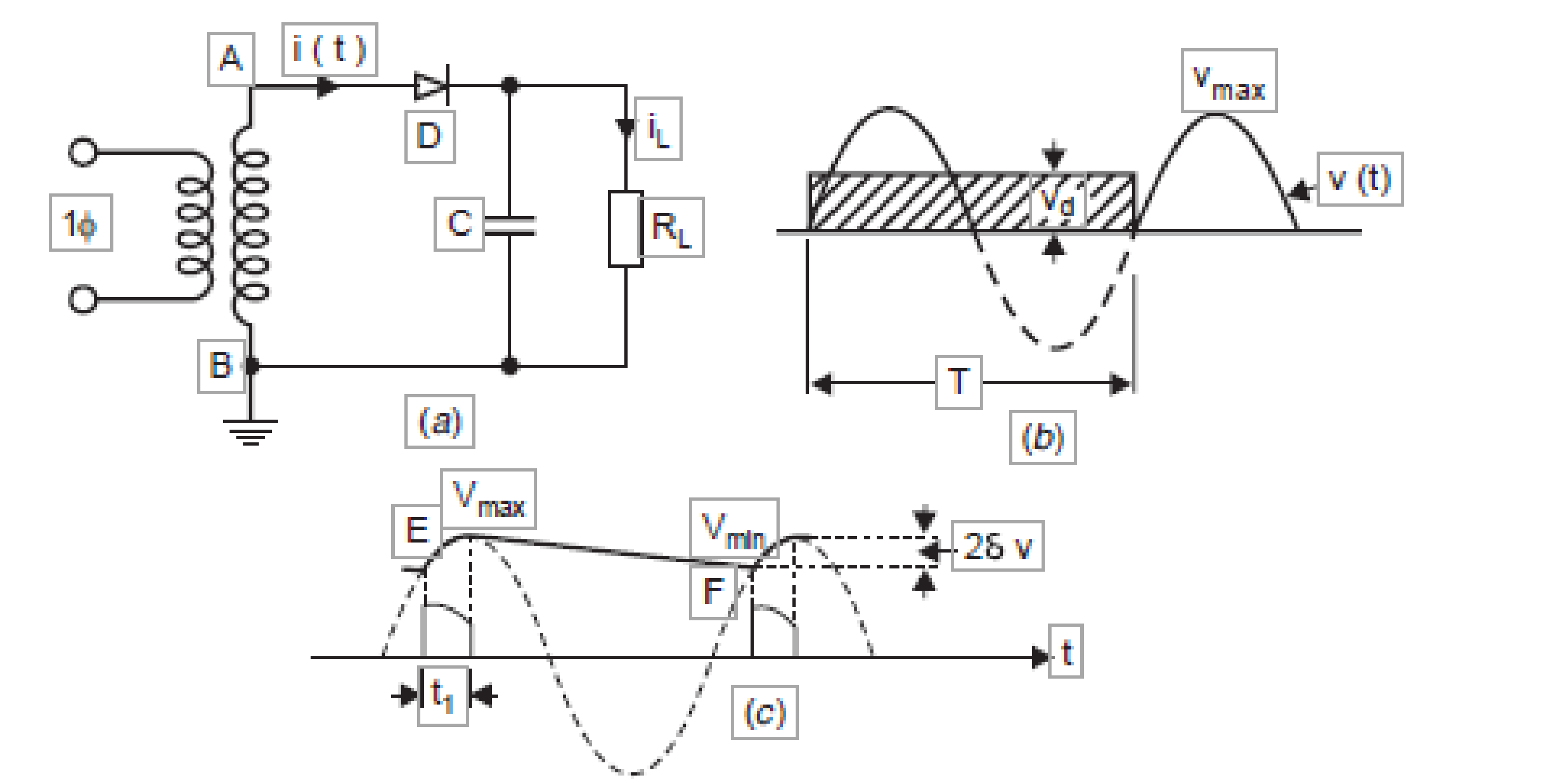
where T is the time period of the voltage wave having a frequency f = 1/T. Test voltages generated using rectifiers are never constant in magnitude. These deviate from the mean value periodically and this deviation is known as ripple. The magnitude of the ripple voltage denoted by δV is defined as half the difference between the maximum and minimum values of voltage i.e.,

$$\delta V = \frac{1}{2}[V_{max} - V_{min}]$$

and ripple factor is defined as the ratio of ripple magnitude to the mean value Vd i.e., δV/Vd. The test voltages should not have ripple factor more than 5% or as specified in a specific standard for a particu-lar equipment as the requirement on voltage shape may differ for different applications.

Half Wave Rectifier Circuit:-

The simplest circuit for generation of high direct voltage is the half wave rectifier shown in Fig. Here RL is the load resistance and C the capacitance to smoothen the D.C. output voltage.



- Without capacitor pulsating DC voltage at the output terminals whereas with the capacitance C, the pulsation at the output terminal are reduced.
- Assuming the ideal transformer and small internal resistance of the diode during conduction, the capacitor C is charged to the maximum voltage Vmax during conduction of the diode D. Assuming that there is no load connected, the DC voltage across capacitance remains constant at Vmax whereas the supply voltage oscillates between ± Vmax. During negative half cycle the potential of point A becomes – Vmax and hence the diode must be rated for 2 Vmax. This would also be the case if the transformer is grounded at A instead of B as shown in Fig. 2.1 (a).
- Such a circuit is known as voltage doubler due to Villard for which the output voltage would be taken across D. This d.c. voltage, however, oscillates between zero and 2Vmax and is needed for the Cascade circuit.

- If the circuit is loaded, the output voltage does not remain constant at Vmax. After point E (Fig. 2.1 (c)), the supply voltage becomes less than the capacitor voltage, diode stops conducting. The capacitor can not discharge back into the a.c. system because of one way action of the diode. Instead, the current now flows out of C to furnish the current iL through the load. While giving up this energy, the capacitor voltage also decreases at a rate depending on the time constant CR of the circuit and it reaches the point F corresponding to Vmin. Beyond F, the supply voltage is greater than the capacitor voltage and hence the diode D starts conducting charging the capacitor C again to Vmax and also during this period it supplies current to the load also. This second pulse of ip(ic + il) is of shorter duration than the initial charging pulse as it serve mainly to restore into C the energy that C meanwhile had supplied to load. Thus, while each pulse of diode current lasts much less than a half cycle, the load receives current more continuously from C.

- Assuming the charge supplied by the transformer to the load during the conduction period t, which is very small to be negligible, the charge supplied by the transformer to the capacitor during conduction equals the charge supplied by the capacitor to the load. Note that ic>> iL. During one period T = 1/f of the a.c voltage, a charge Q is transferred to the load R_L and is given as

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

where I is the mean value of the d.c output iL(t) and VRL(t) the d.c. voltage which includes a ripple as shown in Fig. 2.1 (c).

This charge is supplied by the capacitor over the period T when the voltage changes from Vmax to Vmin over approximately period T neglecting the conduction period of the diode.

Suppose at any time the voltage of the capacitor is V and it decreases by an amount of dV over the time dt then charge delivered by the capacitor during this time is

$$dQ = CdV$$

Therefore, if voltage changes from Vmax to Vmin, the charge delivered by the capacitor

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

Or the magnitude of charge delivered by the capacitor

$$Q = C\left(V_{max} - V_{min}\right)$$

Using equation (2.2)

$$Q = 2\delta VC$$

Therefore,

$$2\delta VC = IT$$

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

Equation shows that the ripple in a rectifier output depends upon the load current and the circuit parameter like f and C. The product f C is, therefore, an important design factor for the rectifiers. The higher the frequency of supply and larger the value of filtering capacitor the smaller will be the ripple in the d.c. output.

❖ **The single phase half-wave rectifier circuits have the following disadvantages:**

The size of the circuits is very large if high and pure d.c. output voltages are desired.
The h.t. transformer may get saturated if the amplitude of direct current is comparable with the nominal alternating current of the transformer.

It is to be noted that all the circuits considered here are able to supply relatively low currents and therefore are not suitable for high current applications such as HVDC transmission.

When high d.c. voltages are to be generated, **voltage doubler or cascaded voltage multipl**ier circuits are used. One of the most popular doubler circuit due to Greinacher is shown in Fig.

Suppose B is more positive with respect to A and the diode D1 conducts thus charging the capacitor C1 to Vmax with polarity as shown in Fig. 2.2. During the next half cycle terminal, A of the capacitor C1 rises to Vmax and hence terminal M attains a potential of 2 Vmax. Thus, the capacitor C2 is charged to 2Vmax through D2. Normally the voltage across the load will be less than 2 Vmax depending upon the time constant of the circuit C2 - RL.

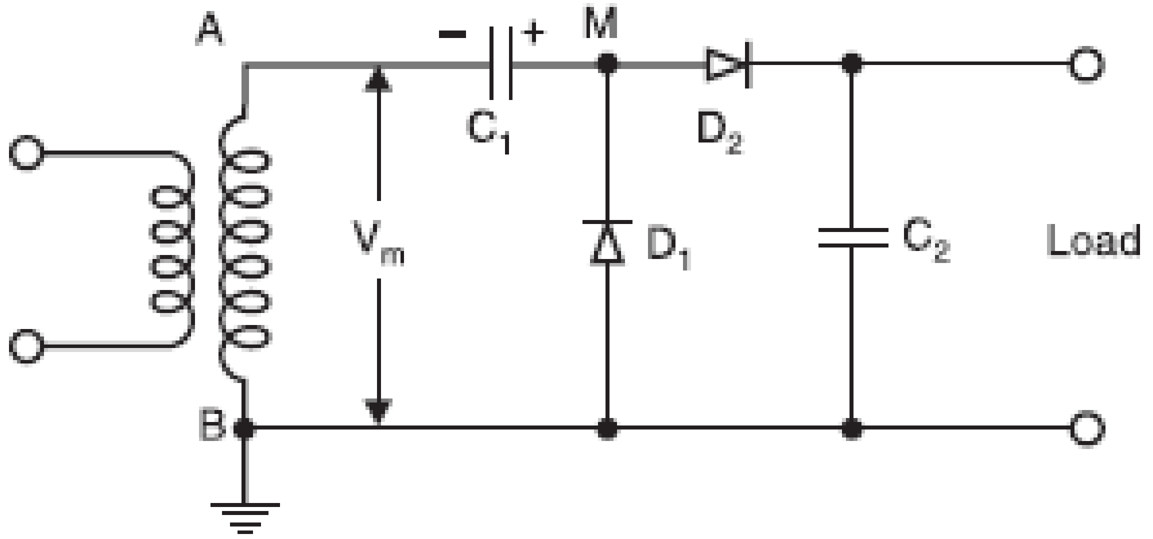


Fig. 2.2 Greinacher voltage doubler circuit

COCKROFT-WALTON VOLTAGE MULTIPLIER CIRCUIT

- Cockroft and Walton suggested an improvement over the circuit developed by Greinacher for producing high D.C. voltages.
- No Load Operation: The portion ABM′MA is exactly indentical to Greinarcher voltage doubler circuit and the voltage across C becomes 2Vmax when M attains a voltage 2Vmax.
- During the next half cycle when B becomes positive with respect to A, potential of M falls and, therefore, potential of N also falls becoming less than potential at M′ hence C2 is charged through D2. Next half cycle A becomes more positive and potential of M and N rise thus charging C′2 through D_2’

D′2. Finally all the capacitors C′1, C′2, C′3, C1, C2,C3 are charged. The voltage across the column of capacitors consisting of C1, C2, C3, keeps on oscillating as the supply voltage alternates. This column, therefore, is known as oscillating column. However, the voltage across the capacitances C′1,C′2, C′3, remains constant and is known as smoothening column. The voltages at M′, N′, and O′ are 2 Vmax 4 Vmax and 6 Vmax. Therefore, voltage B across the capacitors is 2 Vmax except for C1where it is Vmax only. The total output voltage is **2nVmax** where n is the number of stages. Thus, the use of multi stages arranged in the manner shown enables very high voltage to be obtained. The equal stress of the elements (both capacitors and diodes) used is very helpful and promotes a modular design of such generators.

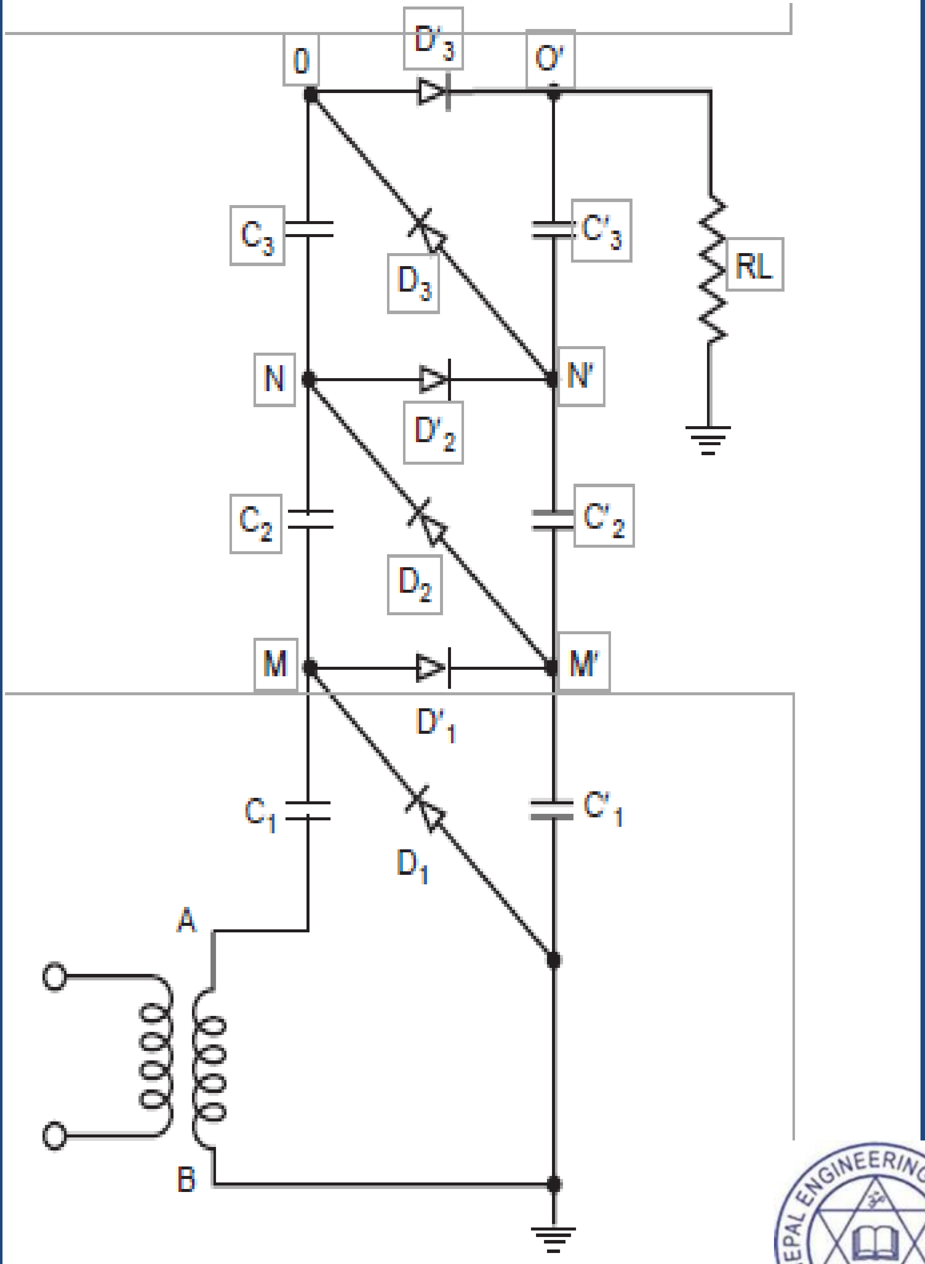


Fig. 2.3

Generator Loaded: When the generator is loaded, the output voltage will never reach the value 2nVmax. Also, the output wave will consist of ripples on the voltage. Thus, we have to deal with two quantities, the voltage drop ΔV and the ripple δV.

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

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

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

For n-stage circuit, the total ripple will be

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

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

Hence $$\Delta V = \frac{I}{fC}\left(\frac{2}{3}n^3 - \frac{n}{6}\right) \qquad (2.10)$$

If $n \geq 4$ we find that the linear term can be neglected and, therefore, the voltage drop can be approximated to

$$\Delta V \approx \frac{I}{fC} \cdot \frac{2}{3} n^3 \qquad (2.11)$$

Generation of High AC Voltage

Why ?

- ❖ Most of transmission and distribution networks are operating on a.c. High voltages and most of the testing equipment relate to high a.c. voltages..
- ❖ Test transformers used for the purpose have low power rating but high voltage ratings. Mainly used for short time tests on high voltage equipment. The currents required will be less a given :

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 magnetizing current which would otherwise saturate the core and produce higher harmonics.

Cascaded Transformers

- ✓ For voltages higher than 300/400 KV , 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, therefore, transport and erection becomes easier.
- ✓ 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. 2.9 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. 2.9. 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 is 3V. 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.

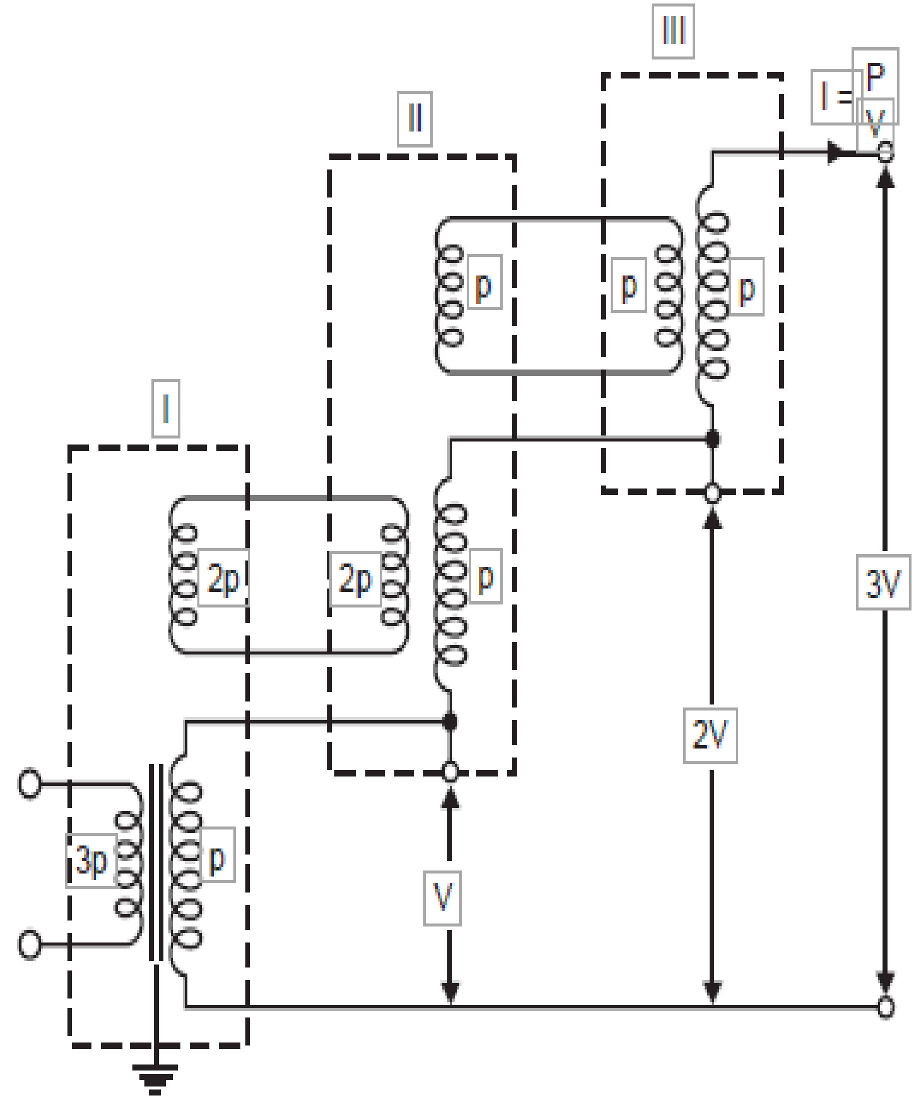


Fig. 2.9 Basic 3 stage cascaded transformer

Resonant Transformers

The equivalent circuit of a single-stage-test transformer along with its capacitive load is shown in Fig. Here L1 represents the inductance of the voltage regulator and the transformer primary, L the exciting inductance of the transformer, L2 the inductance of the transformer secondary and C the capacitance of the load. Normally inductance L is very large as compared to L1 and L2 and hence its shunting effect can be neglected. gths of cables.

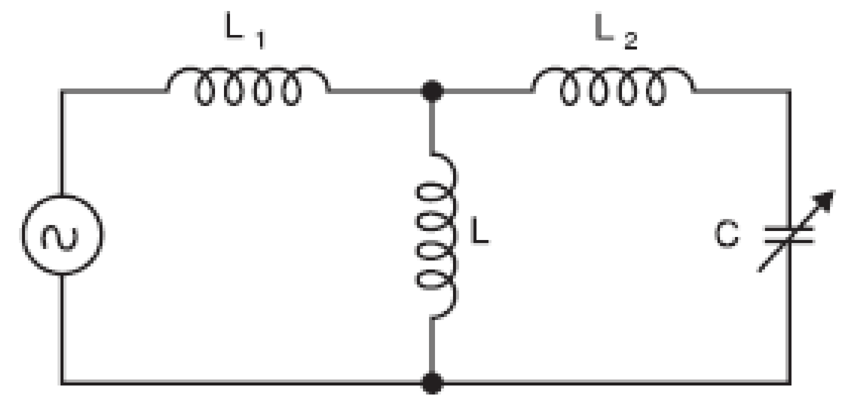


Fig. 2.15 Equivalent circuit of a single stage loaded transformer

Usually the load capacitance is variable and it is possible that for certain loading, resonance may occur in the circuit suddenly and the current will then only be limited by the resistance of the circuit and the voltage across the test specimen may go up as high as 20 to 40 times the desired value. Similarly, presence of harmonics due to saturation of iron core of transformer may also result in resonance. Third harmonic frequencies have been found to be quite disastrous. With series resonance, the resonance is controlled at fundamental frequency and hence no un-wanted resonance occurs. The development of series resonance circuit for testing purpose has been very widely welcome by the cable industry as they faced resonance problem with test transformer while testing short len

$$V_C = \left| \frac{-jVX_C}{R+j(X_L - X_C)} \right| = \frac{V}{R} X_C = \frac{V}{\omega CR}$$

The factor $X_C/R = 1/\omega CR$ is the Q factor of the circuit and gives the magnitude of the voltage multiplication across the test object under resonance conditions. Therefore, the input voltage required for excitation is reduced by a factor $1/Q$, and the output kVA required is also reduced by a factor $1/Q$. The secondary power factor of the circuit is unity.

This principle is utilized in testing at very high voltages and on occasions requiring large current outputs such as cable testing, dielectric loss measurements, partial discharge measurements, etc. A transformer with 50 to 100 kV voltage rating and a relatively large current rating is connected together with an additional choke, if

The test condition is set such that

$\omega (Le+L) = 1/\omega C$

Where ,Le = Total Equivalent Leakage reactance of transformer and regulator

Advantages:-

The use of the Resonant transformer have the following advantages:-

i. Output will be in pure sine form.
ii. Power Requirements are less(5%- 10% of the total KVA.)
iii. No any high surges incase of the test object fail.
iv. Cascading is possible for the high voltage.
v. Simple and compact test arrangements.

The main **disadvantages** is the requirements of the additional variable chokes for with standing voltage and current

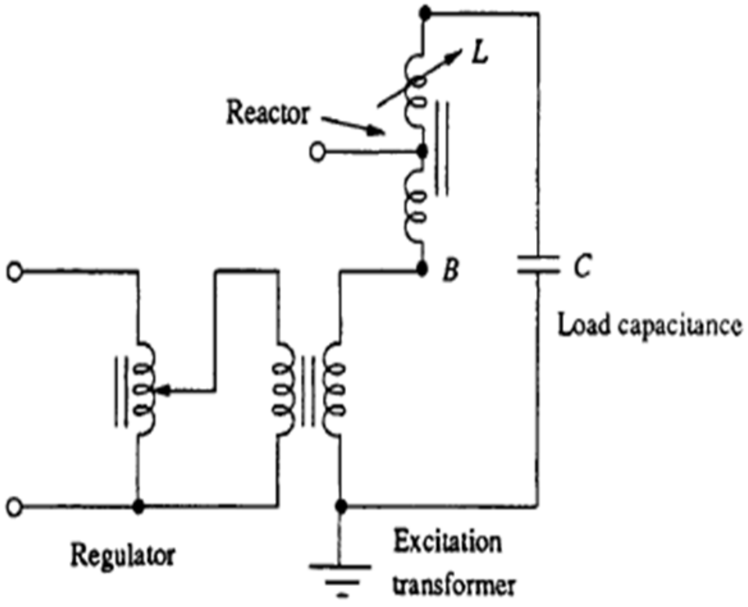


Fig. 6.12c Series resonant a.c. test system

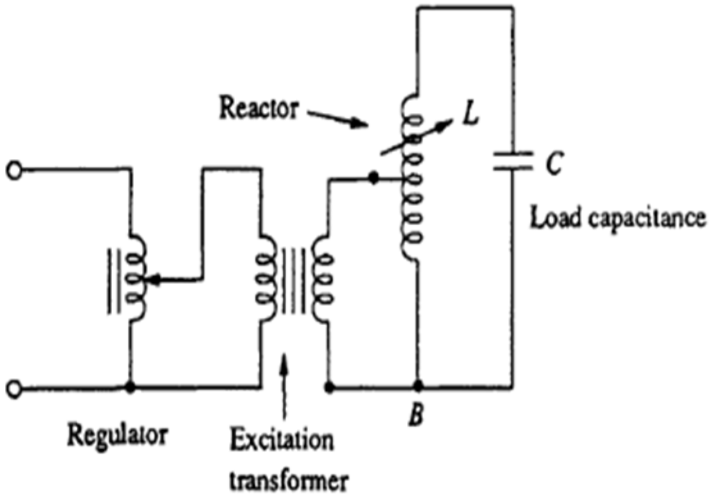


Fig. 6.12d Parallel resonant a.c. test system

- The series and the parallel resonant arrangements are shown as in fig.
- Primary is connected with the regulator(Auto transformer/induction regulator)and secondary of the transformer with reactor/inductor and capacitance.
- L is varied by varying air gap and C represents the test object.
- Quality factor = 50
- In case of the parallel circuit , reactor is connected as auto transformer and the circuit as parallel resonant circuit.
- The output voltage will be more stable w.r.t. to rise of voltage without dependency of Q-factor and tunning circuit.
- Single unit resonant test system can be built up to 500KV. For high voltage cascading can be done

High Frequency AC Voltage and Advantage of High Frequency Transformer

- High frequency HV are required for the rectifier DC power Supply circuit.
- To Test Switching Surges, High frequency high voltage damped oscillation is needed which need HFHV transformer.

ADVANTAGES of HFHV Transformers:-

- Pure Sine wave output
- Less cost and reduced in sizes due to absence of the iron core.
- Slow built up of the voltage over a cycle and hence less chance of damage due to switching surges.
- Uniform distribution of the voltage across the winding.

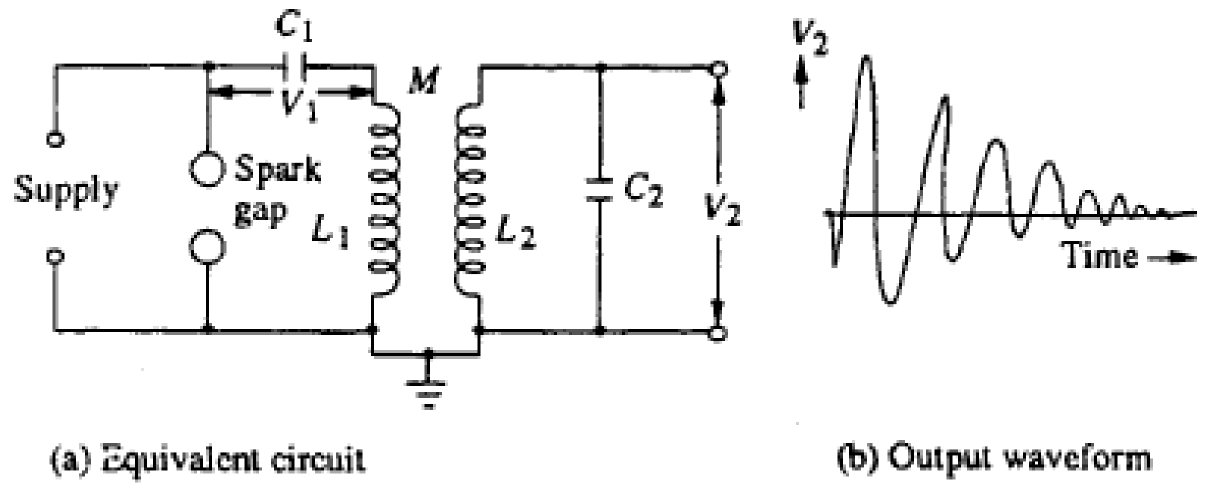


Fig. 6.13 Tesla coil equivalent circuit and its output waveform

The commonly used high frequency resonant transformer is the Tesla coil, which is a doubly tuned resonant circuit shown schematically in Fig. 6.13a. The primary voltage rating is 10 kV and the secondary may be rated to as high as 500 to 1000 kV. The primary is fed from a d.c. or a.c. supply through the condenser C_1. A spark gap G connected across the primary is triggered at the desired voltage V_1 which induces a high self-excitation in the secondary. The primary and the secondary windings (L_1 and L_2) are wound on an insulated former with no core (air-cored) and are immersed in oil. The windings are tuned to a frequency of 10 to 100 kHz by means of the condensers C_1 and C_2.

The output voltage V_2 is a function of the parameters L_1, L_2, C_1, C_2, and the mutual inductance M. Usually, the winding resistances will be small and contribute only for damping of the oscillations.

The analysis of the output waveform can be done in a simple manner neglecting the winding resistances. Let the condenser C_1 be charged to a voltage V_1 when the spark gap is triggered. Let a current i_1 flow through the primary winding L_1 and produce a current i_2 through L_2 and C_2.

The output waveform is shown in Fig. 6.13b.

The peak amplitude of the secondary voltage V_2 can be expressed as,

$$V_{2max} = V_1 e \sqrt{\frac{L_2}{L_1}}$$

where,

$$e = \frac{2\sqrt{(1-\sigma)}}{\sqrt{(1+a)^2 - 4\sigma a}}$$

$$a = \frac{L_2 C_2}{L_1 C_1} = \frac{W_1^2}{W_2^2}$$

(b) Output waveform

A more simplified analysis for the Tesla coil may be presented by considering that the energy stored in the primary circuit in the capacitance C_1 is transferred to C_2 via the magnetic coupling. If W_1 is the energy stored in C_1 and W_2 is the energy transferred to C_2 and if the efficiency of the transformer is η, then

$$W_1 = \frac{1}{2}\eta C_1 V_1^2 = (\tfrac{1}{2} C_2 V_2^2)$$

from which

$$V_2 = V_1 \sqrt{\eta \frac{C_1}{C_2}}$$

It can be shown that if the coefficient of coupling K is large the oscillation frequency is less, and for large values of the winding resistances and K, the waveform may become a unidirectional impulse.

Thank you

Any Question???

Generation of Impulse Voltages

An impulse voltage is a unidirectional voltage which, without appreciable oscillations, rises rapidly to a maximum value and falls more or less rapidly to zero Fig. 3.1. The maximum value is called the peak value of the impulse and the impulse voltage is specified by this value. Small oscillations are tolerated, provided that their amplitude is less than 5% of the peak value of the impulse voltage. In case of oscillations in the wave shape, a mean curve should be considered.

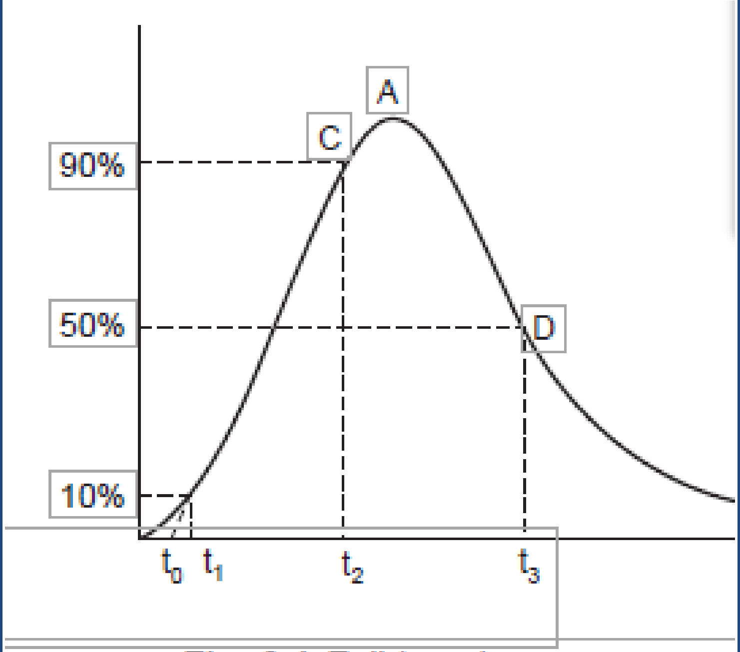


Fig. 3.1 Full impulse wave

If an impulse voltage develops without causing flash over or puncture, it is called a full impulse voltage; if flash over or puncture occur, thus causing a sudden collapse of the impulse voltage, it is called a chopped impulse voltage. A full impulse voltage is characterized by its peak value and its two time intervals, the wave front and wave tail time intervals defined below:

The wave front time of an impulse wave is the time taken by the wave to reach its maximum value starting from zero value. Usually it is

difficult to identify the start and peak points of the wave and, therefore, the wave front time is specified as 1.25 times (t2 – t1), where t2 is the time for the wave to reach to its 90% of the peak value and t1 is the time to reach 10% of the peak value. Since (t2 – t1) represents about 80% of the wave front time, it is multiplied by 1.25 to give total wave front time.

- The nominal wave tail time is measured between the nominal starting point t_0 and the point on the wave tail where the voltage is 50% of the peak value i.e. wave fail time is expressed as $(t_3 – t_0)$.
- The nominal steepness of the wave front is the average rate of rise of voltage between the points on the wave front where the voltage is 10% and 90% of the peak value respectively.
- The standard wave shape specified in BSS and ISS is a 1/50 micro sec. wave i.e. a wave front of 1 micro sec. and a wave tail of 50 micro sec. A tolerance of not more than ±50% on the duration of the wave front and 20% on the time to half value on the wave tail is allowed. The wave is completely specified as 100 kV, 1/50 micro sec. where 100 kV is the peak value of the wave.
- The wave shape recommended by the American Standard Association is 1.5/40 micro sec. with permissible variations of 0.5 micro sec. on the wave front and ±10 micro sec. on the wave tail.

The standard switching impulse has a 250 μs rise time and a 2500 μs decay to 50% of the peak voltage.

$$\boldsymbol{t_1 = 1.25\,(T_2 - T_1)}$$
$$\boldsymbol{t_2 = T_3 - 0^1}$$

The standard lightning impulse has a 1.2 μs rise time and a 50 μs decay to 50% of the peak voltage.

BASIC INSULATION LEVEL AS PER IS (2165 – 1962)

Nominal system volt kV (rms)	Highest system volt kV (rms)	Impulse withstand volt kVp for test		One minute power frequent volt kV (rms)	
		Full insulation	Reduced insulation	Full insulation	Reduced insulation
132 kV	145	650	550	275	230
220 kV	245	1050	900	460	395
400 kV	420		1550		680
			1425		630
Reduced insulation is used where system is effectively earthed.					

Types of the Impulse Generator Circuit and its Analysis

- Fig. 3.3 represents an exact equivalent circuit of a single stage impulse generator along with a typical load.
- C1 is the capacitance of the generator charged from a d.c. source to a suitable voltage which causes discharge through the sphere gap. The capacitance C1 may consist of a single capacitance, in which case the generator is known as a single stage generator or alternatively if C1 is the total capacitance of a group of capacitors charged in parallel and then discharged in series, it is then known as a multistage generator.

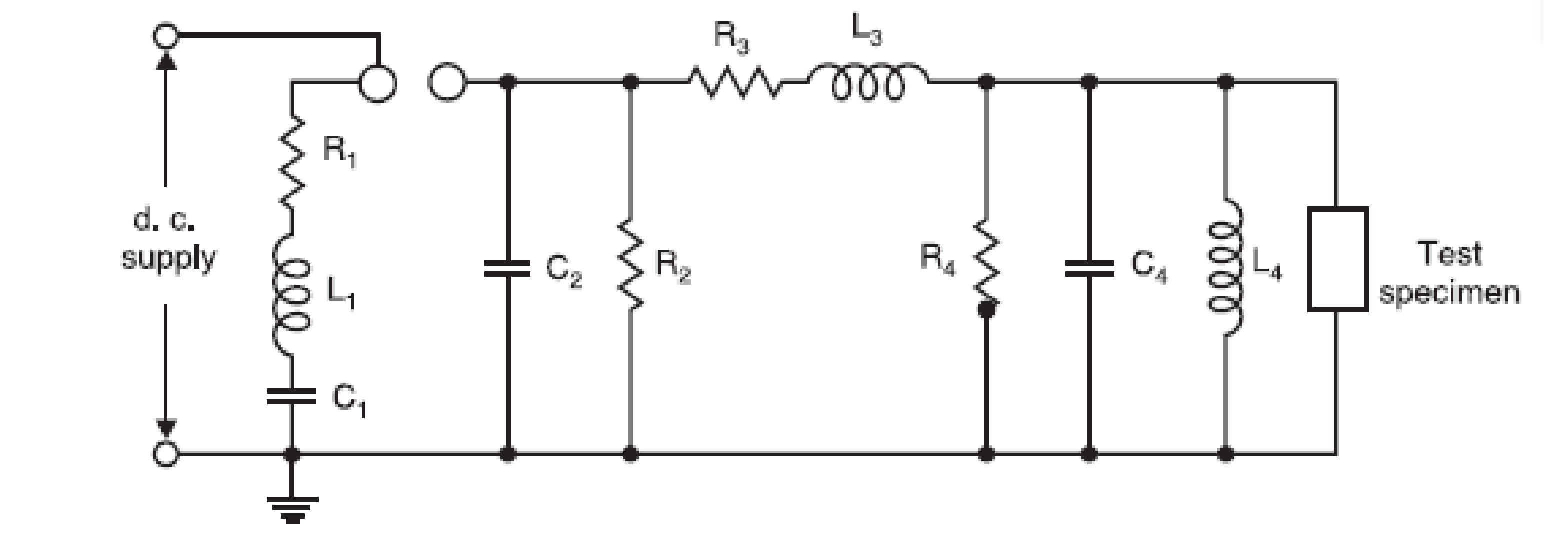


Fig. 3.3 Exact equivalent circuit of a single stage impulse generator with a typical load

- L1 is the inductance of the generator and the leads connecting the generator to the discharge circuit and is usually kept as small as possible.
- The resistance R1 consists of the inherent series resistance of the capacitances and leads and often includes additional lumped resistance inserted within the generator for damping purposes and for output waveform control.
- L3, R3 are the external elements which may be connected at the generator terminal for waveform control. R2 and R4 control the duration of the wave. However, R4 also serves as a potential divider when a CRO is used for measurement purposes.
- C2 and C4 represent the capacitances to earth of the high voltage components and leads. C4 also includes the capacitance of the test object and of any other load capacitance required for producing the required wave shape. L4 represents the inductance of the test object and may also affect the wave shape appreciably.
- Usually for practical reasons, one terminal of the impulse generator is solidly grounded. The polarity of the output voltage can be changed by changing the polarity of the d.c. charging voltage..

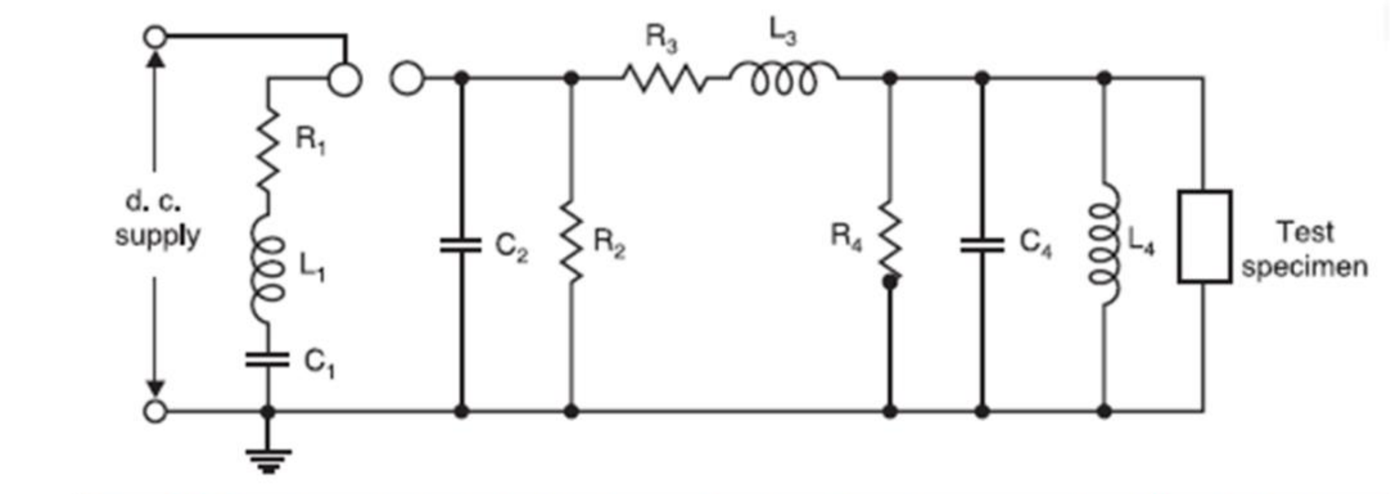


Fig. 3.3 Exact equivalent circuit of a single stage impulse generator with a typical load

The two circuits are widely used and differ only in the position of the wave tail control resistance R2. When R2 is on the load side of R1 (Fig. a) the two resistances form a potential divider which reduces the output voltage but when R2 is on the generator side of R1 (Fig. b) this particular loss of output voltage is absent.

The impulse capacitor C1 is charged through a charging resistance (not shown) to a d.c. voltage V0 and then discharged by flashing over the switching gap with a pulse of suitable value. The desired impulse voltage appears across the load capacitance C2. The value of the circuit elements determines the shape of the output impulse voltage. The following analysis will help us in evaluating the circuit parameters for achieving a particular wave shape of the impulse voltage.

Analysis of Circuit

A double exponential waveform of the type mentioned in Eq. (6.15) may be produced in the laboratory with a combination of a series *R-L-C* circuit under over damped conditions or by the combination of two *R-C* circuits. Different equivalent circuits that produce impulse waves are given in Figs. 6.15a to d. Out of these circuits, the ones shown in Figs. 6.15a to d are commonly used. Circuit shown in Fig. 6.15a is limited tomodel generators only, and commercial generators employ circuits shown in Figs. 6.15b to 6.15d.

$$V = V_0 [\exp(-\alpha t) - \exp(-\beta t)]$$

A capacitor (C_1 or C) previously charged to a particular d.c. voltage is suddenly discharged into the waveshaping network (LR, $R_1R_2C_2$ or other combination) by closing the switch S. The discharge voltage $V_0(t)$ shown in Fig. 6.15 gives rise to the desired double exponential waveshape.

Taking inverse transform of $v_0(s)$ gives

$$v_0(t) = \frac{V}{R_1C_2(\alpha - \beta)}[\exp(-\alpha t) - \exp(-\beta t)]$$

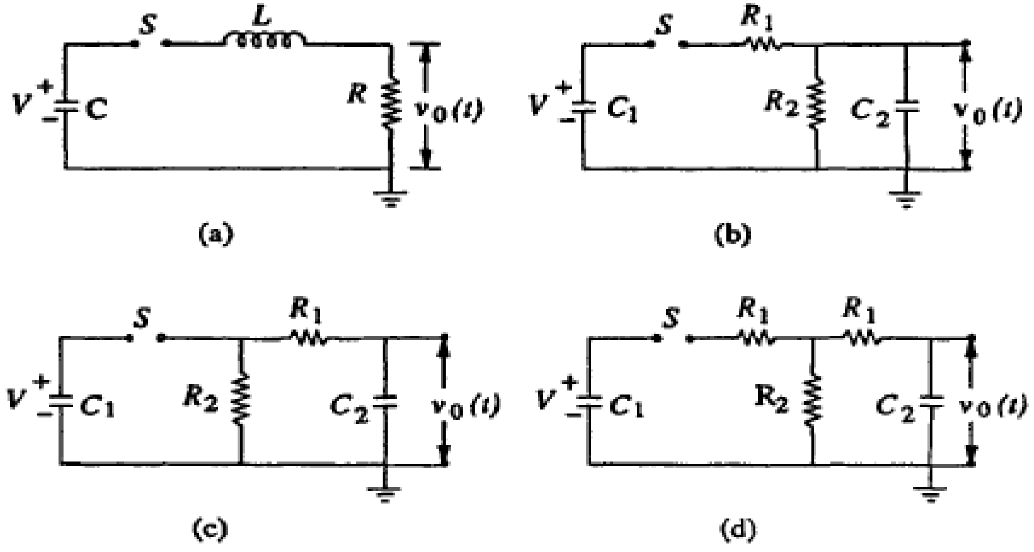


Fig. 6.15 Circuits for producing impulse waves

R-L-C Impulse Circuit Analysis

Referring to Fig. 6.15 the current through the load resistance R is given by

$$V = \frac{1}{C}\int_0^t i\,dt + Ri + L\frac{di}{dt}$$

with initial condition at $t = 0$ being $i(0) = 0$ and the net charge in the circuit $i = dq/dt = 0$. Writing the above equation as a Laplace transform equation,

$$V/s = \left(\frac{1}{Cs} + R + Ls\right) I(s)$$

or,

$$I(s) = \frac{V}{L}\left[\frac{1}{s^2 + \frac{Rs}{L} + \frac{1}{LC}}\right]$$

The voltage across the resistor R (which is the output voltage) is, $v_0(s) = I(s)\,R$; hence,

$$v_0(s) = V\frac{R}{L}\frac{1}{s^2 + \frac{Rs}{L} + \frac{1}{LC}}$$

Hence, the roots of the equation $s^2 + \frac{Rs}{L} + \frac{1}{LC}$ are

$$\alpha = \quad s_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$\beta = \quad s_2 = -\frac{R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

The sum of the roots $(\alpha + \beta) = -\frac{R}{2L}$

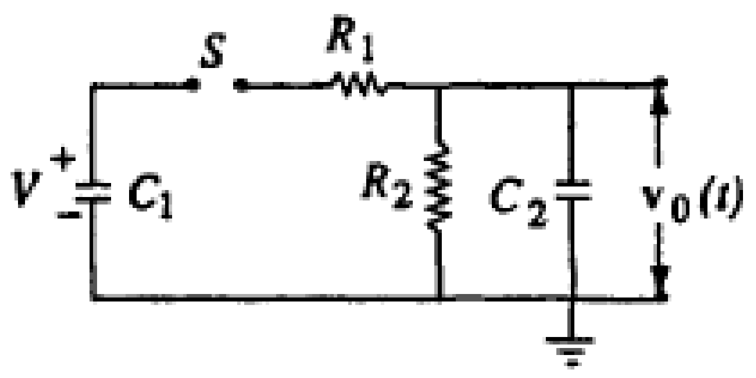
and, the product of the roots $\alpha\beta = \frac{1}{LC}$

The wave front and the wave tail times are controlled by changing the values of R and L simultaneously with a given generator capacitance C; choosing a suitable value for L. β or the wave front time is determined and α or the wave tail time is controlled by the value of R in the circuit. The advantage of this circuit is its simplicity. But the waveshape control is not flexible and independent. Another disadvantage is that the basic circuit is altered when a test object which will be mainly capacitive in nature, is connected across the output. Hence, the waveshape gets changed with the change of test object.

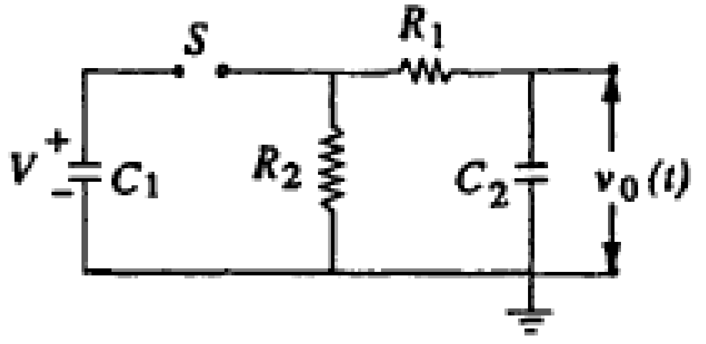
Impulse Generator Circuit

The most commonly used configurations for impulse generators are the circuits shown in Figs. 6.15b and c. The advantages of these circuits are that the wave front and wave tail times are independently controlled by changing either R_1 or R_2 separately. Secondly, the test objects which are mainly capacitive in nature form part of C_2.

For the configuration shown in Fig. 6.15b, the output voltage across C_2 is given by, $v_0(t) = \frac{1}{C_2}\int_0^t i_2\,dt$.



(b)



(c)

$$\alpha + \beta = -\left[\frac{1}{C_1R_1} + \frac{1}{C_2R_2} + \frac{1}{C_2R_1}\right]$$

$$\alpha\beta = \frac{1}{C_1C_2R_1R_2}$$

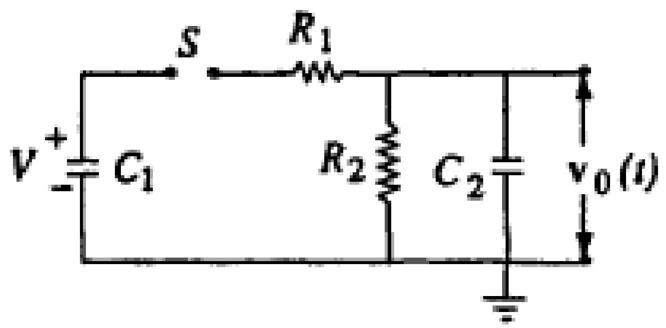
$$\alpha \approx \frac{1}{R_1C_2} \text{ and, } \beta = \frac{1}{R_2C_1}$$

Restriction on the Load and Generator Capacitance – C1/C2

For a given waveshape, the choice of R_1 and R_2 to control the wave front and wave tail times is not entirely independent but depends on the ratio of C_1/C_2. It can be shown mathematically that

$$R_2 = P(y)/C_1 \text{ and } R_1 = Q(y)/C_1$$

where $y = C_1/C_2$ and P and Q are functions of y. In order to get real values for R_1 and R_2 for a given waveshape, a maximum and minimum value of y exists in practice. This is true whether the configuration of Fig. 6.15b or 6.15c is used. For example, with the circuit of Fig. 6.15b, the ratio of C_1/C_2 cannot exceed 3.35 for a 1/5 µ s waveshape. Similarly, for a 1/50 µ s waveshape the ratio C_1/C_2 lies between 6 and 106.5. If the configuration chosen is 6.15c, the minimum value of C_1/C_2 for 1/5 µ s waveshape is about 0.3 and that for the 1/50 µ s waveshape is about 0.01. The reader is referred to *High Voltage Laboratory Techniques* by Craggs and Meek for further discussion on the restrictions imposed on the ratio C_1/C_2.



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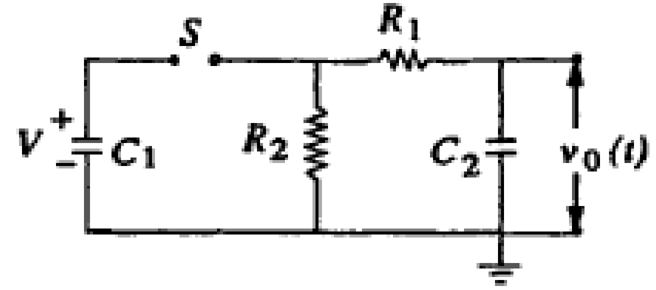


(c)

Effects of Circuit Inductances and Resistance:-

The effect of the inductance is to cause oscillations in the wave front and in the wave tail portions. Inductances of several components and the loop inductance are shown in Fig. 6.16a. Figure 6.16b gives a simplified circuit for considering the effect of inductance. The effect of the variation of inductance on the waveshape is shown in Fig. 6.16c. If the series resistance R_1 is increased, the wave front oscillations are damped, but the peak value of the voltage is also reduced. Sometimes, in order to control the front time a small inductance is added.

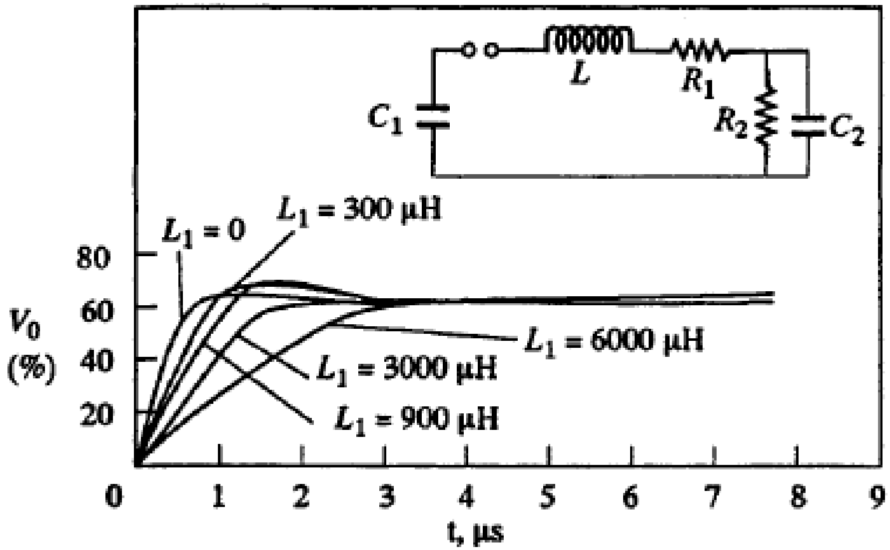


Fig. 6.16 (c) Effect of series inductance on wave front time. v_0 is the percentage of charging voltage V, to which C_1 is charged

suggested a multiplier circuit to obtain impulse voltages with as high a peak value as possible for a given d.c. charging

Wave Shape(Wave front & tail) Control of Impulse

Generally, for a given impulse generator of Fig. 6.15b or c the generator capacitance C_1 and load capacitance C_2 will be fixed depending on the design of the generator and the test object. Hence, the desired waveshape is obtained by controlling R_1 and R_2. The following approximate analysis is used to calculate the wave front and wave tail times.

The resistance R_2 will be large. Hence, the simplified circuit shown in Fig. 6.16b is used for wave front time calculation. Taking the circuit inductance to be negligible during charging, C_1 charges the load capacitance C_2 through R_1. Then the time taken for charging is approximately three times the time constant of the circuit and is given by

$$t_1 = 3.0\, R_1 \frac{C_1 C_2}{C_1 + C_2} = 3\, R_1\, C_e \qquad (6.22)$$

where $C_e = \dfrac{C_1 C_2}{C_1 + C_2}$. If R_1 is given in ohms and C_e in microfarads, t_1 is obtained in microseconds.

For discharging or tail time, the capacitances C_1 and C_2 may be considered to be in parallel and discharging occurs through R_1 and R_2. Hence, the time for 50% discharge is approximately given by

$$t_2 = 0.7\,(R_1 + R_2)\,(C_1 + C_2)$$

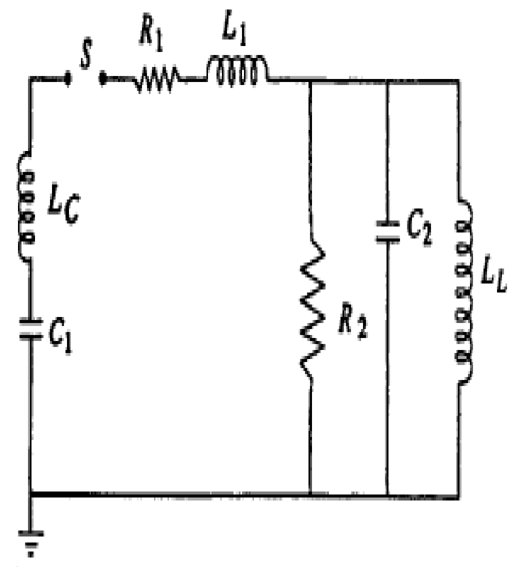


Fig. 6.16 (a) Series inductances in impulse generator circuit

L_C — Inductance of the generator capacitance C_1 and lead capacitances

L_1 — Inductance of the series resistance and the circuit loop inductance

L_L — Test object inductance

Multi Stage Impulse Generator - Marx Circuit

In order to obtain higher and higher impulse voltage, a single stage circuit is inconvenient for the following reasons:

- The physical size of the circuit elements becomes very large.
- High d.c. charging voltage is required.
- Suppression of corona discharges from the structure and leads during the charging period is difficult.
- Switching of vary high voltages with spark gaps is difficult.

In 1923 E. Marx suggested a multiplier circuit to obtain impulse voltages with as high a peak value as possible for a given d.c. charging voltage.

- Based on the output voltage required a number of identical impulse **capacitors are charged in parallel and then discharged in series**, thus multiplied total charging voltage corresponding to the number of stages.
- In Fig. a 4-stage impulse generator circuit, The impulse capacitors C1 are charged to the charging voltage V0 through the high charging resistors Rc in parallel. When all the gaps G break down, the capacitances are connected in series so that C2 is charged through the series connection of all the wave front resistances R1′ and finally all C1′ and C2 will discharge through the resistors R2′and R1′. Usually Rc >> R2 >> R1.

In the above discussion, the generator capacitance C_1 is to be first charged and then discharged into the wave shaping circuits. A single capacitor C_1 may be used for voltages up to 200 kV. Beyond this voltage, a single capacitor and its charging unit may be too costly, and the size becomes very large. The cost and size of the impulse generator increases at a rate of the square or cube of the voltage rating. Hence, for producing very high voltages, a bank of capacitors are charged in parallel and then discharged in series. The arrangement for charging the capacitors in parallel and then connecting them in series for discharging was originally proposed by Marx. Now-a-days modified Marx circuits are used for the multistage impulse generators.

Why the Multistage Impulse Circuit is needed?
Explain Clearly How it works? What are the major component of the Circuit?

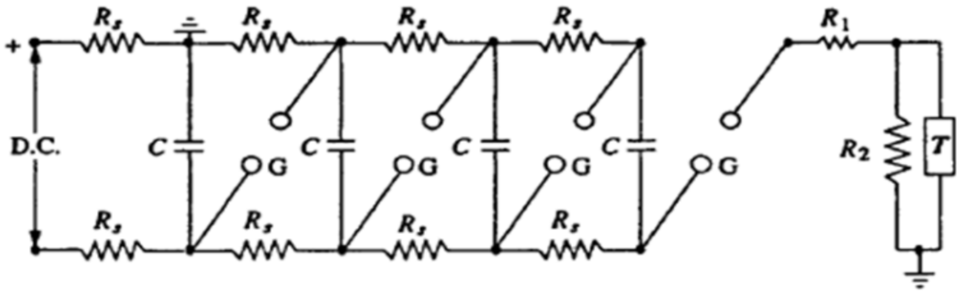


Fig. 6.17a Schematic diagram of Marx circuit arrangement for multistage impulse generator

C — Capacitance of the generator
R_s — Charging resistors
G — Spark gap
R_1, R_2 — Wave shaping resistors
T — Test object

The schematic diagram of Marx circuit and its modification are shown in Figs. 6.17a and 6.17b, respectively. Usually the charging resistance R_s is chosen to limit the charging current to about 50 to 100 mA, and the generator capacitance C is chosen such that the product CR_s is about 10 s to 1 min. The gap spacing is chosen such that the breakdown voltage of the gap G is greater than the charging voltage V. Thus, all the capacitances are charged to the voltage V in about 1 minute. When the impulse generator is to be discharged, the gaps G are made to spark over simultaneously by some external means. Thus, all the capacitors C get connected in series and discharge

into the load capacitance or the test object. The discharge time constant CR_1/n (for n stages) will be very very small (microseconds), compared to the charging time constant CR_s which will be few seconds. Hence, no discharge takes place through the charging resistors R_s. In the Marx circuit is of Fig. 6.17a the impulse wave shaping circuit is connected externally to the capacitor unit.

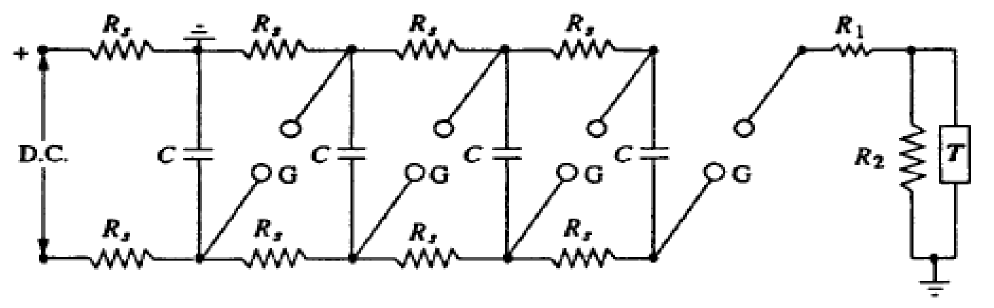


Fig. 6.17a Schematic diagram of Marx circuit arrangement for multistage impulse generator

C — Capacitance of the generator
R_s — Charging resistors
G — Spark gap
R_1, R_2 — Wave shaping resistors
T — Test object

The output voltage is determined by multiplying the number of the stages and charging voltages.

$$V_0 = n * V_i$$

Component of Impulse Generator

DC. Charging Set - Capable of giving a variable DC. voltage of either polarity to charge to the required value.

Charging Resistors - Non-inductive high value (**10 to 100 kilo-ohms**) and maximum voltage between **50 and 100 kV**.

Generator Capacitors and Spark Gaps - Arranged vertically one over the other with all the spark gaps aligned, Capacitors are designed for several charging and discharging operations. On dead short circuit, the capacitors will be capable of giving 10 kA of current. The spark gaps will be usually spheres or hemispheres of 10 to 25 cm diameter.

Wave-shaping Resistors and Capacitors - Non-inductive wound type and capable of discharging impulse currents of 1000 A or more. And voltage of 5O to 100 kV. The load capacitor compressed gas or oil filled with a capacitance of 1 to 10 ^F. The resistors used are usually resin cast with voltage and energy ratings of 200 to 250 kV and 2.0 to 5.0 kWsec. The entire range of lightning and switching impulse voltages can be covered using these resistors either in series or in parallel combination.

Triggering System -This consists of trigger spark gaps to cause spark breakdown of the gaps.

Voltage Dividers -Voltage dividers of either damped capacitor or resistor type and an oscilloscope with recording arrangement are provided for measurement of the voltages across the test object. Sometimes a sphere gap for calibration purposes..

Working of the generator is based on two principles:

1.Discharging action of sharp points, ie., electric discharge takes place in air or gases readily, at pointed conductors.

2.If the charged conductor is brought in to internal contact with a hollow conductor, all of its charge transfers to the surface of the hollow conductor no matter how high the potential of the latter may be.

Explain working principle of the Van De-Graaff generator with neat and clear picture. What are its advantage and disadvantages?

Robert J. Van de Graaff

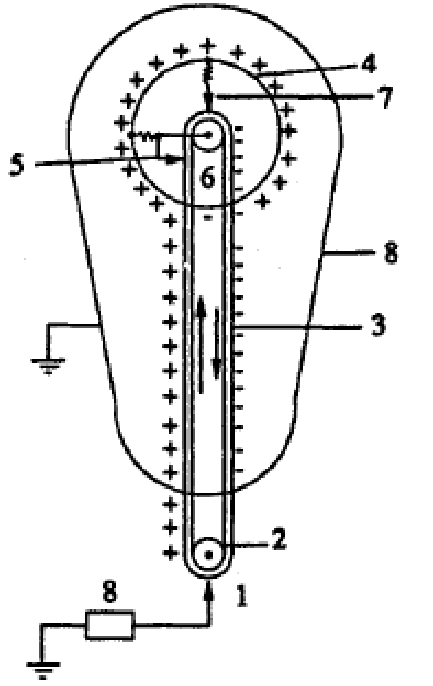


Fig. Van de Graaff generator

1. Lower spray point
2. Motor driven pulley
3. Insulated belt
4. High voltage terminal
5. Collector
6. Upper pulley insulated from terminal
7. Upper spray point
8. Earthed enclosure

Van De-Graff Generator

- Fig. Belt driven electrostatic generator–Van DeGraff, 1931.
- An insulating belt run over pulleys, driven with speed of about 15 to 30 m/sec, by means of a motor connected to the lower pulley.
- The belt near the lower pulley is charged electrostatically by an excitation arrangement. The lower charge spray unit consists of a number of needles connected to the controllable d.c. source (10 kV–100 kV) so that the discharge between the points and the belt is maintained.
- The charge is conveyed to the upper end where it is collected from the belt by discharging points connected to the inside of an insulated metal electrode through which the belt passes.
- The entire equipment enclosed in an earthed metal tank filled with insulating gases of good dielectric strength viz. SF6 etc. So that the potential of the electrode could be

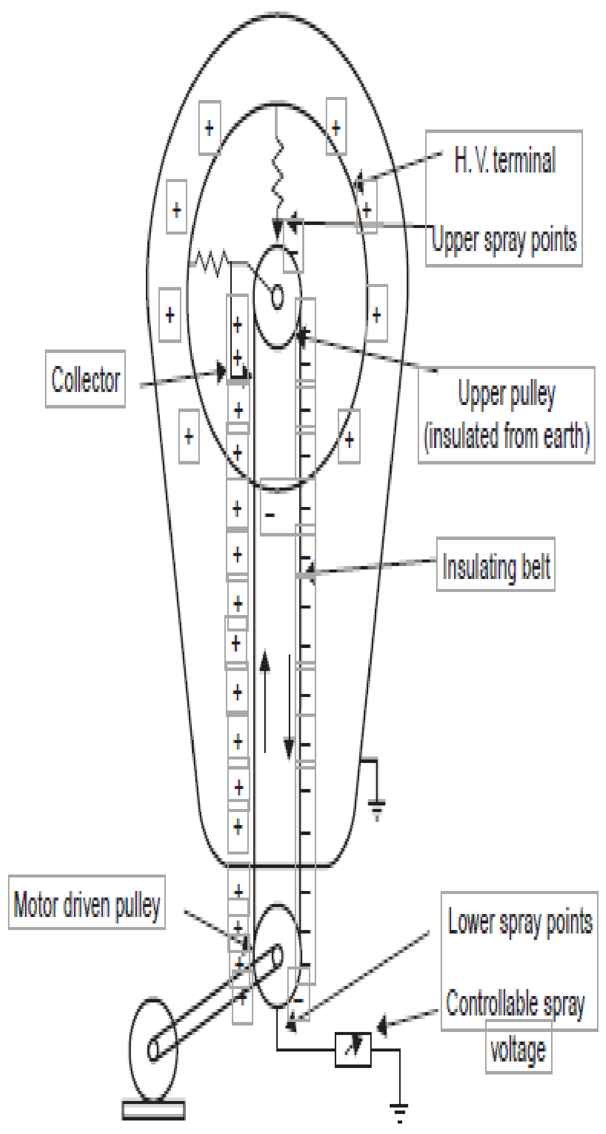


Fig. 2.8 Van de Graaf generator

raised to relatively higher voltage without corona discharges or for a certain voltage a smaller size of the equipment will result.

- ❑ Shape of the h.t. electrode will be such that the surface gradient of electric field is made uniform to reduce again corona discharges.
- ❑ An isolated sphere is the most favorable electrode shape and will maintain a uniform field E with a voltage of Er where r is the radius of the sphere.

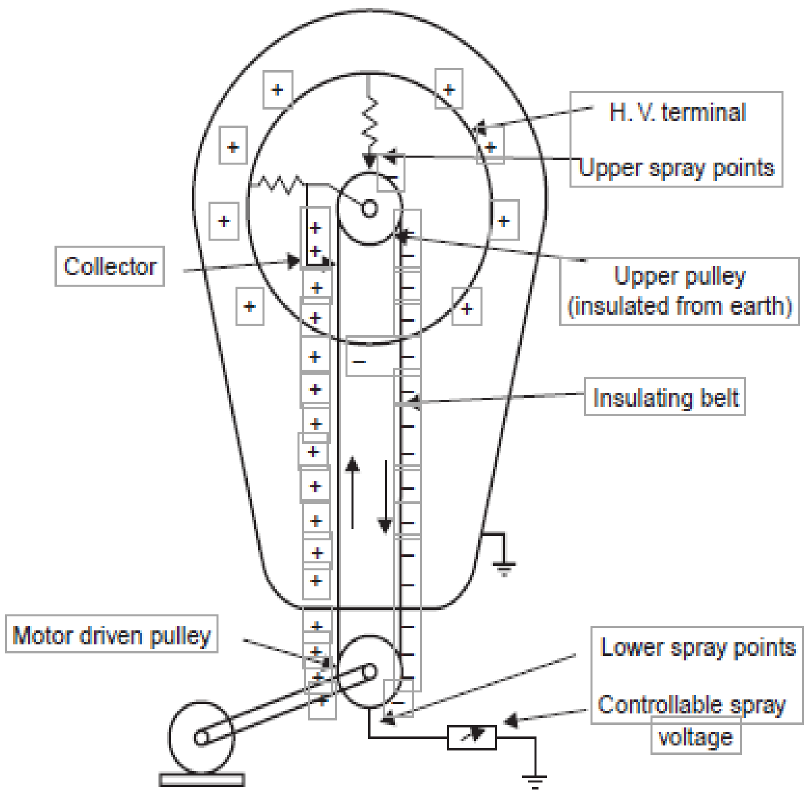


Fig. 2.8 Van de Graaf generator

As the h.t. electrode collects charges its potential rises. The potential at any instant is given as V = q/C where q is the charge collected at that instant. HV can be generated collecting charge for long time. With the rise potential of electrode that may ionise the surrounding medium, so this would be the limiting value of the voltage.

$$\left(I = C\frac{dV}{dt}\right)$$

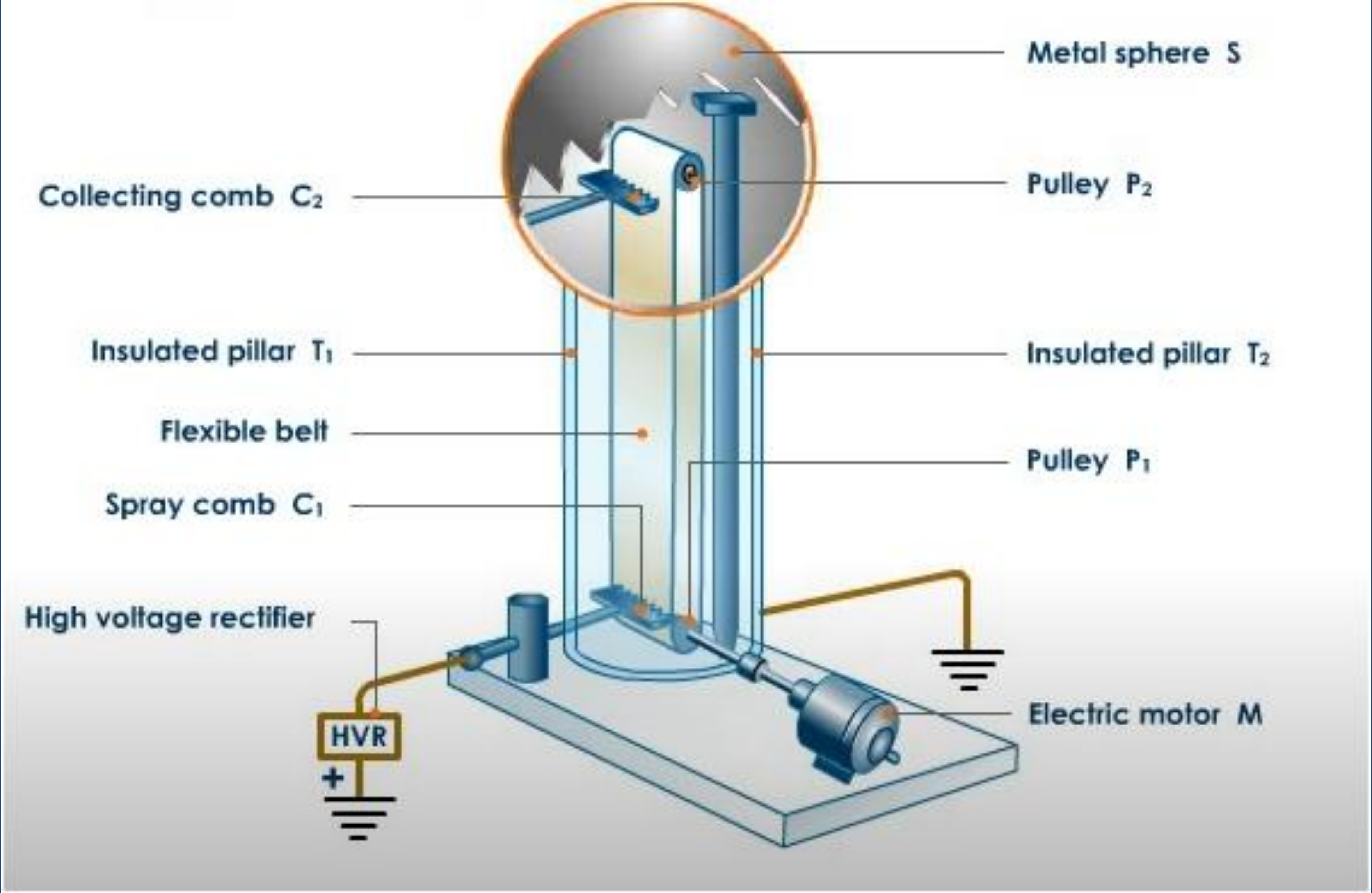
- The moving belt system also distorts the electric field so properly shaped field grading rings used.
- The collector needle system is placed near the point where the belt enters the h.t. terminal.
- . As the pulley is at a higher potential (positive), the negative charges due to corona discharge at the upper spray points are collected by the belt. This neutralizes any remaining positive charge on the belt and leaves an excess of negative charges on the down going belt to be neutralized by the lower spray points. Since these negative charges leave the h.t. terminal, the potential of the h.t. terminal is raised by the corresponding amount.

In order to have a rough estimate of the current supplied by the generator, let us assume that the electric field E is normal to the belt and is homogeneous.
the current supplied by the generator is given as

$$I = \sigma b\nu$$

From equation it is clear that current I depends upon σ, b and ν. The belt width (b) and velocity ν being limited by mechanical reasons, the current can be increased by having higher value of σ. σ can be increased by using gases of higher dielectric strength so that electric field intensity E could be increased without the inception of ionization of the medium surrounding the h.t. terminal. However, with all these arrangements, the actual short circuit currents are limited only to a few mA even for large generators.

Generator parts :-



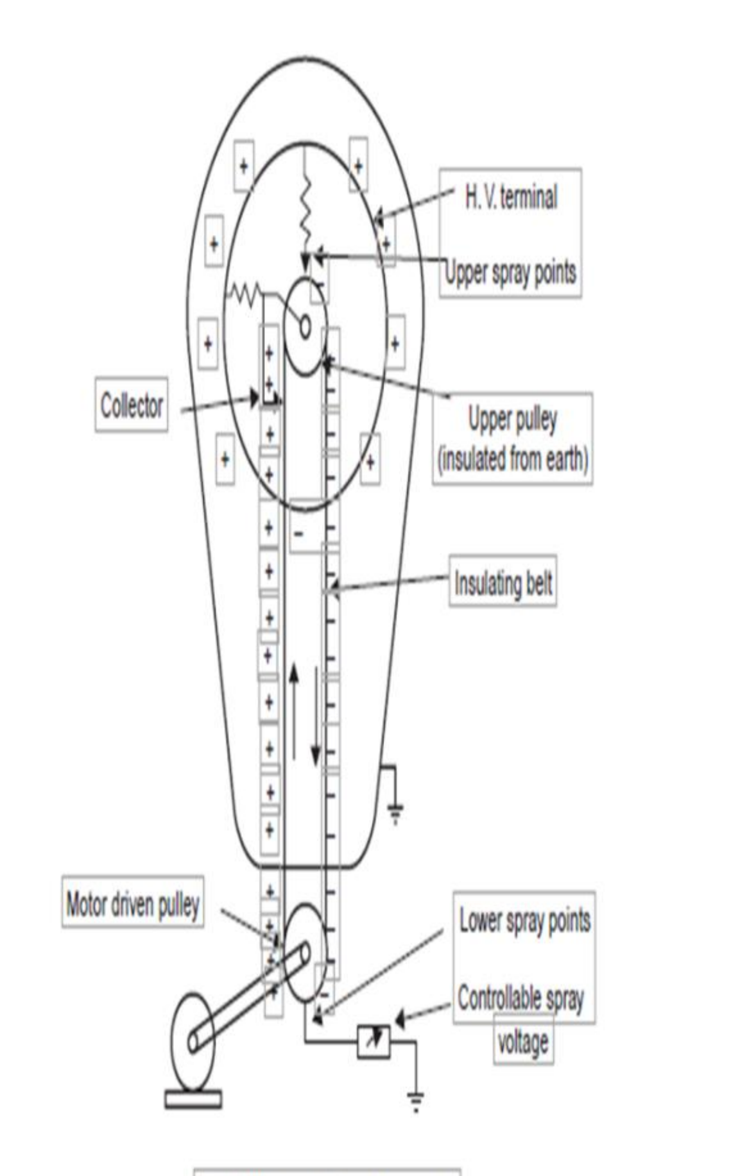


Fig. 2.8 Van de Graaf generator

The advantages of the generator are:

- Very high voltages can be easily generated
- Ripple free output
- Precision and flexibility of control

The disadvantages are:

- Low current output
- Limitations on belt velocity due to its tendency for vibration. The vibrations may make it difficult to have an accurate grading of electric fields.

Useful Area :-

- ✓ These generators are used in **nuclear physics laboratories** for particle acceleration and other processes in research work.

Impulse Current waveform

- The impulse current wave is same as an impulse voltage wave. An impulse current wave is shown in Fig.
- High current impulse generators will have large number of capacitors connected in parallel to the common discharge path.
- The equivalent circuit of the generator is shown below

Where approximates to that of a capacitance C charged to a voltage V_0 which can be considered to discharge through an inductance L and a resistance R.

In practice both L and R are the effective inductance and resistance of the leads, capacitors and the test objects.

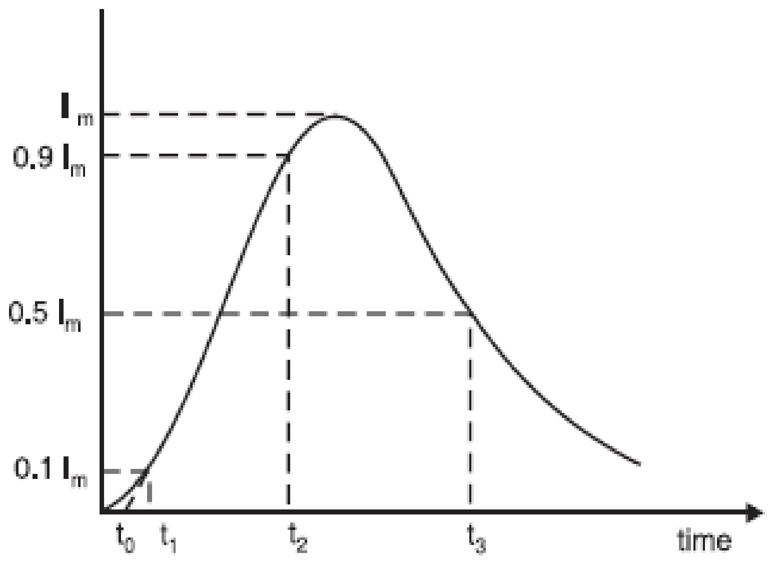


Fig. 3.13 A typical impulse current wave

Taking the inverse Laplace we have the current

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

For current $i(t)$ to be maximum $\frac{di(t)}{dt} = 0$

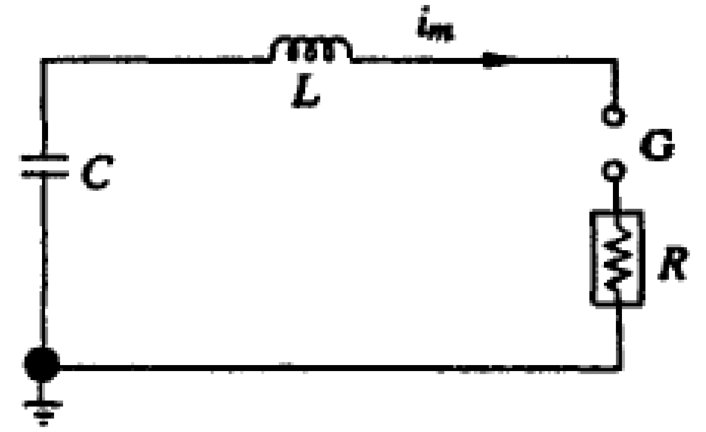
$$\frac{di(t)}{dt} = \frac{V}{\omega L} [\omega e^{-\alpha t} \cos \omega t - \alpha e^{-\alpha t} \sin \omega t] = 0$$

Reason for High Impulse Current =Why?

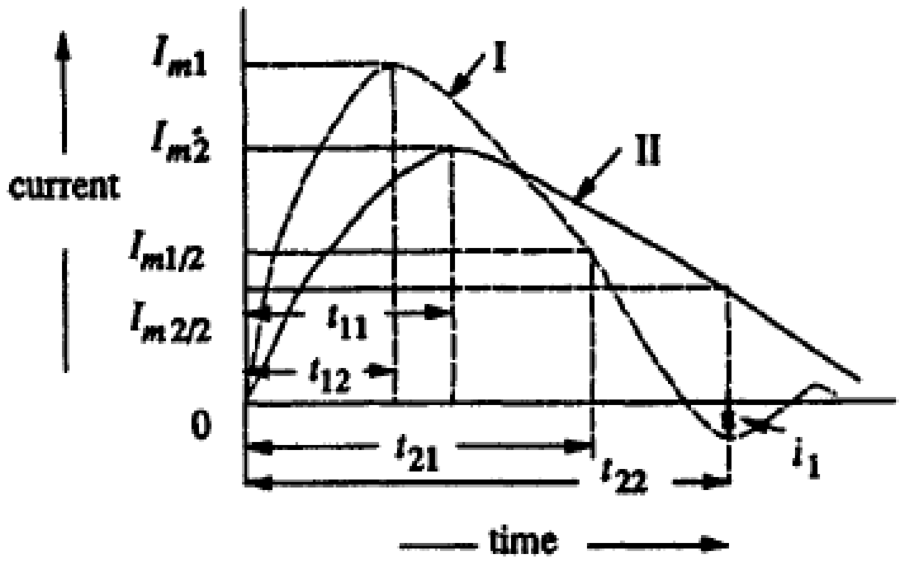
Lightening discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gear like surge diverters have to discharge the lightning currents without damage. Therefore, generation of impulse current waveforms of high magnitude (≈ 100 kA peak) find application in testing work as well as in basic research on non-linear resistors, electric arc studies, and studies relating to electric plasmas in high current discharges.

The waveshapes used in testing surge diverters are 4/10 and 8/20 μ s, the figures respectively representing the nominal wave front and wave tail times (see Fig. 6.14). The tolerances allowed on these times are ± 10% only. Apart from the standard impulse current waves, rectangular waves of long duration are also used for testing. The waveshape should be nominally rectangular in shape. The rectangular waves generally have durations of the order of 0.5 to 5 ms, with rise and fall times of the waves being less than ±10% of their total duration. The tolerance allowed on the peak value is +20% and –0% (the peak value may be more than the specified value but not less). The duration of the wave is defined as the total time of the wave during which the current is at least 10% of its peak value.

Impulse Current Generation Circuit



(a) Basic circuit of an impulse current generator



t_1 and t_{12} = time-to-front of waves I and II
t_{21} and t_{22} = time-to-tail of waves I and II

I — damped oscillatory wave
II — overdamped wave
i_1 — overshoot

(b) Types of impulse current waveforms

Impulse Current

For producing impulse currents of large value, a bank of capacitors connected in parallel are charged to a specified value and are discharged through a series R-L circuit as shown in Fig. 6.20. C represents a bank of capacitors connected in parallel which are charged from a d.c. source to a voltage up to 200 kV. R represents the dynamic resistance of the test object and the resistance of the circuit and the shunt. L is an air cored high current inductor, usually a spiral tube of a few turns.

If the capacitor is charged to a voltage V and discharged when the spark gap is triggered, the current i_m will be given by the equation

$$V = R\, i_m + L \frac{di_m}{dt} + \frac{1}{C}\int_0^t i_m \, dt \qquad (6.24)$$

The circuit is usually underdamped, so that

$$\frac{R}{2} < \sqrt{L/C}$$

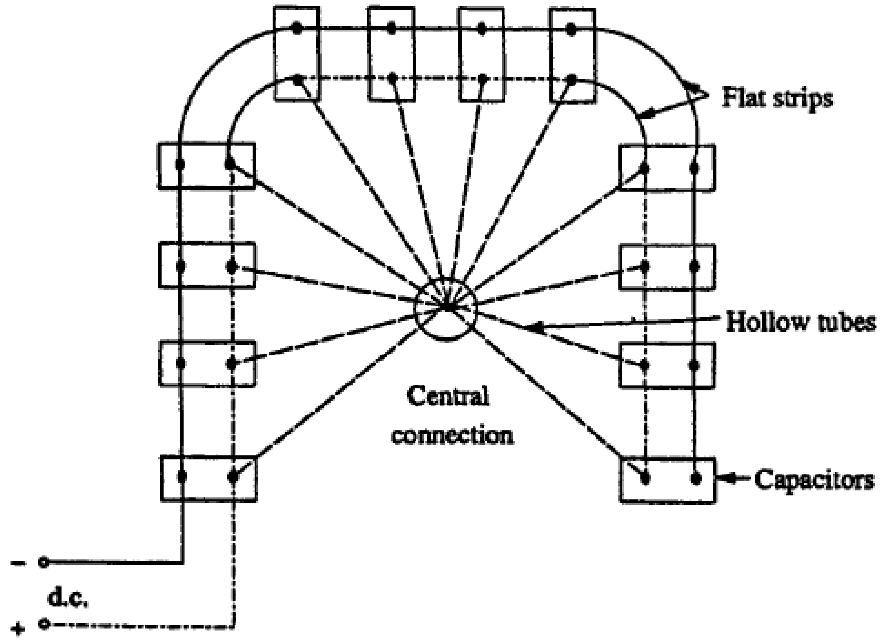
Hence, i_m is given by

$$i_m = \frac{V}{\omega L} [\exp(-\alpha t)] \sin(\omega t) \qquad (6.25)$$

where $$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad (6.25a)$$

High Impulse Current

For producing impulse currents of large value, a bank of capacitors connected in parallel are charged to a specified value and are discharged through a series *R*-*L* circuit as shown in Fig. 6.20. *C* represents a bank of capacitors connected in parallel which are charged from a d.c. source to a voltage up to 200 kV. *R* represents the dynamic resistance of the test object and the resistance of the circuit and the shunt. *L* is an air cored high current inductor, usually a spiral tube of a few turns.



(c) Arrangement of capacitors for high impulse current generation

Fig. 6.20 Impulse current generator circuit and its waveform

Hence, i_m is given by

$$i_m = \frac{V}{\omega L} [\exp(-\alpha t)] \sin(\omega t)$$

where

$$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

Class Test 1

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[20 Minute]

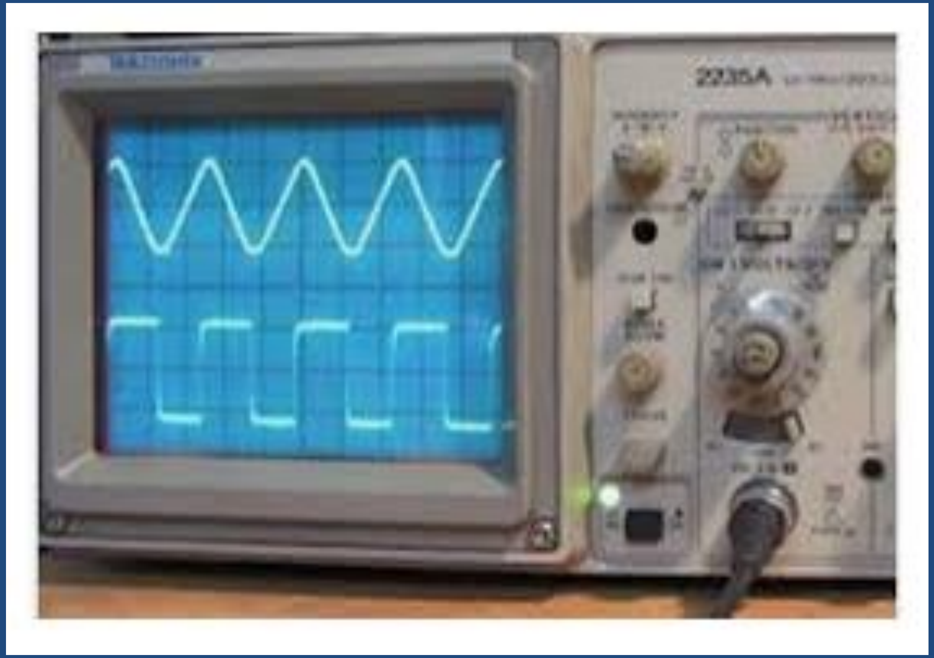
CLASS TEST 1- 24 May 2022

- Syllabus - HIGH VOLTAGE GENERATION

Assignment 1- Submit on "27 May 2022"

- What is meant by High Voltage engineering?
- Why Study of the High Voltage Engineering is needed?

Measurement of
High Voltages and Currents



Why? =Measurement of High Voltage and Currents

- Industrial testing and research laboratories - essential to measure the voltages and currents accurately with perfect safety to the personnel and equipment.
- Person handling the equipment & the metering devices must be protected against over voltages and also against any induced voltages due to stray coupling.
- Linear extrapolation of the devices beyond their ranges are not valid for high voltage meters and measuring instruments.
- Electromagnetic interference is a serious problem in impulse voltage and current measurements. The devices and instruments for measurement of high voltages and currents differ vastly from the low voltage and low current devices.
- Different devices used for high voltage measurements may be classified as in Tables
- High voltages measurement in a variety of ways.
- Direct measurement of HV is up to about 200 kV, and several forms of voltmeters have been devised that will directly across the test circuit.

- High Voltages are also measured by stepping down the voltage by using transformers and potential dividers.
- The spark over of sphere gaps and other gaps are also used, especially in the calibration of meters in high voltage measurements.
- Transient voltages may be recorded through potential dividers and oscilloscopes.
- Lightning surges may be recorded using the Klydonograph.

What are the different methods of the Measurement techniques for HV voltage and current ?

Measurement Techniques :-

High voltage Measurement Techniques

Type of voltage	Method or technique
(a) d.c. voltages	*(i)* Series resistance microammeter
	(ii) Resistance potential divider
	(iii) Generating voltmeters
	(iv) Sphere and other spark gaps
(b) a.c. voltages (power frequency)	*(i)* Series impedance ammeters
	(ii) Potential dividers (resistance or capacitance type)
	(iii) Potential transformers (electromagnetic or CVT)
	(iv) Electrostatic voltmeters
	(v) Sphere gaps
(c) a.c. high frequency voltages, impulse voltages, and other rapidly changing voltages	*(i)* Potential dividers with a cathode ray oscillograph (resistive or capacitive dividers)
	(ii) Peak voltmeters
	(iii) Sphere gaps

Measurement Techniques :-

. . High Current Measurement Techniques

Type of current	Device or technique
(*a*) Direct currents	(*i*) Resistive shunts with milliammeter
	(*ii*) Hall effect generators
	(*iii*) Magnetic links
(*b*) Alternating currents (Power frequency)	(*i*) Resistive shunts
	(*ii*) Electromagnetic current transformers
(*c*) High frequency a.c., impulse and rapidly changing currents	(*i*) Resistive shunts
	(*ii*) Magnetic potentiometers or Rogowski coils
	(*iii*) Magnetic links
	(*iv*) Hall effect generators

MEASUREMENT OF HIGH DIRECT CURRENT VOLTAGES

- **Extension of meter range** with large series resistance is also one solution in HV Measurement.
- The net current limited to one to ten microamperes for full**-scale deflection**.
- HV >=1000 kV or more, **problems** -large power dissipation / leakage currents / limitation of voltage stress per unit length, change in resistance due to temperature variations, etc.
- **Hence**, a **resistance potential divider** with an electrostatic voltmeter is better when high but it suffers from the disadvantages stated above. Series resistance and potential dividers drains current from the source.
- **High Impedance Generating voltmeters** are do not load the source as they are not directly connected to the high voltage terminal and hence are safer.
- Spark gaps such as sphere gaps, simple in construction, are gas discharge devices for accurate measure of the peak voltage. But the measurement is **affected by the atmospheric conditions**.
- But sphere gap measurement of voltages is **independent of the waveform and frequency.**

Why the DC measurement is considered better than AC or Impulse measured method?

Electrostatic Voltmeters [Explain the Working Principle of E.V.?]

Principle:-

In electrostatic fields, the attractive force between the electrodes of a parallel plate condenser is given by

$$F = \left|\frac{-\delta W_s}{dS}\right| = \left|\frac{\delta}{\delta S}\left(\frac{1}{2}CV^2\right)\right| = \left|\frac{1}{2}V^2\frac{\delta C}{\delta S}\right| = \frac{1}{2}\varepsilon_0 V^2\frac{A}{S^2} = \frac{1}{2}\varepsilon_0 A\left(\frac{V}{S}\right)^2$$

where, V= applied voltage between plates,

C = capacitance between the plates,

A = area of cross-section of the plates,

S= separation between the plates,

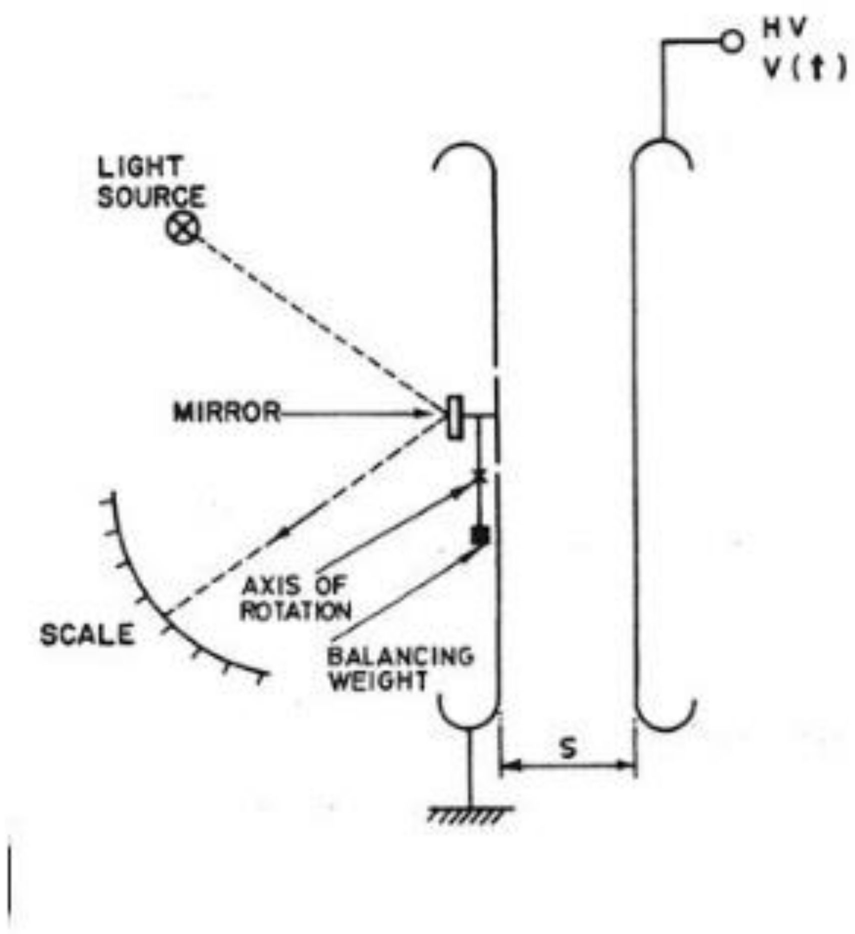
ε_0 = permittivity of the medium (air or free space), and

Ws= work done in displacing a plate

When one of the electrodes is free to move, the force on the plate can be measured by controlling it by a spring or balancing it with a counterweight. For high voltage measurements, a small displacement of one of the electrodes by a fraction of a millimeter to a few millimeters is usually sufficient for voltage measurements. As the force is proportional to the square of the applied voltage, the measurement can be made for a.c. or d.c. voltages.

Electrostatic Voltmeters

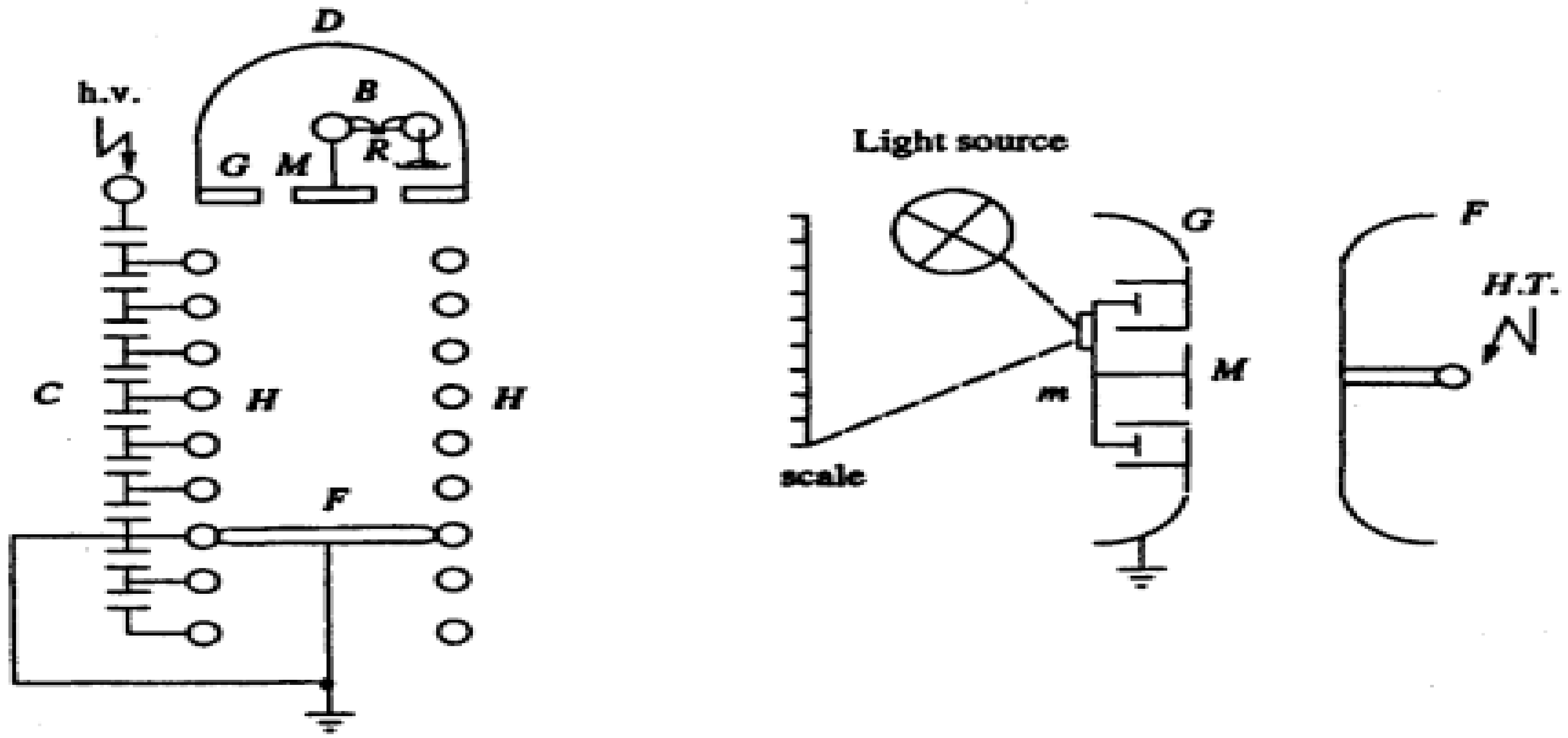
- One of the direct methods of measuring high voltages is by means of electro-static voltmeters.
- For voltages above 10 kV, generally the attracted disc type of electrostatic voltmeter is used.
- When two parallel conducting plates (cross section area 'A' and spacing 's') are charged q and have a potential difference V, then the energy stored is given by $= \frac{1}{2} CV^2$
- It is thus seen that the force of attraction is proportional to the square of the potential difference applied, so that the meter reads the square value (or can be marked to read the rms value).



- Electrostatic voltmeters of the attracted disc type may be connected across the high voltage circuit directly to measure up to about 200 kV, without the use of any potential divider or other reduction method.
- [The force in these electrostatic instruments can be used to measure both a.c. and d.c. voltages].The right hand electrode forms the high voltage plate.
- The centre portion of the left hand disc is cut away and encloses a small disc which is movable and is geared to the pointer of the instrument.The range of the instrument can be altered by setting the right hand disc at pre- marked distances.
- The force of attraction F(t) created by the applied voltage causes the movable part-to which a mirror is attached-to assume a position at which a balance of forces takes place.
- An incident light beam will therefore be reflected toward a scale calibrated to read the applied voltage magnitude.

Construction

- Electrostatic voltmeters are made with parallel plate with guard rings to avoid corona and field fringing.
- An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight with small capacitance (5 to 50 pF) and high insulation resistance ($R > 10^{13}\ \Omega$).
- They are considered as high input impedance. The upper frequency limit is determined from – 1] Natural frequency of the moving system, 2] Resonant frequency of the lead and stray inductances with meter capacitance, 3] R-C behavior of the retaining or control spring (due to the frictional resistance and Elastance).
- An upper frequency limit of 1 MHz can be achieved. The accuracy for AC voltage will be ±0.25%, and for DC will be ±0.1% or less.
- The schematic diagram of an absolute electrostatic voltmeter or electrometer is given in Fig. 7.13. It consists of parallel plane disc type electrodes separated by a small distance. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region. In order to measure the given voltage with precision, the disc diameter is to be increased, and the gap distance is to be made less. The limitation on the gap distance is the safe working stress (V/s) allowed in air which is normally 5 kV/cm or less.



(a) Absolute electrostatic voltmeter

m — mirror

(b) Light beam arrangement

M — Mounting plate
G — Guard plate
F — Fixed plate
H — Guard hoops or rings

B — Balance
C — Capacitance divider
D — Dome
R — Balancing weight

Fig. 7.13 Electrostatic voltmeter

elongation of the spring is kept minimum to avoid field disturbances.

- The range of the instrument is easily changed by changing the gap separation so that V/s or electric stress is the same for the maximum value in any range.
- The control torque is provided by a balancing weight. The moving disc M forms the central core of the guard ring G which is of the same diameter as the fixed plate F.
- The cap D encloses a sensitive balance B, one arm of which carries the suspension of the moving disc. The balance beam carries a mirror which reflects a beam of light.
- As the spacing between the two electrodes is large, the uniformity of the electric field is maintained by the guard rings H which surround the space between the discs F and M.
- The guard rings H are maintained at a constant potential by a capacitance divider ensuring a uniform potential distribution.
- Some instruments are constructed containing compressed air, carbon dioxide, or nitrogen. With the gas pressure of the order of 15 atm & working stresses as high as 100 kV/cm may be used in an electrostatic meter in Light source scale vacuum.
- With compressed gas / vacuum as medium, the meter is compact and much smaller in size.

Spark Gaps for Measurement of High d.c., a.c. and Impulse Voltages (Peak Values)

- A uniform field spark gap will always have a spark over voltage within a known tolerance under constant atmospheric conditions. Hence a spark gap can be used for measurement of the peak value of the voltage, if the gap distance is known.
- A spark over voltage of 30 kV (peak) at 1 cm spacing in air at 2O^{0C} and 760 torr pressure occurs for a sphere gap or any uniform field gap.
- As per experience, these measurements are reliable only for certain gap configurations. Normally, only sphere gaps are used for voltage measurements.
- In certain cases uniform field gaps and rod gaps are also used, but their accuracy is less. The spark gap breakdown, especially the sphere gap breakdown, is independent of the voltage waveform and hence is highly suitable for all types of waveforms from d.c. to impulse voltages of short rise times (rise time > 0.5 Ʊs). As such, sphere gaps can be used for radio frequency a.c. voltage peak measurements also (up to 1 MHz).

Table 4.2

Sphere gap with one sphere earthed

Peak value of disruptive discharge voltages (50% for impulse tests) are valid for (*i*) alternating voltages (*ii*) d.c. voltage of either polarity (*iii*) negative lightning and switching impulse voltages

Sphere Gap Spacing mm	*Voltage KV Peak Sphere dia in cm.*						
	12.5	25	50	75	100	150	200
10	31.7						
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

Sphere Gap with one sphere grounded

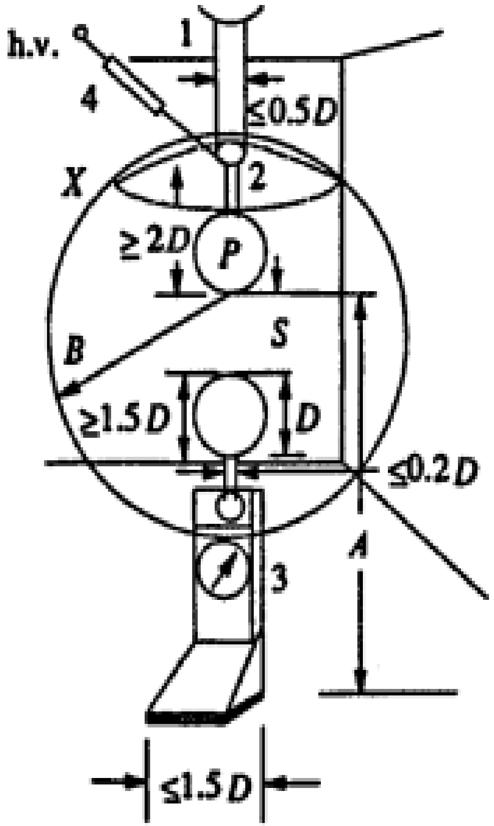
Peak values of disruptive discharge voltages (50% values).

Positive lightning and switching impulse voltages

Sphere Gap	*Peak Voltage kV Sphere dia in cms*						
Spacing mm	12.5	25	50	75	100	150	200
10	31.7						
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)

Sphere Gap Measurements

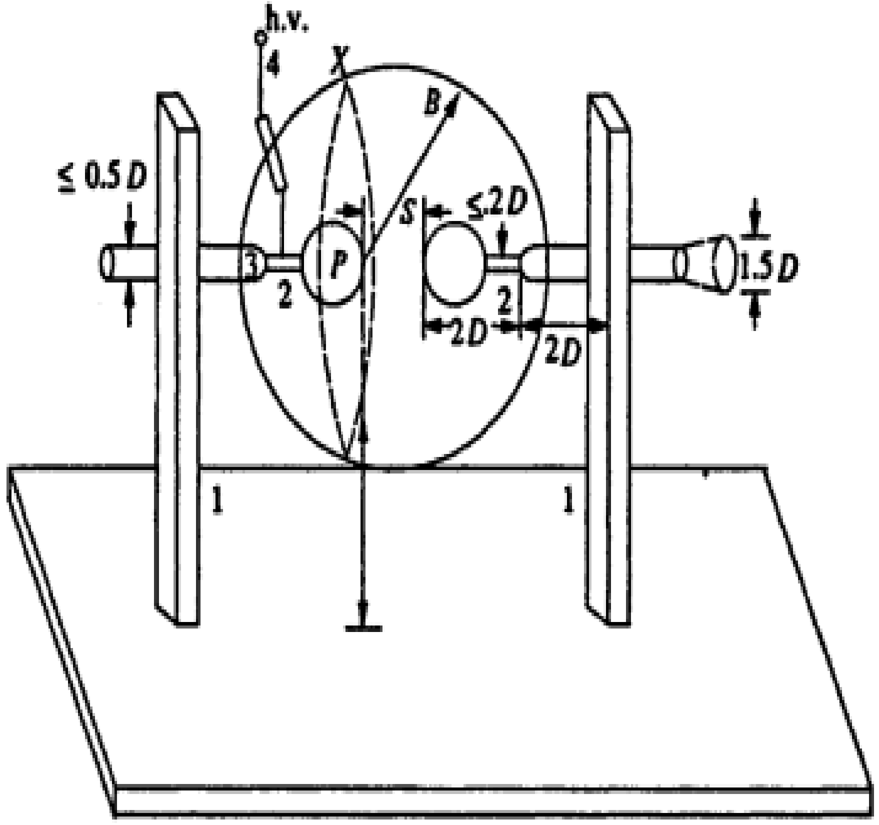
- Sphere gaps can be arranged either (i) vertically or (if) horizontally with both spheres connected to the source voltage or one sphere grounded.
- In horizontal, generally arranged both spheres are symmetrically at high voltage above the ground. The two spheres identical in size and shape. The schematic arrangement is shown in Figs.
- The voltage to be measured is applied on the spheres and the spacing S between them gives a measure of the spark over voltage.
- A series resistance between the source and the sphere gap to 1] limit the breakdown current, 2] to suppress unwanted oscillations in the source voltage when breakdown occurs (in case of impulse voltages).
- The series resistance 100 to 1000 kΩ for a.c. or d.c. voltages and not more than 500 Ω in the case of impulse.
- In the case of a.c. and d.c. measurements, the applied voltage increased until spark over occurs in the gap. Generally, a mean of about five breakdown values is taken when they agree to within ±3%. In the case of impulse voltages, to obtain 50% flashover voltage, two voltage limits, differing by not more than 2% are set such that on application of lower limit value either 2 or 4 flashovers take place and on application of upper limit value 8 or 6 flashovers take place respectively. The mean of these two limits is taken as 50% flashover voltage. In any case, a preliminary spark over voltage measurement is to be made before actual measurements are made. The flashover voltage for various gap and standard diameters of the spheres used can be found.
- The values of sparkover voltages are specified in BS : 358, EEC Publication 52 of 1960 and IS : 1876 of 1962. The clearances necessary are shown in Figs. for measurements to be within ±3%. The values of A and B indicated in the above figures are given in Table.



1 — Insulator support
2 — Sphere shank
3 — Operating gear and motor for changing gap distance
4 — H.V. connection
P — Sparking point
D — Diameter of the sphere
S — Spacing
A — Height of *P* above earth
B — Radius of the clearance from external structures
X — High voltage lead should not pass through this plane within a distance *B* from *P*

(a) Vertical arrangement of sphere gap

Fig. 7.18a Sphere gap for voltage measurement



(b)

Fig. 7.18b Horizontal arrangement of sphere gap
(Legend as in Fig. 7.18a)

Rod Gaps

A rod gap is also sometimes used for approximate measurement of peak values of power frequency voltages and impulse voltages. IEEE recognize that this method gives an **accuracy within ±8%.** The rods will be either square edged or circular in cross-section. The length of the rods may be 15 to 75 cm and the spacing varies from 2 to 2000 cm. The spark over voltage, as in other gaps, is affected by humidity and air density. The power frequency breakdown voltage for 1.27 cm square rods in air at 25^{0C} and at a pressure of 760 ton with the vapor pressure of water of 15.5 torr is given in Table 7.8. The humidity correction is given in Table 7.9. The air density correction factor can also be found from the test resources.

Table 7.8 Sparkover Voltage for Rod Gaps

Gap spacing (cm)	Sparkover voltage (kV)	Gap spacing (cm)	Sparkover voltage (kV)
2	26	30	172
4	47	40	225
6	62	50	278
8	72	60	332
10	81	70	382
15	102	80	435
20	124	90	488
25	147	100	537

The rods are 1.27 cm square edged at $t = 27°C$, $p = 760$ torr, and vapour pressure of water = 15.5 torr.

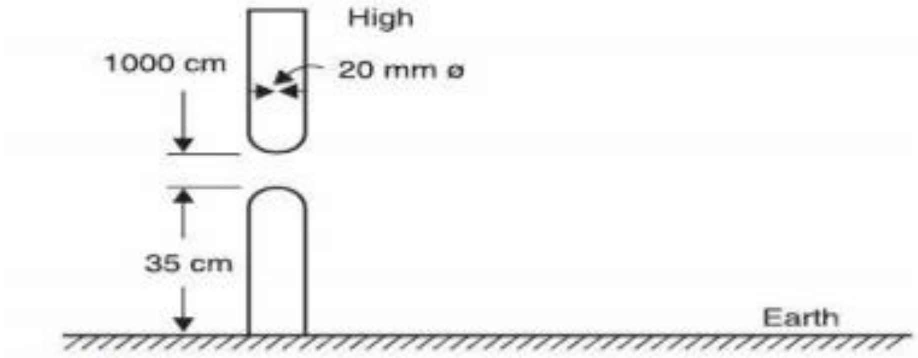


Figure: 4.2 Electrode arrangements for a rod gap to measure HVDC

Table 7.9 Humidity Correction for Rod Gap Sparkover Voltages

Vapour pressure of water (torr)	2.54	5	10	15	20	25	30
Correction factor %	– 16.5	– 13.1	– 6.5	– 0.5	4.4	7.9	10.1

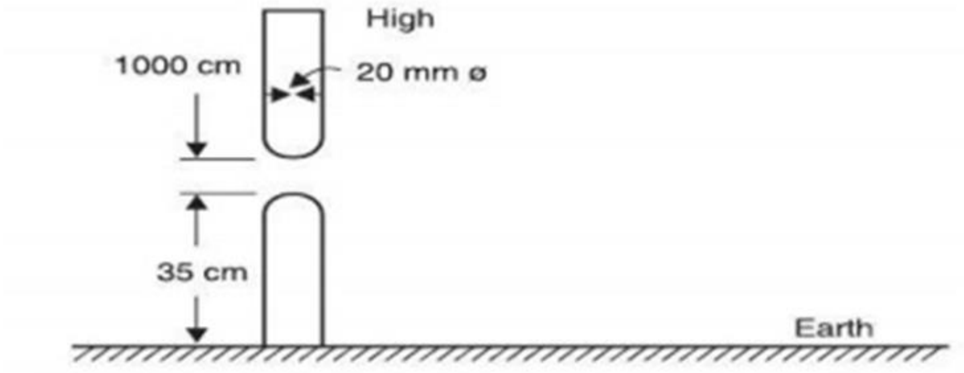


Figure: 4.2 Electrode arrangements for a rod gap to measure HVDC

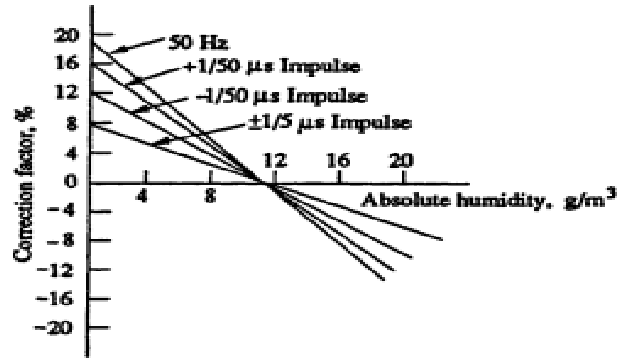


Fig. 7.22 Correction factor for rod gaps

In case of impulse voltage measurements, the **IEC** and **IEEE** recommend horizontal mounting of rod gaps on insulators at a height of 1.5 to 2.0 times the gap spacing above the ground. One of the rods is usually earthed. For 50% flashover voltages, the procedure followed is the same as that for sphere gaps. Corrections for humidity for 1/50 p. s impulse and 1/50 \i s impulse waves of either polarity are given in Fig. 7.22. The spark over voltages for impulse waves are given in Table 7.10.

Table 7.10 Sparkover Voltages of Rod Gaps for Impulse Voltages at Temperature = 20°c, Pressure = 760 torr and Humidity = 11 g/cm²

Gap length (cm)	1/5 μ s wave (kV)		1/50 μ s wave (kV)	
	ositive	Negative	Positive	Negative
5	60	66	56	61
10	101	111	90	97
20	179	208	160	178
30	256	301	226	262
40	348	392	279	339
50	431	475	334	407
60	513	557	397	470
80	657	701	511	585
100	820	855	629	703

<u>Factors Influencing the Spark over Voltage of Sphere Gaps:-</u>

Various factors that affects the spark over voltage of the sphere gap are :-

- Near by Earthed Objects
- Atmospheric Conditions
- Irradiations
- Polarity and rise time of the voltage waveforms

➢ **Near By Earth Objects :** The effect was observed that the spark over voltage is reduced. The reduction was observed to be

$\Delta V = m \log (B/D) + C$

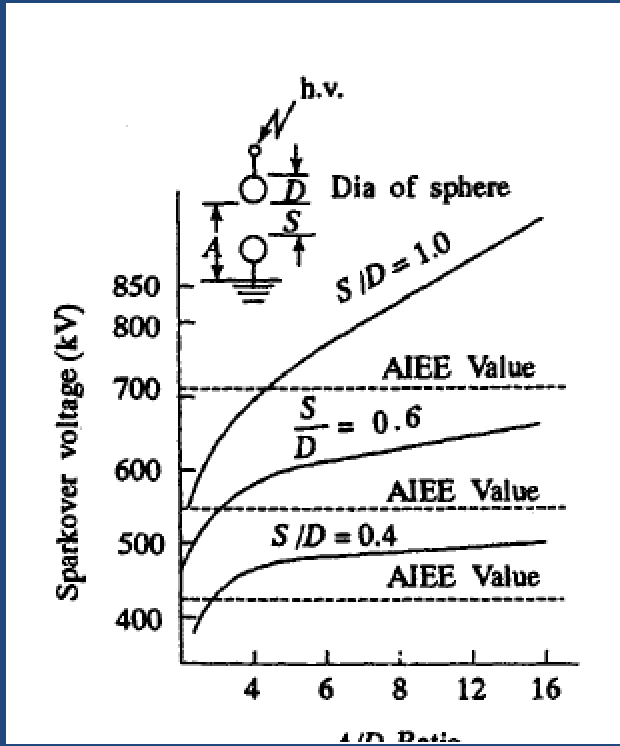
$\Delta V =$ percentage reduction,

$B =$ diameter of earthed enclosing cylinder,

$D =$ diameter of the spheres,

$S =$ spacing, and m and C are constants.

The reduction was less than 2% for *SID* <= 0.5 and *BID* >=0.8.Even for *SID* = 1.0and *BID* >= 1.0 the reduction was only 3%.



Effect of the Atmospheric Condition:-The spark over voltage of a spark gap depends on the air density which varies with the changes in both temperature and pressure. If the spark over voltage is *V* under test conditions of temperature *T* and pressure *p* torr and if the spark over voltage is *Vo* under standard conditions of temperature $T = 20^{0C}$ and pressure $p = 760$ tor, then

$$V = kVo$$

where *k* is a function of the air density factor *d*, given by

$$d = \frac{p}{760}\left(\frac{293}{273+T}\right)$$

The relationship between *d* and *k* is given in Table 7.6.

Table 7.6 Relation between Correction Factor *k* and Air Density Factor *d*

d	0.70	0.75	0.80	0.85	0.90	0.95	1.0	1.05	1.10	1.15
k	0.72	0.77	0.82	0.86	0.91	0.95	1.0	1.05	1.09	1.12

The sparkover voltage increases with humidity.
The increase is about 2 to 3% over normal humidity range of 8 g/m3 to 15 g/m3•
The influence of humidity on sparkover voltage of a 25 cm sphere gap for 1cm spacing is presented in Fig. 7.20.
Hence, it may be **concluded that**
1] the humidity effect increases with the size of spheres and is maximum for uniform field gaps,
2] the sparkover voltage increases with the partial pressure of water vapour in air.

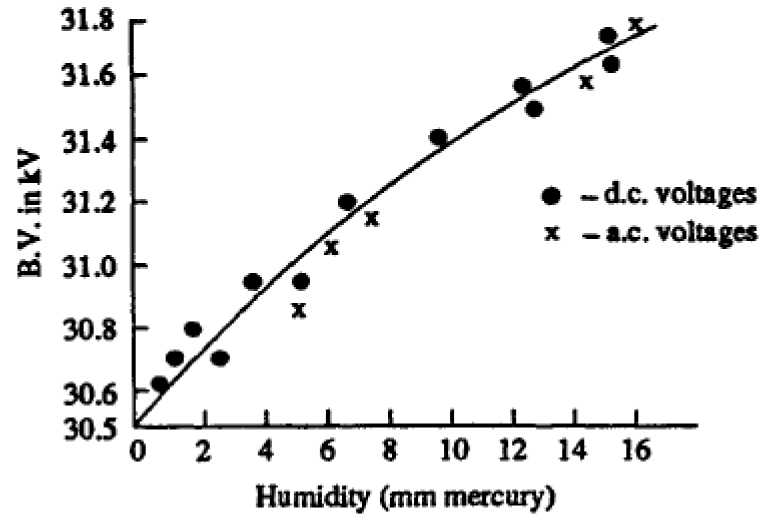


Fig. 7.20 Influence of humidity on d.c. and a.c. breakdown voltages (25 cm dia sphere gap, 1 cm spacing)

Effect of Irradiation

- Illumination of sphere gaps with ultra-violet or x-rays aids easy ionization in gaps.
- The effect of irradiation is pronounced for small gap spacings.
- A reduction of about 20% in sparkover voltage was observed for spacings of 0.1*D* to 0.3 *D* for a 1.3 cm sphere gap with d.c. voltages. The reduction in sparkover voltage is less than *5%* for gap spacings more than 1cm, and for gap spacings of 2 cm or more it is about 1.5%.
- Hence, irradiation is necessary for smaller sphere gaps of gap spacing less than 1cm for obtaining consistent values

Effect of polarity and waveform

- The spark over voltages for positive and negative polarity impulses are different.
- Experimental investigation showed that for sphere gaps of 6.25 to 25 cm diameter, the difference between positive and negative d.c. voltages is not more than 1%.
- For smaller sphere gaps (2 cm diameter and less) the difference was about 8% between negative and positive impulses of 1/50 μs waveform.
- Similarly, the wave front and wave tail durations also influence the breakdown voltage. For wave fronts of less than 0.5 μs and wave tails less than 5 μs the breakdown voltages are not consistent and hence the use of sphere gap is not recommended for voltage measurement in such cases.

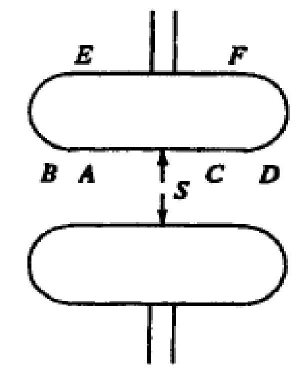
Uniform Field Electrode Gaps

Sphere gaps, although widely used for voltage measurements, have only **limited range with uniform electric field**. Hence, it is **not possible to ensure that the sparking always takes place along the uniform field region**. **Rogowski** presented a design for uniform field electrodes for sparkover voltages **up to 600 kV**. The sparkover voltage in a uniform field gap is given by

$$V = AS + B.\mathrm{sqrt}(S)$$

where *A* and B are constants, *S is* the gap spacing in cm, and *V is* the sparkover voltage. Typical uniform field electrodes are shown in Fig. 7.21. The constants *A* and *B* were found to be 24.4 and 7.50 respectively at a temperature *T* = 25°C and pressure = 760 torr. Since the sparking potential is a function of air density, the sparkover voltage for any given air density factor *d* is modified as

$$v = 24.4\,dS + 7.50\,\mathrm{Sqrt}(dS)$$



AC, EF — Flat portion (≥ *S*)

Curvature *A* to *B* and *C* to *D* ≥ 108

Curvature *B* to *E* and *D* to *F* continuously increasing

(a) Electrodes for 300 kV (rms) spark gap

Transformer and Potential Divider Methods

Transformer ratio method

The use of the primary voltage to estimate the secondary voltage is a fairly rough method of measurement, but is satisfactory enough for most ac tests. In this method (figure 6.7), the voltage on the low voltage side of the high-tension transformer is measured. The actual voltage across the load is not measured.

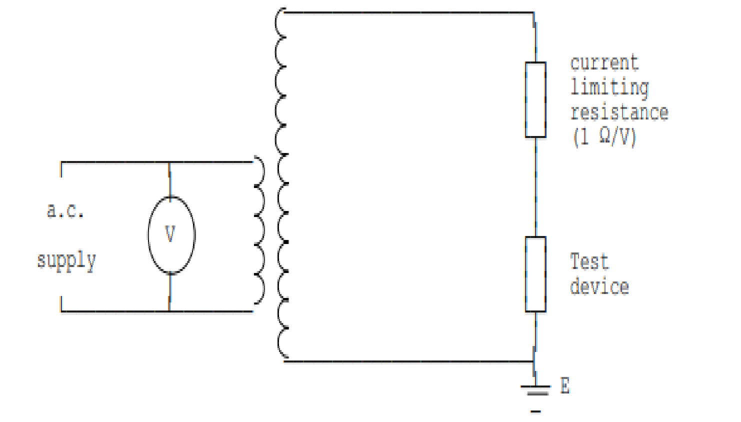


Figure 6.7 - transformer ratio method

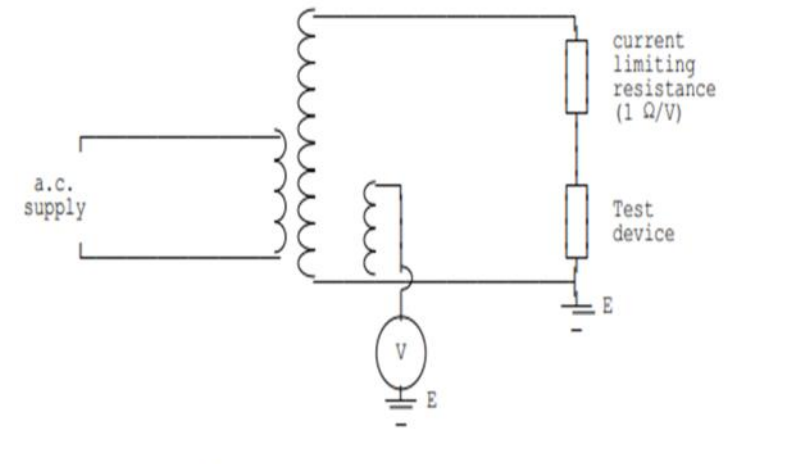


Figure 6.8 - with additional potential winding

Since the current taken by the device under test is usually very small, currents such as due to corona may cause considerable error in the measured voltage. This method measures the rms voltage. In order to determine the peak value it is necessary to determine the wave form of the secondary voltage.Some high voltage transformers (figure 6.8) carry a separate voltmeter-coil having a number of turns which is a definite fraction of the secondary turns. This method cannot be used with the cascade arrangement of the transformers.

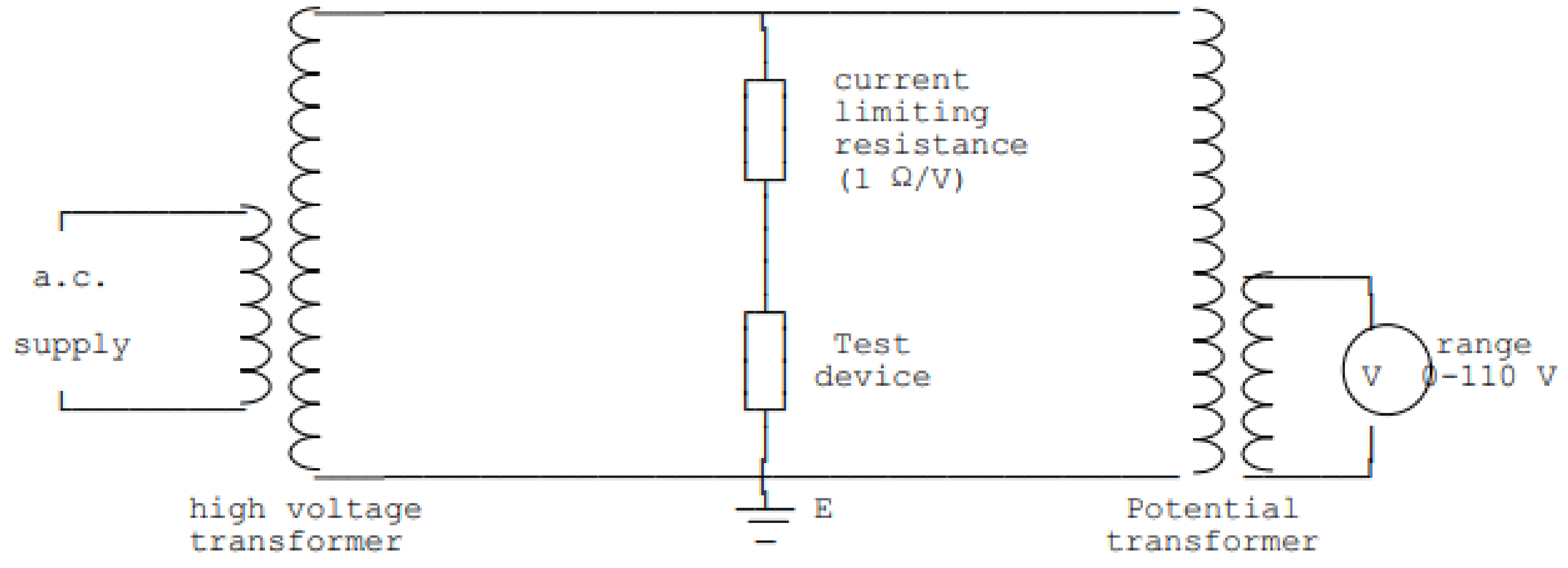


Figure 6.9 - with potential transformer

It may also be possible to have a potential transformer connected across the test device and the voltage measured, however this is an expensive arrangement. Even this method may not be very satisfactory under very high voltage conditions and the series resistance method of measurement may be used.

Resistive potential divider method

In this method, a high resistance potential divider is connected across the high-voltage winding, and a definite fraction of the total voltage is measured by means of a low voltage voltmeter. In this method, a high resistance potential divider is connected across the high-voltage winding, and a definite fraction of the total voltage is measured by means of a low voltage voltmeter

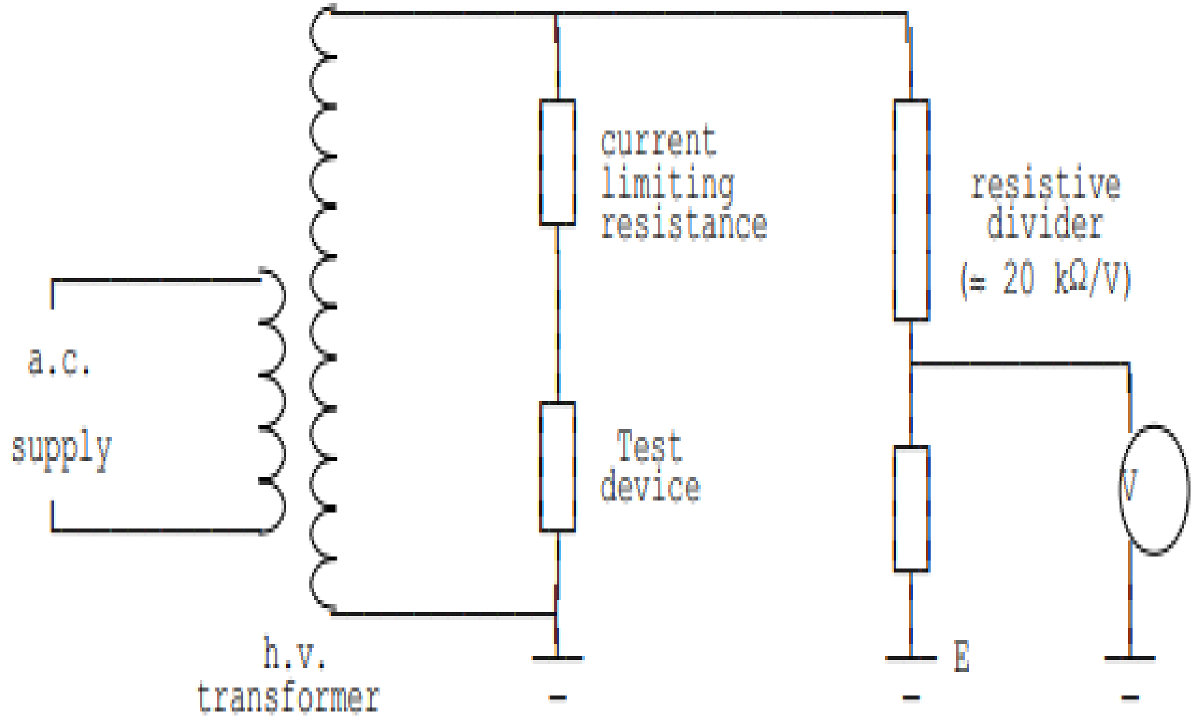


Figure 6.11 - Resistive potential divider method

Capacitive potential divider Method :-

For alternating work, instead of using a resistive potential divider, we could use a capacitive potential divider. In this two capacitances C1 and C2 are used in series, the electrostatic voltmeter being connected across the lower capacitor. If the system is kept at a fixed position, we can make corrections for the fixed stray capacitances. Or if screens are used, the capacitance to the screen would be a constant, and we could lump them up with the capacitances of the arms. Neglecting the capacitance of the voltmeter (or lumping the electrostatic voltmeter capacitance with C2) the effective capacitance of C1 and C2 in series is C1C2/(C1+C2), and since the charge is the same,

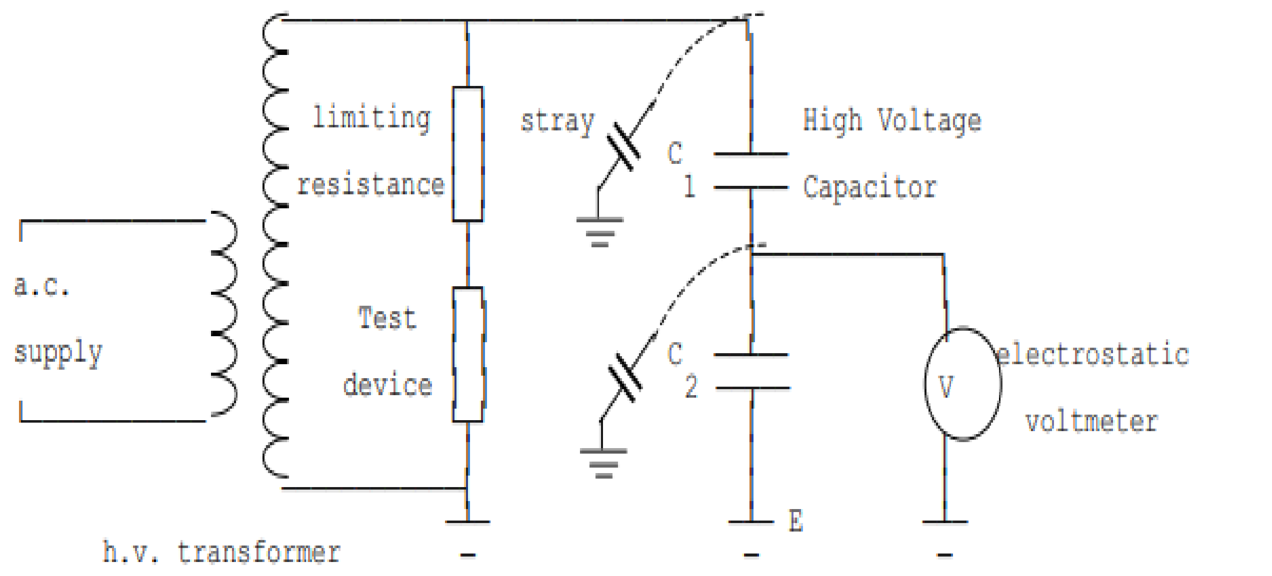


Figure 6.13 - Capacitive potential divider method

$$\text{Voltage across } C_2 = \frac{1/C_2}{(C_1+C_2)/C_1 C_2} . V = \frac{C_1}{C_1+C_2} . V$$

- The capacitance of HV. standard capacitor must be accurately known and free from dielectric losses – Air capacitances uses.
- This method measures the RMS value. It is sometimes more useful to have a measure of the peak value because of the break down voltage which produces the actual breakdown stress in the material under test.
- If the shape of the voltage waveform is known, the peak voltage may be obtained from the RMS voltage.
- It is often more satisfactory however, to use some method of voltage measurement which gives the peak value of the voltage directly.

Measurement of Impulse Voltage and Currents

Peak Voltmeter with Potential Divider :- Explain working principle with neat diagrame?

Passive circuits are not very frequently used these days for measurement of the peak value of a.c. or impulse voltages. The development of fully integrated operational amplifiers and other electronic circuits has made it possible to sample and hold such voltages and thus make measurements and, therefore, have replaced the conventional passive circuits. However, it is to be noted that if the passive circuits are designed properly, they provide simplicity and adequate accuracy and hence a small description of these circuits is in order. Passive circuits are cheap, reliable and have a high order of electromagnetic compatibility. However, in contrast, the most sophisticated electronic instruments are costlier and their electromagnetic compatibility (EMC) is low. The passive circuits cannot measure high voltages directly and use potential dividers preferably of the capacitance type. Fig. 4.14 shows a simple peak voltmeter circuit consisting of a capacitor voltage divider which reduces the voltage V to be measured to a Fig. 4.14 Peak voltmeter low voltage Vm.

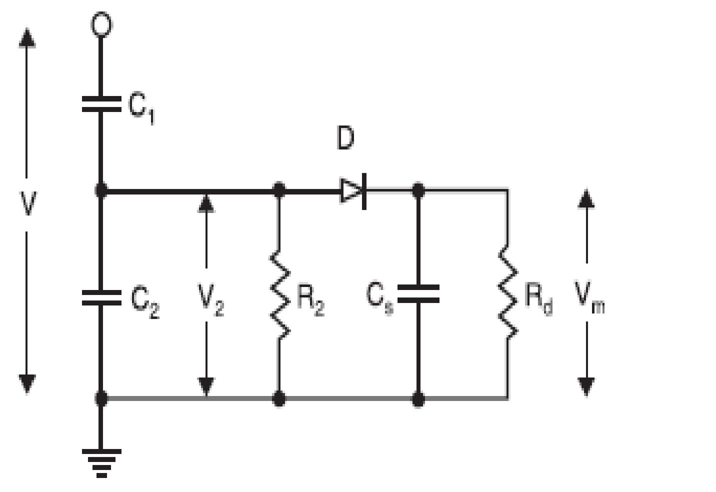


Fig. 4.14 Peak voltmeter

Suppose R2 and Rd are not present and the supply voltage is V. The voltage across the storage capacitor Cs will be equal to the peak value of voltage across C2 assuming voltage drop across the diode to be negligibly small. The voltage could be measured by an electrostatic voltmeter or other suitable voltmeters with very high input impedance. If the reverse current through the diode is very small and the discharge 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, the voltage V2 decreases proportionately and since now the voltage across C2 is smaller than the voltage across Cs to which it is already charged, therefore, the diode does not conduct and the voltage across Cs does not follow the voltage across C2. Hence, a discharge resistor Rd must be introduced into the circuit so that the voltage across Cs follows the voltage across C2. From measurement point of view it is desirable that the quantity to be measured should be indicated by the meter within a few seconds and hence Rd is so chosen that RdCs ≈ 1 sec. As a result of this, following errors are introduced. With the connection of Rd, the voltage across Cs will decrease continuously even when the input voltage is kept constant. Also, it will discharge the capacitor C2 and the mean potential of V2(t) will gain a negative d.c. component. Hence a leakage resistor R2 must be inserted in parallel with C2 to equalise these unipolar discharge currents. The second error corresponds to the voltage shape across the storage capacitor which contains ripple and is due to the discharge of the capacitor Cs. If the input impedance of the 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-constant cannot be changed. If RdCs = 1 sec, the discharge error amounts to 1% for 50 Hz and 0.33%

for 150 Hz. The third source of error is related to this discharge error. During the conduction time (when the voltage across Cs is lower than that across C2 because of discharge of Cs through Rd) of the diode the storage capacitor Cs is recharged to the peak value and thus Cs becomes parallel with C2. If discharge error is ed, recharge error er is given by

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

Hence Cs should be small as compared with C2 to keep down the recharge error.

It has also been observed that in order to keep the overall error to a low value, it is desirable to have a high value of R2. The same effect can be obtained by providing an equalising arm to the low voltage arm of the voltage divider as shown inFig. 4.15. This is accomplished by the addition ofa second network comprising diode, Cs and Rd for negative polarity currents to the circuit shown in Fig. 4.14. With this, the d.c. currents in both branches are opposite in polarity and equalise each other. The errors due to R2 are thus eliminated.

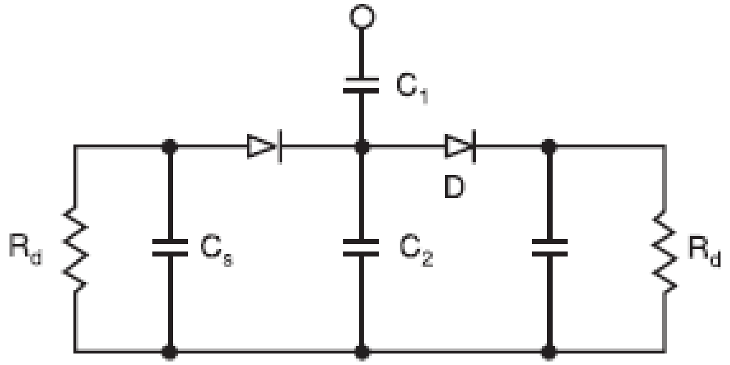


Fig. 4.15 Modified peak voltmeter circuit

IMPULSE VOLTAGE MEASUREMENTS USING VOLTAGE DIVIDERS

If the **amplitudes of the impulse voltage** is **not high** and is in the range of a few kilovolts, it is possible to measure them even when these are of short duration by **using CRO**. However, if **the voltages** to be measured are of **high magnitude** of the order of **magavolts** which normally is the case for testing and research purposes, **various problems arise**. The **voltage dividers** required are of special design and need a thorough understanding of the interaction present in these voltage dividing systems. Fig. 4.17 shows a **layout of a voltage testing circuit** within a high voltage testing area. The voltage generator G is connected to a test object—T through a lead L.

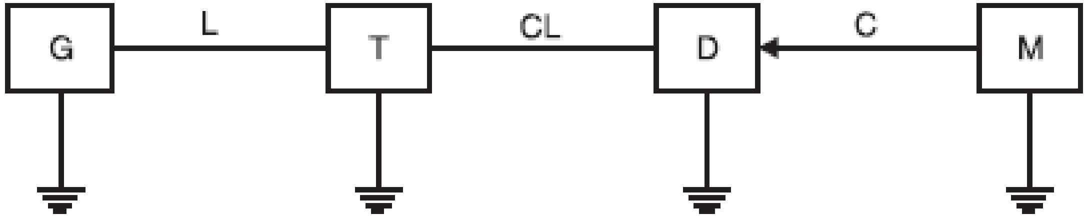


Fig. 4.17 Basic voltage testing circuit

These three elements form a voltage generating system. The **lead L** consists of a lead wire and a **resistance** to **damp oscillation** or to **limit short-circuit currents** if of the **test object fails**. The measuring system starts at the terminals of the test object and consists of a connecting lead CL to the voltage divider D. The output of the divider is fed to the measuring instrument (CRO etc.) M. The appropriate **ground return should assure low voltage drops** for even highly transient phenomena and keep the ground potential of zero as far as possible.

- The test object is a predominantly capacitive and forms an oscillatory circuit with the inductance of the load.
- These oscillations are likely to be excited by any steep voltage rise from the generator output, but detected by the voltage divider and resistor in series with CL damps out these oscillations. The voltage divider - connected outside the generator circuit towards the load circuit (Test object) for accurate measurement. In case it is connected within the generator circuit, and the test object discharges (chopped wave) the whole generator including voltage divider will be discharged by this short circuit at the test object and thus the voltage divider is loaded by the voltage drop across the lead L. As a result, the voltage measurement will be wrong.
- The voltage divider should be located away from the generator circuit. The dividers cannot be shielded against external fields. All objects in the vicinity of the divider which may acquire transient potentials during a test will disturb the field distribution and thus the divider performance. Therefore, the connecting lead CL is an integral part of the potential divider circuit.
- In order to avoid electromagnetic interference between the measuring instrument M and C the high voltage test area, the length of the delay cable should be adequately chosen. Very short length of the cable can be used only if the measuring instrument has high level of electromagnetic compatibility (EMC). For any type of voltage to be measured, the cable should be co-axial type. The outer conductor provides a shield against the electrostatic field and thus prevents the penetration of this field to the inner conductor. Even though, the transient magnetic fields will penetrate into the cable, no appreciable voltage is induced due to the symmetrical arrangement. Ordinary coaxial cables with braided shields may well be used for d.c. and a.c. voltages. However, for impulse voltage measurement double shielded cables with predominently two insulated braided shields will be used for better accuracy.

- During disruption of test object, very heavy transient current flow and hence the potential of the ground may rise to dangerously high values if proper earthing is not provided.
- For this, large metal sheets of highly conducting material such as copper or Aluminum are used. Most of the modern high voltage laboratories provide such ground return along with a **Faraday Cage** for a complete shielding of the laboratory. Expanded metal sheets give similar performance. At least metal tapes of large width should be used to reduce the impedance.

Voltage Divider

- Voltages dividers for a.c., d.c. or impulse voltages may of resistors or capacitors or a convenient 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 would form oscillatory circuit with the inherent capacitance of the test object and this may lead to inaccuracy in measurement.
- The height of a voltage divider depends upon the flash over voltage and. Now, the potential distribution may not be uniform and hence the height also depends upon the design of the high voltage electrode, the top electrode. For voltages in the megavolt range, the height of the divider becomes large. As a thumb rule following clearances between top electrode and ground may be assumed.

2.5 to 3 metres/MV for DC voltages.

2 to 2.5 m/MV for lightning impulse voltages.

More than 5 m/MV rms for AC voltages.

More than 4 m/MV for switching impulse voltage.

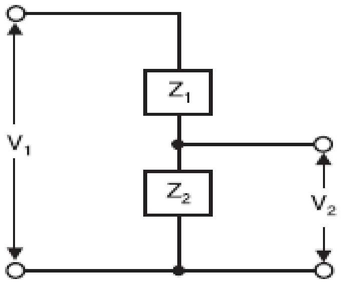


Fig. 4.18 Basic diagram of a potential divider circuit

The potential divider is most simply represented by two impedances Z1 and Z2 connected in series and the sample voltage required for measurement is taken from across Z2, Fig. 4.18.

If the voltage to be measured is V1 and sampled voltage V2,then

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

If the impedances are pure resistances $$V_2 = \frac{R_2}{R_1 + R_2} V_1$$

and in case pure capacitances are used $$V_2 = \frac{C_1}{C_1 + C_2} V_1$$

- The voltage V_2 is only a few hundred volts so the value of Z_2 is so chosen that V_2 across it gives sufficient deflection on a CRO.
- Maximum voltage across the impedance Z_1 and since the voltage to be measured is in megavolt the length of Z_1 is large which result in inaccurate measurements because of the stray capacitances associated with long length voltage dividers (especially with impulse voltage measurements) unless special precautions are taken.
- On the low voltage side of the potential dividers where a screened cable of finite length has to be employed for connection to the oscillograph other errors and distortion of wave shape can also occur.

Resistance Potential Dividers

- It is appear because of their simplicity of construction, less space requirements, less weight and easy portability. These can be placed near the test object **which might not always be confined to one location**.
- The length of the divider depends the factors - The **maximum voltage** to be measured and if **height is a limitation**, the length **can be** based on a surface flash over gradient in the order of 3–4 kV/cm irrespective of whether the resistance **R1 is of liquid or wire wound construction**. The length also depends upon the resistance value but this is implicitly bound up with the **stray capacitance** of the resistance column, the product of the two (RC) giving a time constant the value of which must not exceed the duration of the wave front it is required to record.
- It is to be noted with caution that **the resistance** of the potential divider should be **matched** to the **equivalent resistance** of a given **generator** to obtain a given wave shape.

Fig. 4.19 (a) shows a common form of resistance potential divider used for testing purposes where the wave front time of the wave is less than 1 micro sec.

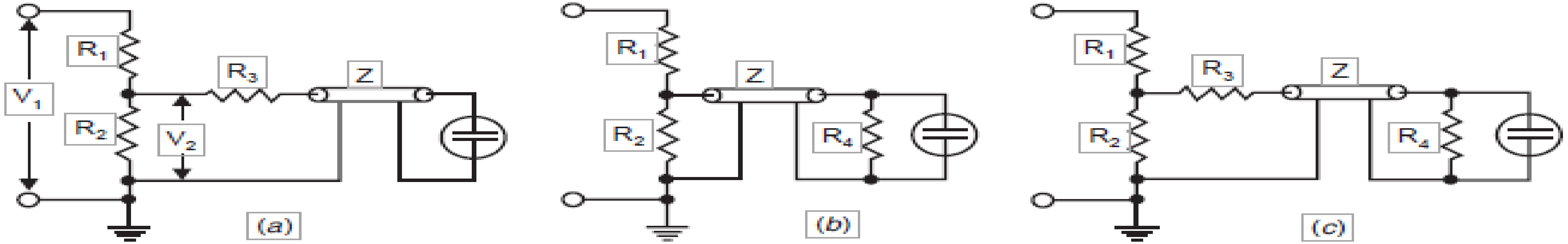


Fig. 4.19 Various forms of resistance potential dividers recording circuits (*a*) Matching at divider end (*b*) Matching at Oscillograph end (*c*) Matching at both ends of delay cable

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 $Z = R_3 + R_2$. From Fig. 4.19 (a), the voltage appearing across R_2 is

$$V_2 = \frac{Z_1}{Z_1 + R_1} V_1$$

where Z1 is the equivalent impedance of R2 in parallel with (Z + R3), the surge impedance of the cable being represented by an impedance Z to ground.

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, the voltage entering the delay cable is

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

As this voltage wave reaches the CRO end of the delay cable, it suffers reflections as the impedance offered by the CRO is infinite and as a result the voltage wave transmitted into the CRO is doubled. The CRO, therefore, records a voltage

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

The reflected wave, however, as it reaches the low voltage arm of the potential divider does not suffer any reflection as Z = R2 + R3 and is totally absorbed by (R2 + R3).

Since R2 is smaller than Z and Z1 is a parallel combination of R2 and (R3 + Z), Z1 is going to be smaller than R2 and since R1 > > R2, R1 will be much greater than Z1 and, therefore to a first approximation Z1 + R1 ≈ R1.

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

Fig. 4.19 (b) and (c) are the variants of the potential divider circuit of Fig. 4.19 (a). The cable matching is done by a pure ohmic resistance R4 = Z at the end of the delay cable and, therefore, the voltage reflection coefficient is zero i.e. the voltage at the end of the cable is transmitted completely into R4 and hence appears across the CRO plates without being reflected. As the input impedance of the delay cable is R4 = Z, this resistance is a parallel to R2 and forms an integral part of the divider's low voltage arm. The voltage of such a divider is, therefore, calculated as follows:

Equivalent impedance

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

Therefore, Current $\quad I = \dfrac{V_1(R_2 + Z)}{R_1(R_2 + Z) + R_2 Z}$

and voltage $\quad V_2 = \dfrac{IR_2 Z}{R_2 + Z} = \dfrac{V_1(R_2 + Z)}{R_1(R_2 + Z) + R_2 Z} \dfrac{R_2 Z}{R_2 + Z}$

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

or voltage ratio $\quad \dfrac{V_2}{V_1} = \dfrac{R_2 Z}{R_1(R_2 + Z) + R_2 Z}$

Due to the matching at the CRO end of the delay cable, the voltage does not suffer any reflection at that end and the voltage recorded by the CRO is given as

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

Normally for undistorted wave shape through the cable

$$Z \approx R_2$$

Therefore,

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

For a given applied voltage V1 this arrangement will produce a smaller deflection on the CRO plates as compared to the one in Fig. 4.19 (a).

The arrangement of Fig. 4.19 (c) provides for matching at both ends of the delay cable and is to be recommended where it is felt necessary to reduce to the minimum irregularities produced in the delay cable circuit. Since matching is provided at the CRO end of the delay cable, therefore, there is no reflection of the voltage at that end and the voltage recorded will be half of that recorded in the arrangement of Fig. 4.19 (a) viz.

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

It is desirable to enclose the low voltage resistance (s) of the potential dividers in a metal screening box. Steel sheet is a suitable material for this box which could be provided with a detachable close fitting lid for easy access. If there are two low voltage resistors at the divider position as in Fig. 4.19 (a) and (c), they should be contained in the screening box, as close together as possible, with a removable metallic partition between them. The partition serves two purposes (i) it acts as an electrostatic shield between the two resistors (ii) it facilitates the changing of the resistors. The lengths of the leads should be short so that practically no inductance is contributed by these leads. The screening box should be fitted with a large earthing terminal. Fig. 4.20 shows a sketched cross-section of possible layout for the low voltage arm of voltage divider.

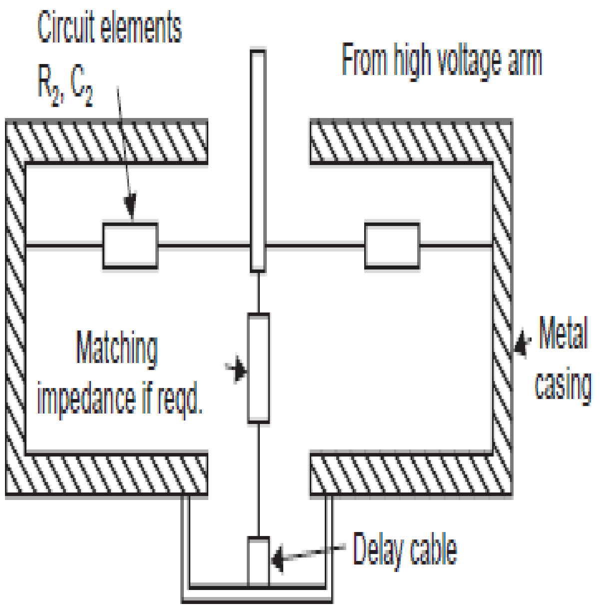


Fig. 4.20 Cross-section of low voltage arm of a voltage divider

Klydonograph or Surge Recorder

- Since lightning surges are **infrequent and random** in nature, it is necessary to install a large number of recording devices to obtain a reasonable amount of surge data produced on transmission lines and other equipment.
- Simple devices - **Klydonograph** is one such device which makes use of the patterns known as **Litchenberg figures** which are produced on a photographic film by surface corona discharges.
- The Klydonograph (Fig. 4.24) consists of a rounded electrode resting upon the emulsion side of a photographic film or plate which is kept on the smooth surface of an insulating material plate backed by a plate electrode. The minimum critical voltage to produce a figure is about 2 kV and the maximum voltage that can be recorded is about 20 kV, as at higher voltages spark overs occurs which spoils the film. The device can be used with a potential divider to measure higher voltages and with a resistance shunt to measure impulse current.
- There are characteristic differences between the figures for positive and negative voltages. However, for either polarity, the radius of the figure is a function only of the applied voltage. The oscillatory voltages produce superimposed effects for each part of the wave. Thus it is possible to know whether the wave is unidirectional or oscillatory. Since the size of the figure for positive polarity is larger, it is preferable to use positive polarity figures. This is particularly desirable in case of measurement of surges on transmission lines or other such equipment which are ordinarily operating on a.c. voltage and the alternating voltage gives a black band along the centre of the film caused by superposition of positive and negative figures produced on each half cycle

- For each surge voltage it is possible to obtain both positive and negative polarity figures by connecting pairs of electrodes in parallel, one pair with a high voltage point and an earthed plate and the other pair with a high voltage plate and an earthed point.
- Klydonograph being a simple and inexpensive device, a large number of elements can be used for measurement. Used in the past quite extensively for providing statistical data on magnitude, polarity and frequency of voltage surges on transmission lines.
- Accuracy of measurement is only of the order of 25 per cent.

Application :-

To record the Lighting impulse on Transmission Line.

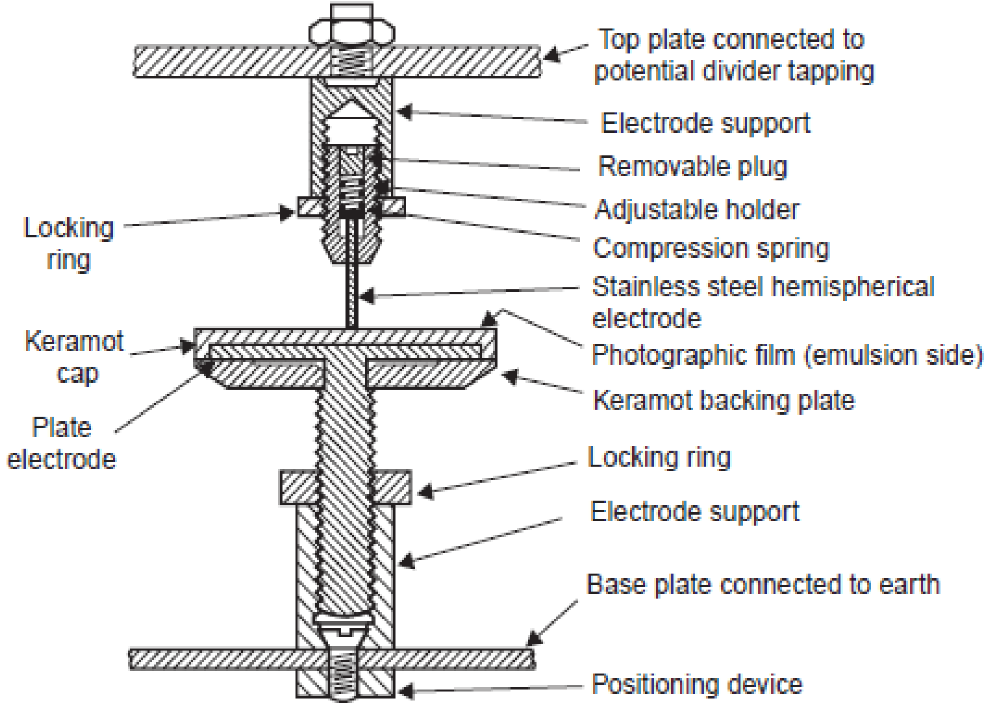


Fig. 4.24 Klydonograph

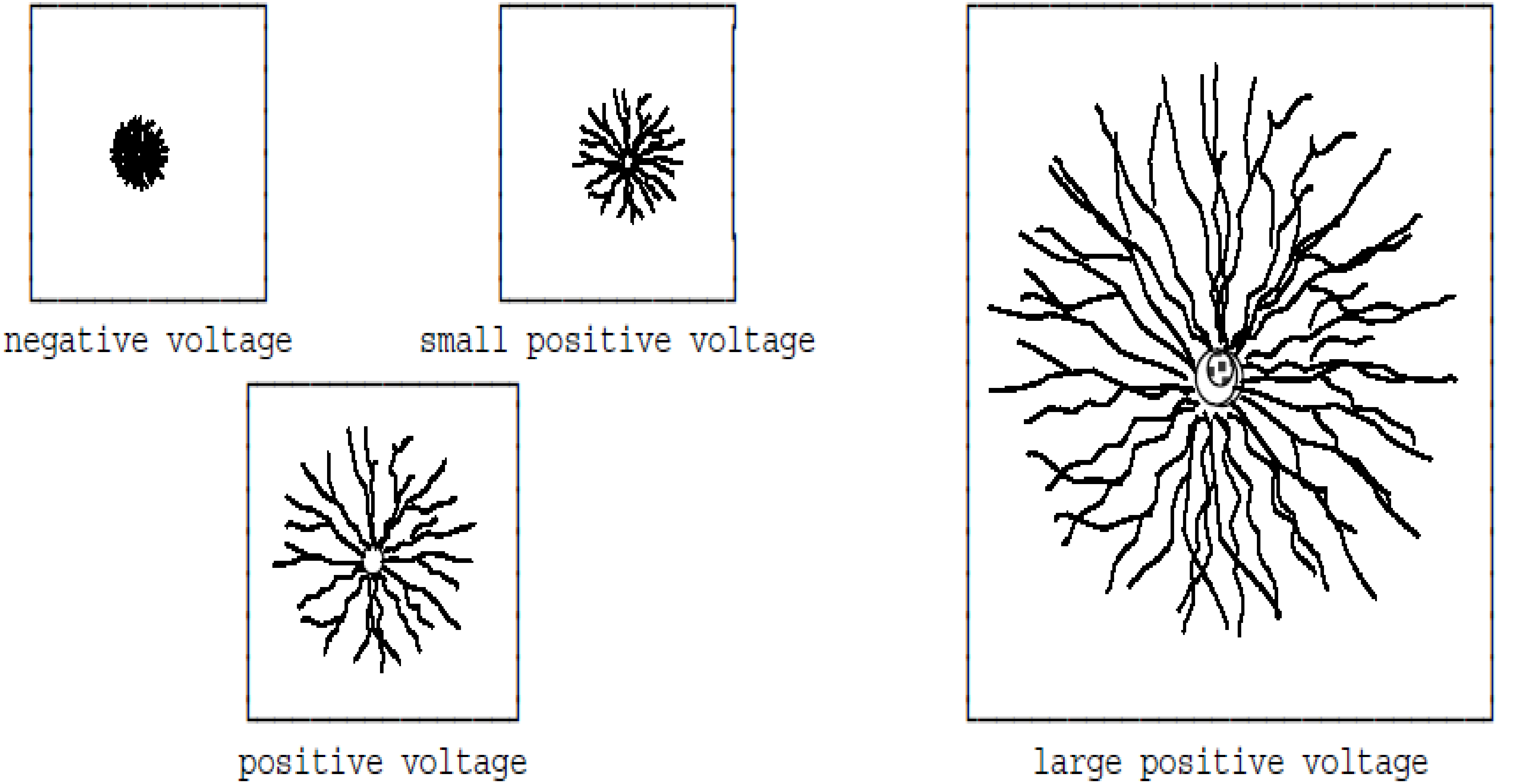


Figure 6.28 - Litchenberg patterns

MEASUREMENT OF HIGH D.C., AND IMPULSE CURRENTS

- In power systems, it is often necessary to measure **high currents**, arising **due to short circuits**.
- For conducting **temperature rise** and **heat run tests** on power equipment like conductors, cables, circuit breakers, etc., measurement of high currents is required.
- During lighting discharges and switching transients also, large magnitudes of impulse and switching surge currents occur, which require **special measuring techniques** at high potential levels.

- High currents are used in power system for testing circuit breakers, cables lightning arresters etc. and high currents are encountered during lightning discharges, switching transients and shunt faults. These currents require special techniques for their measurements.
- Low resistance shunts are used for measurement of these currents. The voltage drop across the shunt resistance is measured with the help of a millivolt meter. The value of the resistance varies usually between 10 micro ohm and 13 milliohm. This depends upon the heating effect and the loading permitted in the circuit. The voltage drop is limited to a few millivolts usually less than 1 V. These resistances are oil immersed and are made as three or four terminal resistances to provide separate terminals for voltage measurement for better accuracy.

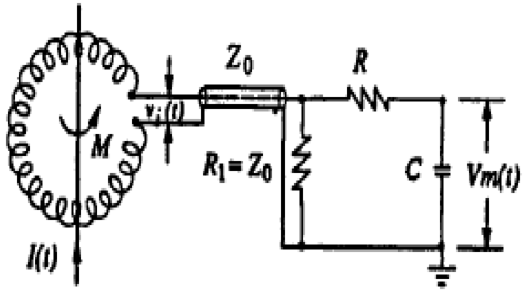
Measurement of High Impulse Currents Using Magnetic Potentiometers (Rogowski Coils) and Magnetic Links

- The **Rogowski** coil an electrical device that is used to measure AC current, the high-speed transient, pulsed current or sinusoidal current. The name **Rogowski** coil was named after the German physicist Walter Rogowski.

If a coil is placed surrounding a current carrying conductor, the voltage signal induced in the coil is

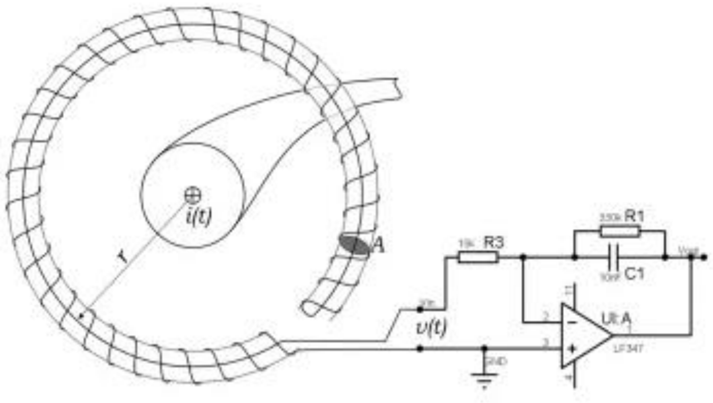
V(t) = **M dI(t)/dt** **[Mutual Induction or Transformer Action]**

where *M* is the mutual inductance between the conductor and the coil, and I(t) is the current flowing in the conductor. Usually, the coil is wound on a nonmagnetic former of toroidal shape and is coaxially placed surrounding the current carrying conductor. The number of turns on the coil is chosen to be large, to get enough signal induced. The coil is wound cross-wise to reduce the leakage inductance. Usually an integrating circuit (see Fig. 7.52) is employed to get the output signal voltage proportional to the current to be measured. The output voltage is given by – [**V_{out} proportional to current measured by the coil.] & M/CR = Scale factor of integrator.**



$V_i(t)$ — Induced voltage in the coil $= M\frac{d[I(t)]}{dt}$
Z_0 — Coaxial cable of surge impedance Z_0
R-C — Integrating network

Fig. 7.52 Rogowski coil for high impulse current measurements



$$V_m(t) = \frac{1}{CR}\int_0^t v_i(t) = \frac{M}{CR} I(t)$$

Rogowski coils with electronic or active integrator circuits have large bandwidths (about 100 MHz). At frequencies greater than **100 MHz** the response is affected by the skin effect, the capacitance distributed per unit length along the coil, and due to the electromagnetic interferences. However, miniature probes having nanosecond response time are made using very few turns of copper strips for UHF measurements.

Advantages of Rogowski Coil

The advantages of **Rogowski** coils include:

- It can **respond to fast-changing currents**.
- The second terminal of the coil is returning to the first terminal. And it makes an open circuit coil. So, there is **no danger of opening of the secondary coil**.
- The air is used as a medium. There is **no magnetic core** is used. So, there is no question of saturation of the core. In this coil, temperature compensation is simple.

In order to keep output current constant, the AC current transformer (CT) needs to increase the number of secondary turns for large currents. Hence, for equal rating, the size of the Rogowski coil is small compared to a conventional current transformer.

It is available in two types; flexible as well as rigid.

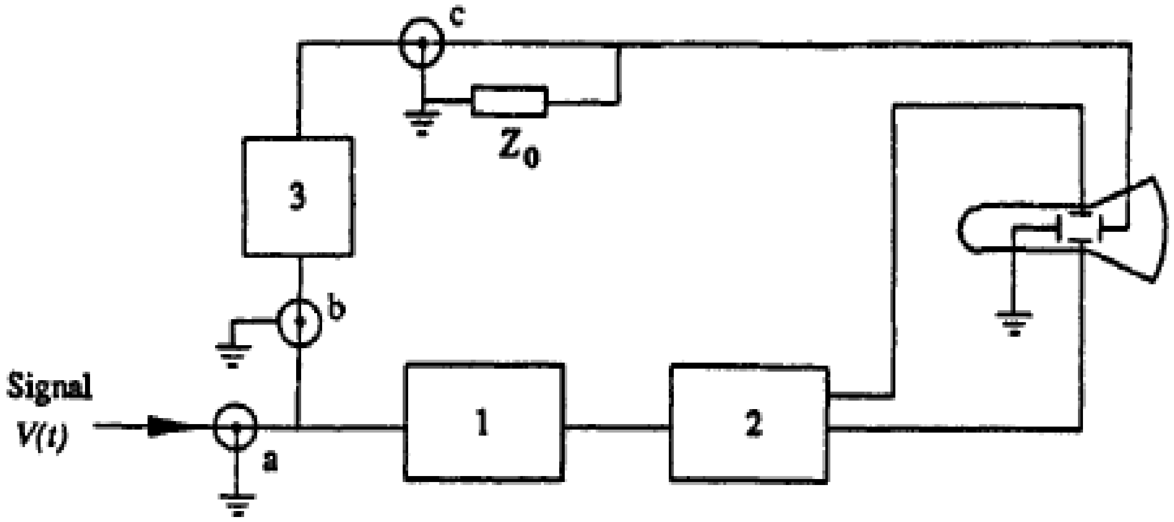
Magnetic Links

- Magnetic links are **short high retentivity steel strips** arranged on a circular wheel or drum. These strips have the property that the remanent magnetism for a current pulse of 0.5/5 μs is same as that caused by a d.c. current of the same value.
- Hence, these can be used for measurement of peak value of impulse currents. The strips will be kept at a known distance from the current carrying conductor and parallel to it The **remanent magnetism** is then measured in the laboratory from which the peak value of the current can be estimated.
- These are useful for field measurements, mainly for estimating the **lightning currents on the transmission lines and towers**. By using a **number of links**, accurate measurement of the peak value, polarity, and the percentage oscillations in lightning currents can be made.

When waveforms of rapidly varying signals (voltages or currents) have to be measured or recorded, certain difficulties arise. The peak values of the signals in high voltage measurements are too large. may be several kilovolts or kiloamperes. There fore, direct measurement is not possible. The magnitudes of these signals are scaled down by voltage dividers or shunts to smaller voltage signals. The reduced signal *Vm(t)* is normally proportional to the measured quantity. The procedure of transmitting the signal and displaying or recording it is very important The associated electromagnetic fields with rapidly changing signals induce disturbing voltages, which have to be avoided.

Cathode Ray Osclllographs for Impulse Measurements :-

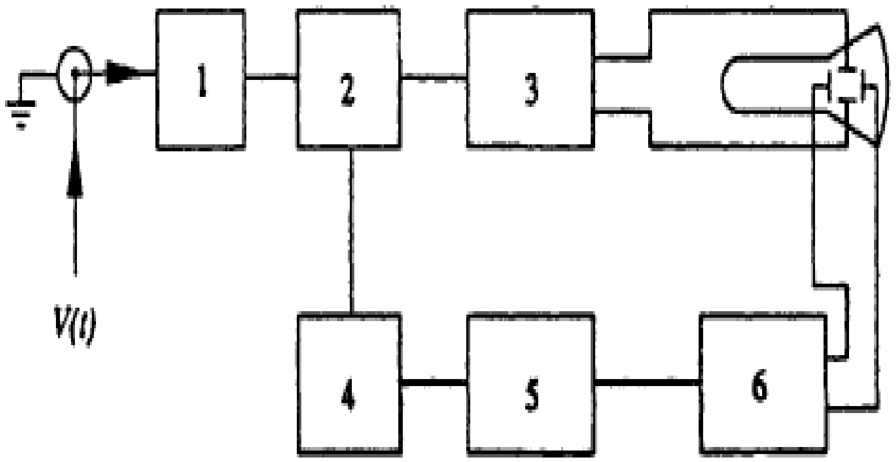
Modern oscillographs are sealed tube hot cathode oscilloscopes with photographic arrangement for recording the waveforms. The cathode ray oscilloscope for impulse work normally has input voltage range from *5* mV/cm to about 20 V/cm. In addition, there are probes and attenuators to handle signals up to 600 V (peak to peak). The bandwidth and rise time of the oscilloscope should be adequate. Rise times of *5* n s and bandwidth as high as 500 MHz may be necessary.



1. Trigger amplifier
2. Sweep generator
3. External delay line

(a) Vertical amplifier input
(b) Input to delay line
(c) Output of delay line to CRO *Y* plates

Fig. 7.54a Block diagram of a surge test oscilloscope (older arrangement)



1. Plug-in amplifier
2. *Y* amplifier
3. Internal delay line
4. Trigger amplifier
5. Sweep generator
6. *X* amplifier

Fig. 7.54b Simplified block diagram of surge test oscilloscopes (recent schemes)

Thank you

Introduction to High Voltage Testing

Standard Testing Procedures:

INTRODUCTION – Why Testing is needed?

- Electrical insulating materials used in various forms to provide insulation for the apparatus.
- Materials may be solid, liquid, gas, or even a combination of these such as paper impregnated with oil.
- Good insulating properties over a wide range of operating parameters, Temperature range (0°C to l 10°C) and frequency range (d.c. to several MHz in the radio and high frequency ranges).
- Since it is difficult to test the quality of an **insulating material** after it forms **part of an equipment**, suitable tests must be done to ensure their quality in the said ranges of operation. Also, these tests are devised to ensure that the material is not destroyed as in the case of high voltage testing.
- These tests confirms the **electrical properties**, such as the **resistivity (d.c.)**, the **dielectric constant**, and **loss factor** over a wide frequency range. In the high voltage apparatus, the quality of insulation is assessed by measuring the loss factor at high voltages and also by conducting **partial discharge** tests to detect any deterioration or faults in the internal insulation of the apparatus.

- These tests may be conducted at a desired temperature or over a temperature range by keeping the test specimen in controlled temperature ovens. A knowledge of the variation of electrical properties over the operating range can be obtained from these tests and this will help the design engineer to take into account such variations in the design of electrical insulation for equipment.
- The production of electrical energy in big plants under the most economic condition makes it necessary that more and more energy be transported over longer and longer distances. Therefore, transmission at extra high voltages and the erection of systems which may extend over whole continents has become the most urgent problems to be solved in the near future.
- The very fast development of systems is followed by studies of equipment and the service conditions they have to fulfill. These conditions will also determine the values for testing at alternating, impulse and d.c. voltages under specific conditions.
- As we go for higher and higher operating voltages (say above 1000 kV) certain problems are associated with the testing techniques. Some of these are:
  - Dimension of high voltage test laboratories.
  - Characteristics of equipment for such laboratories.
  - Some special aspects of the test techniques at extra high voltages.

- In alternating voltage system, a careful choice of the characteristics of the testing transformer is essential.
- It is known that the flash over voltage of the insulator in air or in any insulating fluid depends upon the capacitance of the supply system. This is due to the fact that a voltage drop may not maintain preliminary discharges or breakdown. It is, therefore, suggested that a capacitance of at least 1000 pF must be connected across the insulator to obtain the correct flash over or puncture voltage and also under breakdown condition (a virtual short circuit) the supply system should be able to supply at least 1 amp for clean and 5 amp for polluted insulators at the test voltage.
- There are some difficult problems with impulse testing equipment also especially when testing large power transformers or large reactors or large cables operating at very high voltages. The equivalent capacitance of the impulse generator is usually about 40 nano farads independent of the operating voltage which gives a stored energy of about 1/2 × 40 10–9 × 36 × 109 = 720 KJ for 6 MV generators which is required for testing equipments operating at 150 kV. It is not at all difficult to pile up a large number of capacitances to charge them in parallel and then discharge in series to obtain a desired impulse wave. But the difficulty exists in reducing the internal reactance of the circuit so that **a short wave front with minimum oscillation** can be obtained. For example for a 4 MV circuit the inductance of the circuit is about 140 μH and it is impossible to test an equipment with a capacitance of 5000 pF with a front time of 1.2 μ sec. and less than 5% overshoot on the wave front. Cascaded rectifiers are used for high voltage d.c. testing. A careful consideration is necessary when test on polluted insulation is to be performed which requires currents of 50 to 200 mA but ex-tremely predischarge streamer of 0.5 to 1 amp during milliseconds occur. The generator must have an internal reactance in order to maintain the test voltage without too high a voltage drop.

Test :-

- The over voltages are of three types:-
  - Power frequency Over Voltage
  - Impulse voltage surge due to lighting
  - Switching

Power frequency over voltage – Ferranti effect & Regulation

- Above 132kV , Over voltage caused by switching , Transient and Travelling waves plays major role.
- Impulse due to switching and lighting.

Routine Test and Type Test :-

- High voltage test confirms the characterstics of insulators used in HV system.
- As per the standard recommendations certain types routine and type test will be performed on the specimen.
- The recommended HV test specially confirms:-
    - Insulator charcterstics
    - Standardise the insulation level
    - Information on Basic Impulse Level(BIL)
    - Verification of the name plate rating.

- Factory /Manufacturer conduct both Type and Routine test on the object as per standard.
- **Type test** –Destructive test/Puncture test, Perform in one Samaple product for the technical clarity
- **Routine Test**-Nondestructive Test will perform to all sample.

For the Circuit breaker –

- **Type test** – Impulse voltage Dry with stand test / One minute power frequency voltage dry with stand test / One minute power frequency voltage wet with stand test
- **Routine test** - One minute power frequency voltage dry with stand test /Megger(Insulation resistance test

General Tests Carried Out on High Voltage Equipment:

[Sustained low-frequency Tests, High Voltage Direct Current Tests, High Frequency Tests, Surge or Impulse Tests, Flashover Tests]

- Power demand is rising rapidly. So, huge quantity of power to transmit.
- Bulk power transmission can be most efficiently done through high voltage, Hence, **high voltage system** becomes most essential. So, equipment should be capable of withstanding this high voltage stress.
- In addition to that normal high voltage, HV equipment capable of withstanding different over voltages during its operational life span. These different over voltages may occur during various abnormal conditions.
- To ensure abnormal over voltages, the equipment must go through different high voltage testing procedures.
- Some of these tests ensures- permittivity, dielectric losses per unit volume and dielectric strength of an Insulators. Some are carried out on the complete equipments. These tests are far measuring and ensuring, capacitance, dielectric losses, break down voltage, and flash over voltage etc. of the equipment as a whole.

High Voltage Testing Procedure

- Electrical equipment must be capable of withstanding overvoltages during operation.
- Thus by suitable testing procedure we must ensure that this is done. High voltage testing can be broadly classified into testing of insulating materials (samples of dielectrics) and tests on completed equipment.
- The tests carried out on samples of dielectric consist generally of the measurement of permittivity, dielectric loss per unit volume, and the dielectric strength of the material.
- The first two can be measured using the High Voltage Schering Bridge. The tests carried out on completed equipment are the measurement of capacitance, the power factor or the total dielectric loss, the ultimate breakdown voltage and the flash-over voltage.
- The breakdown voltage tests on completed equipment is only done on a few samples since it permanently damages and destroys the equipment from further use.
- However since all equipment have to stand up to a certain voltage without damage under operating conditions, all equipment are subjected to withstand tests on which the voltage applied is about twice the normal voltage, but which is less than the breakdown voltage.

Types of High Voltage Test

There are mainly four **types of high voltage testing methods** applied on high voltage equipment and these are

- Sustained low frequency tests.
- Constant DC test.
- High frequency test.
- Surge or impulse test.

Sustained Low Frequency Test

- Sustained low frequency tests are done at power frequency (50 Hz), and are the commonest of all tests.
- These tests are made upon specimens of insulation materials for the determination of dielectric strength and dielectric loss, for routine testing of supply mains, and for work tests on high voltage transformers, porcelain insulators and other apparatus. Since the dielectric loss is sensitive to electric stress, the tests are carried out at the highest ultimate stress possible.
- For testing of porcelain insulators and in high tension cables, voltages as high as 2000 kV may be used. High voltage a.c. tests at 50 Hz are carried out as Routine tests on low voltage (230 or 400 V) equipment.
- Each one of these devices are subjected to a high voltage of 1 kV + 2 × (working voltage). A 230 V piece of equipment may thus be subjected to about 1.5 to 2 kV.
- These tests are generally carried out after manufacture before installation. The HV is applied across the device under test by means of a transformer. The transformer need not have a high power rating.
- If a very high voltage is required, the transformer is usually build up in stages by cascading. By means of cascading, the size of the transformer and the insulation bushing necessary may be reduced in size.
- The transformers are usually designed to have poor regulation so that if the device under test is faulty and breakdown occurs, the terminal voltage would drop due to the high current caused. A resistance of about 1 ohm/volt is used in series with the transformer so as to limit the current in the event of a breakdown to about 1 A. In all high voltage tests, safety precautions are taken so as to ensure that there is no access to the testing area when the high voltage is on. There would be switches that would automatically be operated when the door to the area is opened etc..

Procedure:-

- ✓ The testing procedure is very simple.
- ✓ High voltage is applied across a specimen of insulation or equipment under test by means of a high voltage transformer. A resistor in series with the transformer to limit the short circuit current in the event of breakdown occurred in the device under test. The resistor is rated with as many ohms as the high voltage applied across the device under test.
- ✓ For example if we apply 200 KV during the test, the resistor must have 200 KΩ, so that during ultimate short circuit condition, the faulty current must be limited to 1 A. For this test the power frequency high voltage is applied to the specimen or equipment under test for a long specific period to ensure the continuous high voltage withstanding capability of the device.
- ✓ The transformer used for producing extra high voltage in this **type of high voltage testing** procedure, may not be of high power rating. Although although the output voltage is very high, but maximum current is limited to 1A in this transformer. Sometimes, cascaded transformers are used to get very high voltage, if required.

High Voltage DC Test

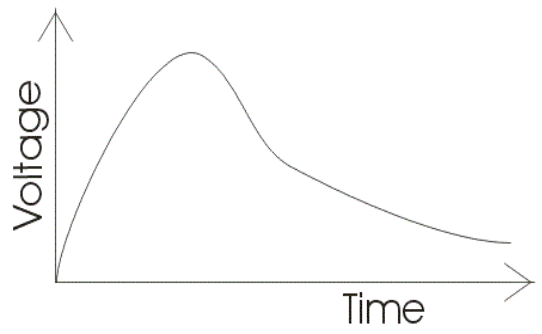
- ✓ High voltage DC test is normally applicable to those equipment which are used in high voltage DC transmission system. But this test is also applicable for high voltage AC equipment, when high voltage AC testing is not possible due to unavoidable condition.
- ✓ For example mainly at site, after installation of equipment, it is quite difficult to arrange for high voltage alternating power as high voltage transformer may not be available at site. Hence, high voltage test with alternating power is not possible at site after installation of equipment. At that situation high voltage DC test is most suitable.
- ✓ In high voltage direct current test of AC equipment, direct voltage about two times of the normal rated voltage is applied across the equipment under test for 15 minutes to 1.5 hours. Although high voltage DC test is not complete substitute of high voltage AC test but still it is applicable where HVAC test is not at all possible.

High Frequency Test

- The insulators used at high voltage transmission system, may be subjected to breakdown or flash-over during high frequency disturbances.
- The high frequency disturbances occur in the HV system due to **switching operations** or any other external causes. High frequency in power may cause failure of insulators even at comparatively low voltage due to high dielectric loss and heating.
- The insulation of all high voltage equipment must ensure the high frequency voltage withstanding capacity during its normal life span. Mainly sudden interruption of line current during switching and open circuit fault, gives rise to the frequency of voltage wave form in the system.
- Dielectric loss for every cycle of the power is nearly constant. So at high frequency the dielectric loss per second becomes much higher than that of normal power frequency. This fast and large dielectric loss causes excessive heating of the insulators. Excessive heating ultimately results to insulation failure may be by blasting of insulators. So to ensure this high frequency voltage withstanding capacity, high frequency test is carried out on high voltage equipment.

Surge Test or Impulse Test

- ✓ Heavy influence of surge or lighting on the **Transmission Line**.
- ✓ Breakdown transmission line insulator and may also attack, transformer connected at the end of the transmission lines.
- ✓ Surge test or impulse tests are very high or extra high voltage tests, carried out for investing the influences of surges or lightning on the transmission equipment.
- ✓ Normally direct lightening strokes on transmission line is very rare. But when a charged cloud comes closer to the transmission line, the line is oppositely charged due to the electrical charge inside the cloud. When this charged cloud is suddenly discharged due to lightning stroke nearby, the induced charge of the line no longer bound but travel through the line with velocity of light. So it is understood that even when the lightning do not strike the transmission conductor, directly, still there will be a transient over voltage disturbance.
- ✓ Due to lightning discharge on the line or nearby to the line, a step fronted voltage wave travel along the line. The wave form is shown below.



- ✓ During traveling of this wave, high voltage stress occurred on the insulator. Due to which violent rupture of insulators is often caused by such lightning impulse. So proper investigation of the insulator and insulating parts of high voltage equipment, should be done properly by high voltage testing.
- ✓ The lightning impulse is totally natural phenomenon so it does not have any predetermined shape and size of the steep-fronted voltage. So, for performing this **high voltage testing**, a standard voltage wave is applied. This standard voltage may not have any similarity in height and shape with the actual impulse voltage due to lightning or surges.
- ✓ In Britain in BSS 923 : 1940, the standard testing wave is expressed as 1/50 νsec which means, the voltage rises to its peak within 1 micro second and fall to 50% of its peak value within 50 micro second. As per Indian standard, the impulse voltage is expressed as 12/50 νsec. That indicates, the voltage rises to its peak at 12 micro seconds and falls back to 50% of its peak at 50 micro second.

Flash-over Tests

- ✓ Porcelain insulators are designed so that spark over occurs at a lower voltage than puncture, thus safe guarding the insulator, in service against destruction in the case of line disturbances.
- ✓ **Flash-over** tests are very importance in this case .
- ✓ The flash-over is due to a breakdown of air at the insulator surface, and is independent of the material of the insulator. As the flash-over under wet conditions and dry conditions differ , tests such as the one minute dry flash-over test and the one minute wet flash-over test are performance.
- ✓ (i) 50 percent dry impulse flash-over test, using an impulse generator delivering a positive 1/50 s impulse wave. The voltage shall be increased to the 50 percent impulse flash-over voltage (the voltage at which approximately half of the impulses applied cause flash-over of the insulator)
- ✓ (ii) Dry flash-over and dry one-minute test - In this the test voltage (given in the B.S.S.) is applied . The voltage is raised to this value in approximately 10 seconds and shall be maintained for one minute. The voltage shall then be increased gradually until flash- over occurs .
- ✓ (iii) Wet flash-over and one minute rain test In this the insulator is sprayed throughout the test with artificial rain drawn from source of supply at a temperature within 10 degrees of centigrade of the ambient temperature in the neighborhood of the insulator. The resistivity of the water is to be between 9,000 and 11,000 ohm cm. In the case of the testing of insulating materials , it is not the voltage which produces spark-over breakdown which is important , but rather the voltage for puncture of a given thickness (ie. dielectric strength) .

- ✓ The measurements made on insulating materials are usually , therefore , those of dielectric strength and of dielectric loss and power factor , the latter been intimately connected with the dielectric strength of the material.
- ✓ It is found that the dielectric strength of a given material depends ,apart from chemical and physical properties of the material itself, upon many factors including,

(a) thickness of the sample tested

(b) shape of the sample

(c) previous electrical and thermal treatment of the sample

(d) shape , size , material and arrangement of the electrodes

(e) nature of the contact which the electrodes make with the sample

(f) waveform and frequency of the applied voltage (if alternating)

(g) rate of application of the testing voltage and the time during which it is maintained at a constant value.

(h) temperature and humidity when the test is carried out (i) moisture content of the sample.

Testing of Cables, Line Insulators, Bushings, Isolators, Circuit Breakers and Surge Arrestors

Tests on Insulators

The tests on insulators can be divided into three groups. These are the **type tests**, **sample tests** and the **routing tests.**

Type tests

These tests are done to determine whether the particular design is suitable for the purpose.

(a) Withstand Test: The insulator should be mounted so as to simulate practical conditions. A 1/50 s wave of the specified voltage (corrected for humidity, air density etc.,) is applied. Flashover or puncture should not occur. [If puncture occurs, the insulator is permanently damaged]. The test is repeated five times for each polarity.

(b) Flash-over test: A 1/50 s wave is applied. The voltage is gradually increased to the 50% impulse flashover voltage. The test is done for both polarities. There should be no puncture of insulation during these tests.

(c) Dry One-minute test: The insulator, clean and dry, shall be mounted as specified and the prescribed voltage (corrected for ambient conditions) should be gradually brought up (at power frequency) and maintained for one minute. There shall not be puncture or flash-over during the test. Dry flash-over test: The voltage shall then be increased gradually until flash-over occurs. This is repeated ten times. There shall be no damage to the insulator.

d) **One-minute Rain test:** The insulator is sprayed throughout the test with artificial rain drawn from a source of supply at a temperature within **10^o C** of the ambient temperature of the neighborhood of the insulator. The rain is sprayed at an angle of **45^o** on the insulator at the prescribed rate of **3 mm/minute**. The resistivity of the water should be 100 ohm-m ± 10%. The prescribed voltage is maintained for one minute. Wet flash-over test: The voltage shall then be increased gradually until flash-over occurs. This is repeated ten times. There shall be no damage to the insulator.

e) **Visible discharge test:** This states that after the room has been darkened and the specified test voltage applied, after five minutes, there should be no visible signs of corona.

Sample Tests

The sample is tested fully, up to and including the point of breakdown. This is done only on a few samples of the insulator.

(a) **Temperature cycle test:** The complete test shall consist of five transfers (hot-cold-hot-....), each transfer not exceeding 30 s.

(b) **Mechanical loading test:** The insulator shall be mechanically loaded up to the point of failure. When failure occurs, the load should not be less than 2000 lbf. [**45KN, 30KN, 60KN, 90KN**……]

(c) **Electro-mechanical test:** The insulator is simultaneously subjected to electrical and mechanical stress. (i.e. it shall be subjected to a power frequency voltage and a tensile force simultaneously. The voltage shall be 75% of dry flash-over voltage of the unit. There should be no damage caused.

(d) **Overvoltage test:** The insulator shall be completely immersed in an insulating medium (oil), to prevent external flashover occurring. The specified overvoltage must be reached without puncture. The voltage is then gradually increased until puncture occurs.

(e) Porosity test: Freshly broken pieces of porcelain shall show no dye penetration after having been immersed for 24 hours in an **alcoholic mixture** of fushing at a pressure of 2000 p.s.i.

Routine Tests

These are to be applied to all insulators and shall be commenced at a low voltage and shall be increased rapidly until flash-over occurs every few seconds. The voltage shall be maintained at this value for a minimum of five minutes, or if failures occur, for five minutes after the last punctured piece has been removed. At the conclusion of the test the voltage shall be reduced to about one-third of the test voltage before switching off.

At the field level Insulation resistance test only perform.

Mechanical Routine Test:

A mechanical load of 20% in excess of the maximum working load of the insulator is applied after suspending the insulator for one minute. There should be no mechanical failure of the insulator.

Tests on Transformers

The following sequence of tests is generally adopted for transformers.

System Voltage	I.E.C. Impulse Withstand Voltage
11 kV	75 kV
33 kV	170kV
66 kV	325 kV
132 kV	550 kV
275 kV	1050 kV

Apply **full wave impulse at 75% I.E.C**. withstand value. Since the transformer should be able to withstand the I.E.C. voltage, there should be no damage to the transformer. The values of R and C in the impulse generator are adjusted after deriving to get the required waveform.

Apply full wave at 100% I.E.C. withstand value and observe whether there is any breakdown. The waveform observed should be identical to applied waveform (other than for amplitude) : then the device has passed the test.

Chopped wave test at 115% full wave amplitude : For this kind of test , the impulse generator would have to be fitted with a rod gap or controlled trigatron type gap. Since there is no voltage across insulator after chopping takes place, from the waveform it is not possible to say whether any damage has taken place. Therefore apply full wave test **again and compare the wave and at 100% of I.E.C. voltage** and see whether there is any distortion in the waveform indicating damage.(same as test 2)

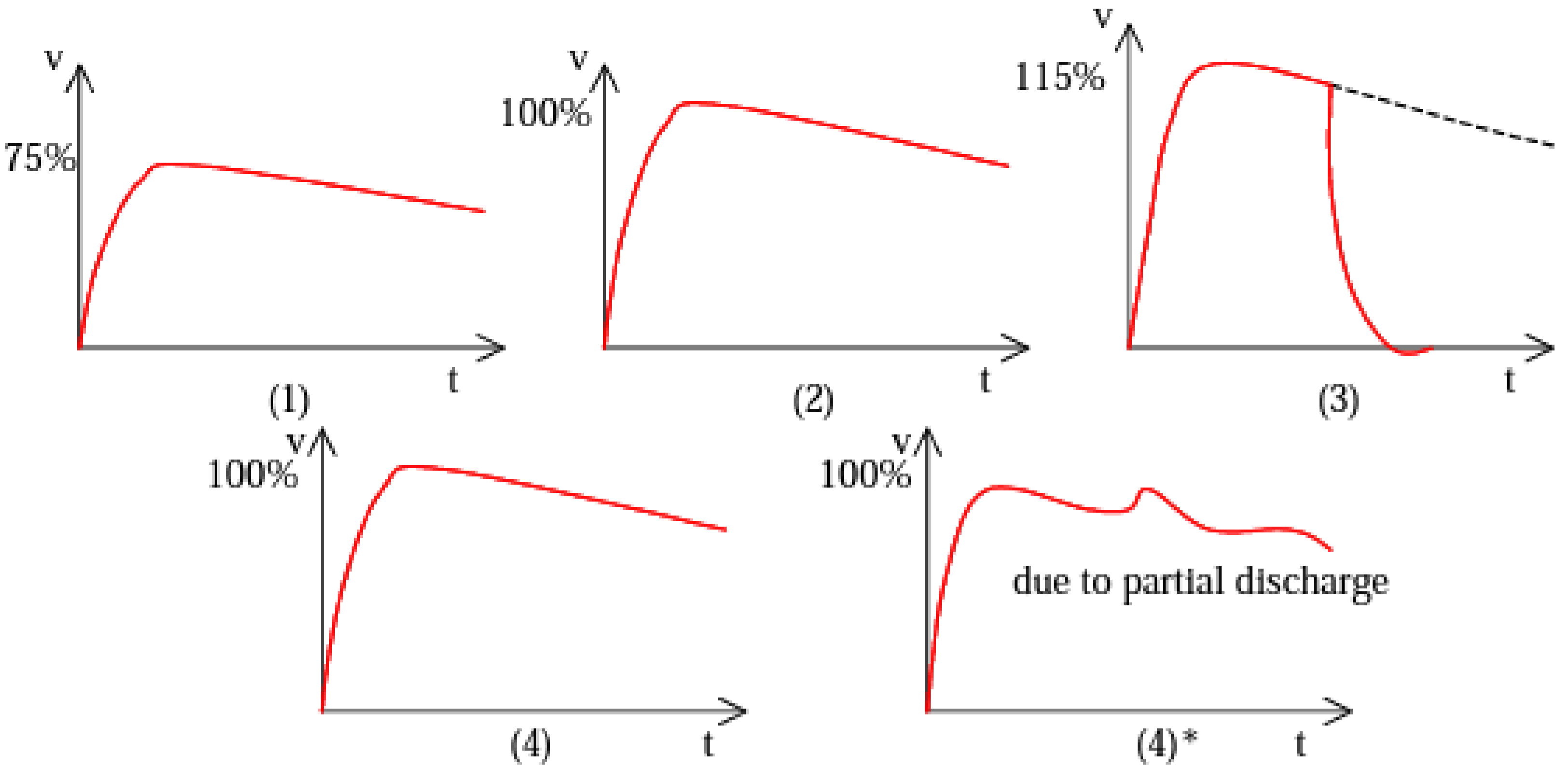
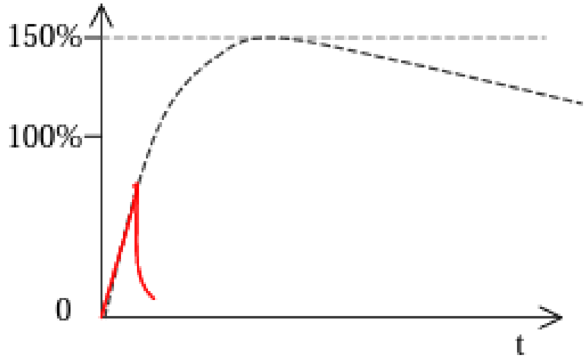


Figure . - Test waveforms



- chopped waveform at 150% voltage

Since the chopped wave test exerts considerable stress on the winding, there is some controversy on the requirement of this test. Thus the chopped wave requirement is not universal. In the American industry, the chopped wave is conducted at 150% full wave and such that the chopping is done at less than the peak value. In this case the stress might in fact be very much more than in the British method.

Tests on Cables

For cables not in the supper voltage class the tests to be carried out are laid down in the appropriate British standard specifications.

Thus for **paper impregnated insulated cables** with lead or alloy sheaths, **BS 480 Part I: 1954**, the tests (purely electrical) are as follows;

(1) Acceptance Tests at Works

(a) Conductor resistance –Insulation resistance with Resistance tester(Megger)

(b) Voltage test: The applied voltage must be of approximately sinusoidal shape and of any frequency between 25 and 100 Hz. It must be increased gradually to the full value and maintain continuously for 15 minutes between conductors and between each conductors and sheath. The required values of the test voltages are tabulated in the specification and, as one illustration of the magnitude relative to the normal voltages, the figures for the 11 kV cables for earthed system are given in the table.

Voltage Designation	Belted Cables				Single-core, S.L. & Screened Cables	
	(i)		(ii)		(ii)	
	(1)	(2)	(1)	(2)	(1)	(2)
11 kV	24 kV	36 kV	14 kV	21 kV	15 kV	22 kV

where (i) Between conductors, (ii) Between any conductor and sheath

(1) Cable as manufactured, (2) After bending test

It will be seen that a voltage test is made before and after a bending test. In this the cable has to be bent around a cylinder of specified diameter to make one complete turn: it is then unwound and the process repeated in the opposite direction . The cycle of process has to be carried out three times.

(c) Dielectric power-factor / Voltage test (for 33 kV cables only) : Each core of every drum of completed cable is tested for dielectric power factor at room temperature at the following a.c. single phase 50 Hz voltages : 9.5 kV , 19 kV , 28.5 kV, 38.0 kV.

The measured power-factor at normal working voltage shall not the value declared by the manufacturer and shall in no case exceed 0.01 . The ionization - ie. the difference in power-factor between half the normal working voltage and the twice the normal working voltage - shall not exceed the value declared by the manufacture and shall no case exceed 0.0006 for 3-core screened cable or 0.001 for single core and screened S.L.type cable. The manufacturer can also be asked to produced evidence to show that the power factor at normal working voltage does not exceed 0.01 at series of temperature ranging from 15 C to 65 C.

(2) Sample test at works

These include bending test above and a dripping or drainage test for cables which have to be installed vertically.

(3) Test when installed

A voltage test similar to the above is carried out in the same manner but with some what reduced voltages. Thus the value of 24 kV, 14 kV and 11 kV for belted cable as manufactured and the value 15 kV for single core, S.L. and screened cables, become 20 kV, 11.5 kV and 12 kV respectively.

Tests on Pressurized Cables

Type approval tests, are stipulated for each design of cable and accessory. These tests are carried out on the maximum and the minimum conductor sizes for each design and voltage rating, and if successful, no further type tests are required, except in the case of changes in the design. The dielectric thermal resistance test included in the schedule is applied only to the minimum conductor sizes. The tests are as follows:

(a) **Loading cycle test**: A test loop, comprising the cable and each type of accessory to be subjected to 20 load cycles to a minimum conductor temperature 5^o C in excess of the design value, with the cable energised to 1.5 times the working voltage. The cable to be tested at a stipulated minimum internal pressure.

(b) **Thermal stability test** (132 kV cables only): After test (a), the cable to be enerzised to 1.5 times working voltage and the loading current adjusted to give a maximum temperature 5^o C in excess of the design value. The current to be maintained at this value for a period of 6 hours, with other test conditions unaltered, to prove that the cable is thermally stable. For 275 kV cables, 1.33 times the working voltage is proposed.

(c) **Impulse test:** A test loop, comprising cable and each type of accessory to be subjected to 10 positive and 10 negative impulses at test voltage. [Ex: Working voltage 132 kV, Impulse test voltage 640 kV, Peak working voltage ratio during impulse test 6.0]

(d) **Cold power-factor/voltage test**: The power factor of a 100 m length of cable to be measured at 0.5, 1.0, 1.5 and 2 times the working voltage with the cable at the stipulated **minimum internal pressure**. The values not to exceed the makers' guaranteed values.

(e) **Dielectric thermal resistance test:** The thermal resistance of the cable is measured.

(f) **Mechanical Test of metallic reinforcement:** A sample of cable to withstand twice the maximum specified internal pressure for a period of seven days.

(g) **Binding test:** The cable to be subjected to three binding cycles round a drum of diameter 20 times the diameter of the pressure retaining sheath. The sample then to withstand the routine voltage test carried out on all production lengths of cable.

Tests on High Voltage Bushings

Bushing:- A single or composite structure carrying a conductor or providing passage for a conductor, through a partition, such as a wall or tank cover, or through a ring type current transformer and insulating it there from, it includes the means of attachment to the partition.

(i) **Solid Bushing**: A bushing consisting of a single piece of solid insulating material which is continuous between its outer surface and the inner conducting surface, which may be the main conductor or a conducting layer connected thereto.

(ii) **Plain Bushing**: A bushing consisting of a single piece of solid insulating material, with a space between the conductor and the inner surface of the solid insulation. The space is occupied by air, oil or other insulating medium which forms part of the insulation. [See item (iii)]

(iii) **Oil filled Bushing**: A bushing consisting of an oil-filled insulating shell, the oil providing the major radial insulation. [Note: The conductor may be further insulated by a series of spaced concentric cylinders which may be provided with cylindrical conducting layers with the object of controlling the internal and external electric fields.]

(iv) **Condenser busing**: A bushing in which cylindrical conducting layers are arranged coaxially with the conductor within a solid body of insulating materials, (including materials impregnated with oils or other impregnants),the lengths and diameters of the cylinders being designed with the object of controlling the internal and external electric fields [Note: A conductor bushing may be provided with a weather shield, in which case the intervening space may be filled with oil or other insulating medium.it is recommended that the term condenser bushing with oil filling be used for this type.]

Tests on Bushings

Rating of bushings: Some of the relevant clauses from the standard is given in the following sections.

Clause 4: A bushing shall be rated in terms of the following:

a) voltage(refer table 1, clause 5)
b) normal current (refer tables 2 and 3 clause 6)
c) frequency (refer clause 7)
d) insulation level (see clause 8 below)

Clause 8: The insulation level of bushing is designed by a voltage which the bushing must be capable of withstanding under the specified test conditions.

For impulse tested bushings the rated insulation level is expressed as an impulse voltage value i.e. the impulse withstand voltage with 1/50 s full wave For non-impulse tested bushings the rated insulation level is expressed as a power frequency voltage value i.e. one minute dry withstand voltage.

Type Tests
Clause 14: Power frequency test
Clause 15: Impulse test
Clause 17: Momentary dry withstand test (power frequency voltage)
Clause 18: Visible discharge test (power frequency voltage)
Clause 19: Wet withstand test (power frequency voltage)
Clause 20: Puncture withstand test (power frequency voltage)
Clause 21: Full wave withstand test (impulse voltage)
Clause 22: Puncture withstand test (impulse voltage)

Sample Tests
Clause 23: Temperature rise test
Clause 25: Thermal stability test
Clause 26: Temperature cycle test
Clause 27: Porosity test

Routine Tests
Clause 29: One minute dry withstand test (power frequency voltage)
Clause 30: Oil lightness test
Clause 31: Power factor voltage test

Tests on Circuit Breaker

An equipment when designed to certain specification and is fabricated, needs testing for its performance. The general design is tried and the results of such tests conducted on one selected breaker and are thus applicable to all others of identical construction. These tests are called the **type tests**. These tests are classified as follows:

1. Short circuit tests:
   (*i*) Making capacity test.
   (*ii*) Breaking capacity test.
   (*iii*) Short time current test.
   (*iv*) Operating duty test

2. Dielectric tests:
   (*i*) Power frequency test:
   (*a*) One minute dry withstand test.
   (*b*) One minute wet withstand test.
   (*ii*) Impulse voltage dry withstand test.
3. Thermal test.
4. Mechanical test

Once a particular design is found satisfactory, a large number of similar C.Bs. are manufactured for marketing. Every piece of C.B. is then tested before putting into service. These tests are known as routine tests. With these tests it is possible to find out if incorrect assembly or inferior quality material has been used for a proven design equipment. These tests are classified as (i) operation tests,(ii) millivoltdrop tests, (iii) power frequency voltage tests at manufacturer’s premises, and (iv) power frequency voltage tests after erection on site.

Dielectric Tests

- The dielectric characteristics of circuit breaker or switchgear unit depend upon the basic design i.e. clearances, bushing materials, etc. 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.
- The test voltage is applied for a period of one minute between (i) **phases with the breaker closed**,(ii) **phases and earth with C.B. open**, and (iii) **across the terminals with breaker open**. With this the breaker must not flash over or puncture. For C.Bs, **the impulse tests generally are unnecessary** because it is not exposed to impulse voltage of a very high order. The high frequency switching surges do occur but the effect of these in cable systems used for indoor switchgear are found to be safely withstood by the switchgear if it has withstood the normal frequency test.
- Since the outdoor switchgear is subjected to over voltages caused by lightning. The effect of these voltages is much more serious than the power frequency voltages in service. Therefore, this class of switchgear is subjected in addition to power frequency tests, the impulse voltage tests.
- The test voltage should be a standard 1/50 μ sec wave, the peak value of which is specified according to the rated voltage of the breaker. A higher impulse voltage is specified for non-effectively grounded system than those for solidly grounded system. The test voltages are applied between (i) each pole and earth in turn with the breaker closed and remaining phases earthed, and (ii) between all terminals on one side of the breaker and all the other terminals earthed, with the breaker open. The specified voltages are withstand values i.e. the breaker should not flash over for 10 applications of the wave. Normally this test is carried out with waves of both the polarities.

The wet dielectric test is used for outdoor switchgear. In this, the external insulation is **sprayed for two minutes** while the rated service voltage is applied; the test overvoltage is then maintained for 30 seconds during which no flash over should occur. The effect of rain on external insulation is partly beneficial, insofar as the surface is thereby cleaned, but is also harmful if the rain contains impurities.

Thermal Tests

These tests are made to check the thermal behaviour of the breakers. In this test the **rated current through all three phases** of the switchgear is passed continuously **for a period long** enough to achieve steady state conditions. **Temperature readings** are obtained by means of **thermocouples** whose hot junctions are placed in appropriate positions. The temperature rise above ambient, of conductors, must normally not exceed 40°C when the rated normal current is less than 800 amps and 50°C if it is 800 amps and above.

An additional requirement in the type test is the measurement of the **contact resistances** between the isolating contacts and between the moving and fixed contacts. These points are generally the main sources of excessive heat generation. The voltage drop across the breaker pole is measured for different values of d.c. current which is a measure of the resistance of current carrying parts and hence that of contacts.

Mechanical Tests

C.B. must open and close at the correct speed and perform such operations without mechanical failure. The breaker mechanism is, therefore, subjected to a mechanical endurance type test involving repeated opening and closing of the breaker. **B.S. 116: 1952 requires 500 such operations without failure** and with no adjustment of the mechanism. Some manufacture feel that as many as 20,000 operations may be reached before any useful information regarding the possible causes of failure may be obtained. A resulting change in the material or dimensions of a particular component may consider-ably improve the life and efficiency of the mechanism.

Short Circuit Tests

These tests are carried out in short circuit testing stations to prove the ratings of the C.Bs. Before discussing the tests it is proper to discuss about the short circuit testing stations.

There are two types of testing stations; (i) field type, and (ii) laboratory type.

In case of field type stations the power required for testing is directly taken from a **large power system**. The breaker to be tested is connected to the system. Whereas this method of testing is economical for high voltage C.Bs. it suffers from the following drawbacks:

The tests cannot be repeatedly carried out for research and development as it **disturbs the whole network**.

The power available depends upon the **location of the testing stations**, **loading conditions**, **installed capacity**, etc.

Test conditions like the desired recovery voltage, the **RRRV** etc. cannot be achieved conveniently.

In case of laboratory testing, the power required for testing is provided by specially designed generators. This method has the following advantages:

- Test conditions such as current, voltage, power factor, restriking voltages can be controlled accurately.
- Several indirect testing methods can be used.
- Tests can be repeated and hence research and development over the design is possible.
- The limitations of this method are the cost and the limited power availability for testing the breakers.

Short Circuit Test Plants

The essential components of a typical test plant are represented in Fig. 5.4. The short-circuit power is 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-breaker is available to interrupt the test short circuit current if the test breaker should fail. Initiation of the short circuit may be by the master breaker, but is always done by a making switch which is specially designed for closing on very heavy currents but never called upon to break currents. The generator winding may be arranged for either star or delta connection according to the voltage required; by further dividing the winding into two sections which may be connected in series or parallel, a choice of four voltages is available. In addition to this the use of resistors and reactors in series gives a wide range of current and power factors. The generator, transformer and reactors are housed together, usually in the building accommodating the test cells.

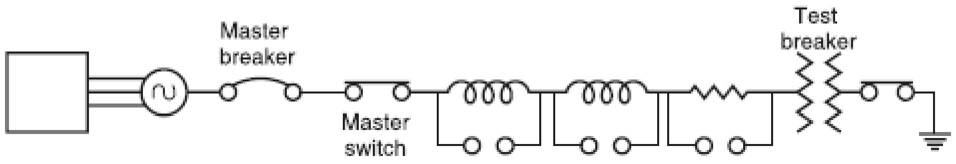


Fig. Schematic diagram of a typical test plant

TEST VOLTAGE

For different transmission voltages, the test voltages required are given in the following Tables:

Table 5.2

Test voltages for a.c. equipments

System nominal voltage (rms)	Power frequency withstand voltage (rms)	Impulse withstand voltage	Switching surge withstand voltage
400	520	1425	875
525	670	1800	1100
765	960	2300	1350
1100	1416	2800	1800
1500	1920	3500	2200

Table 5.3

Test voltages for d.c. equipments

Normal voltage	D.C. withstand voltage kV	Impulse withstand voltage kV	Switching surge withstand voltage kV
± 400 KV	800	1350	1000
± 600 KV	1200	1900	1500
± 800 KV	1600	2300	2000

Test voltages required for different system voltage (a.c. system)

Nominal voltage KV (rms)	Power frequency voltage kV (rms)	Impulse withstand voltage kV	Switching surge voltage kV
400	800	2400	1150
765	1000	3000	1750
1100	1400	3700	2300
1500	1900	4600	2800

TESTING OF SURGE DIVERTERS

- Surge diverters or lightning arresters reliable apparatus to protect the power system against transient voltages due to lightning and switching surges. They are invariably used Low voltages (400 V) to highest system transmission voltages of 765 kV or above. Hence, testing in standard laboratories with standard test procedures are of great importance in modem power system practice.
- A surge diverter non-conductor for operating power frequency voltages and It should behave as a short circuit for transient over voltages of impulse character, discharge the heavy current, and recover its insulation without allowing the follow-up of the power frequency current.
- In Table, the impulse current ratings of the surge diverters in relation to their voltage are given, and the testing is usually done at these current ratings.

Table 10.1 Surge Diverter Voltage and Current Ratings

Diverter class	Diverter rating	Impulse current rating (8/20 μ s) (Amperes)	High current rating (4/10 μ s) (Amperes)	Long duration rating—duration is given in μ s (Amperes)
A	Low voltage (230 V to 600 V)	1500 2500	10,000 25,000	50 (500 μ s)
B	Distribution voltages (400 V to 33 kV)	5000	65,000	75 (1000 μ s)
C	Station type lightning arresters (11 kV and above)	10,000	100,000	150 (2000 μ s)

Tests on Surge Diverters

Power Frequency Spark over Test

This is routine test The test is conducted using a series resistance to limit the current in case a spark over occurs. The arrester has to withstand at least 1.5 times the rated value of the voltage for five successive applications. The test is generally done also under dry and wet conditions.

Hundred per cent Standard Impulse Spark over Test

This test is conducted to ensure that the "diverter operates positively when **over voltages of impulse nature occur**. The impulse generator is adjusted to give the standard impulse voltage of a preset magnitude specified in the specifications. The arrester has to spark over every time in each of the ten successive applications. The test is done with both positive and negative polarity waveforms. Sometimes, the test is done by starting at a voltage level that does not give flashover at all, and is repeated in increasing steps of voltage till hundred per cent flashover occurs. The magnitude of the voltage at which hundred per cent flashover occurs is the required spark over voltage.

Front of Wave Spark over Test

In order to ensure that the surge diverter flashes over for very steep fronted waves of high peaks, this test is conducted using an overvoltage having a rate of rise of **100kV/µs, per 12 kV** of the rating. The estimated maximum steepness of the waves are specified in standards and specifications. The test is done by conducting hundred per cent spark over voltage test for increasing magnitudes of the standard impulse wave. The time to spark over is measured. The volt-time characteristic of the diverter is plotted, and the intersection of the *V-t* characteristic and the line with slope of the virtual steepness of the front gives the front of a wave sparkover voltage.

Residual Voltage Test

This test is conducted on prorated diverters of ratings in the range 3 to 12 kV only. The voltage developed across the Non-Linear Resistor units (NLR) during the flow of surge currents through the arrester is called the 'residual voltage'. A prorated arrester is a complete, suitably housed section of an arrester including series gaps and non-linear series resistors in the same proportion as in the complete arrester.) Standard impulse currents of the rated magnitudes arc applied, and the voltage developed across the diverter is recorded using a suitable voltage divider and a CRO. The magnitudes of the currents are approximately 0.5, 1.0, and 2.0 times the rated currents. From the oscillogram, a graph is drawn between the current magnitudes and the voltage developed across the diverter prorated unit From the graph, the residual voltage corresponding to the exact rated current is obtained.

High Current Impulse Test on Surge Diverters

This test is also done on pro rated diverter units in the range of 3 to 12 kV. A high current impulse wave of 4/10 μs of peak value mentioned in the specifications is applied to a spare unit of identical characteristics. Two such applications are done on the units under test, allowing sufficient time for the cooling of the unit to the room temperature. The unit is said to pass the test, if

(l) the power frequency sparkover voltage before and after the test does not differ by more than 10%,

(ii} the voltage and current waveforms of the diverter do not differ significantly in the two applications, and

(iii) the non-linear resistance elements in the diverter do not show any sign of puncture or external fiashover.

Long Duration Impulse Current Test

This test is also done on pro-rated units of 3 to 12kV. The circuit used for generating a rectangular impulse wave consists of an artificial transmission line with lumped inductances and capacitances. The duration of the current pulse i is given by 2(n - I)**Sqrt(LC)* ,where *n* is the number of stages or sections used, and L and C are the inductance and capacitance of each unit.

Rectangular wave is generated, if the surge impedance of the diverter is equal to the test current. As per the specifications, 20 applications are made with specified current in five groups. The interval between the successive applications is about 1 min. It is usual to record the waveforms in the first two and the last two applications of the current wave. The diverter is said to have passed the test, if

(l) the power frequency spark over voltage before and after the application of the current wave does not differ by 10%,
(ii) the voltage across the diverter at the first and the last application does not differ by more than 8%, and
(iii) there is no sign of puncture or other damage.

Operating Duty Cycle Test

This test is conducted on pro-rated units of diverters and gives better closeness to actual conditions. The diverter is kept energized at its rated power frequency supply voltage. The rated impulse current wave is applied first at a phase angle of about 30° from the AC voltage zero. If the power frequency follow-on current is not established, the angle at which current wave is applied is advanced in steps of 10° up to 90° or the peak position of the supply voltage wave till the follow-on current is established. In the course of application of the current wave, if the power frequency voltage is reduced during the flow of current, it can be compensated up to a maximum of 10% of the overvoltage. During the follow-on current period, the peak voltage across the diverter should be less than or equal to the rated peak voltage. **Twenty applications** of the impulse current at the selected points **on the voltage** wave are made in four groups. The time interval between each application is about 1 min, and between successive groups it is about half an hour. The arrester is said to have passed the test, if

the average power frequency sparkover voltage before and after the test does not differ by more than 10%.
(il) the residual voltage at the rated current does not vary by more than 10%,
(iil) the follow-on power frequency current is interrupted each time, and
(iv) no significant change, signs of flashover, or puncture occurs to the pro-rated unit.

Other Tests

The other tests that are normally conducted on surge diverters are

(i) mechanical tests like porosity test, temperature cycle tests, and others,

(ii) pressure relief test,

(iii) the voltage withstand test on the insulator housing of the diverter, the switching surge flashover test, and the pollution tests.

These tests are usually done on diverters used on Extra High Voltage (EHV) systems.

TESTING OF ISOLATORS

- In this section, the testing of isolators common characteristics is tested.
- The testing of isolators are concerned since isolators are not used for interrupting high currents. At best, they interrupt small currents of the order of 0.5 A (for rated voltages of 420 kV and below) which may be the capacitive currents of bushings, busbars etc. In fact, the definition of an Isolator or a Disconnector as per IS: 9921 (Part I) - 1981 is as follows:
- An isolator or a disconnector is a mechanical switching device, which provides in the open position, an isolating distance in accordance with special requirements. An isolator is capable of opening and closing a circuit when either negligible current is broken or made or when no significant change in the voltage across the terminals of each of the poles of the isolator occurs.
- It is also capable of carrying currents under normal circuit conditions, and carrying for a specified time, currents under abnormal conditions such as those of a short circuit.
- Normal Insulation resistance test
- Contact resistance test
- Power frequency Over Voltage test on insulators Type test for a piece as sample.
- No arc quenching medium so operation only at No load condition.
- Mechanical Test

Non-destructive Insulation Test Techniques

- Electrical appliances are insulated with gaseous or liquid or solid or a suitable combination of these materials and insulated between live parts or between live part and grounded part of the appliance.
- The materials may be subjected to varying degrees of **voltages, temperatures and frequencies** and it is expected of these materials to work satisfactorily over these ranges which may occur occasionally in the system.
- Character - dielectric losses low and the insulation resistance high in order to prevent thermal breakdown of these materials. The void inside the insulating materials deteriorate the dielectric materials so must avoid.
- ✓ When an insulating material is subjected to a voltage for investigation, it is usually not possible to draw conclusion regarding the cause of breakdown from the knowledge of the breakdown voltage particularly in solid materials. Earlier, the quality of insulation was judged, mainly by the insulation resistance and its dielectric strength. However, these days high voltage equipment and installations are subjected to various tests. These tests should also yield information regarding the **life expectancy** and the **long term stability** of the insulating materials.
- ✓ One of the possible testing procedure is to over-stress insulation with high AC and/ or DC or surge voltages. However, the disadvantage of the technique is that during the process of testing the equipment may be damaged if the insulation is faulty. For this reason, following non-destructive testing methods that permit early detection for insulation faults are used:

(i) Measurement of the insulation resistance under d.c. voltages
(ii) Determination of loss factor tan δ and the capacitance C
(iii) Measurement of partial discharges.

LOSS IN A DIELECTRIC

An ideal dielectric is loss-free and if its relative permittivity is ε_r, its permittivity is given by

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

and ε also known as the dielectric constant is a real number. A real dielectric is always associated with loss. The following are the mechanisms which lead to the loss:

(i) **Conduction** loss P_c by ionic or electronic conduction. The dielectric, has σ as conductivity.
(ii) **Polarization** loss P_p by orientation boundary layer or deformation polarization.
(iii) **Ionization** loss P_i by partial discharges internal or external zones.

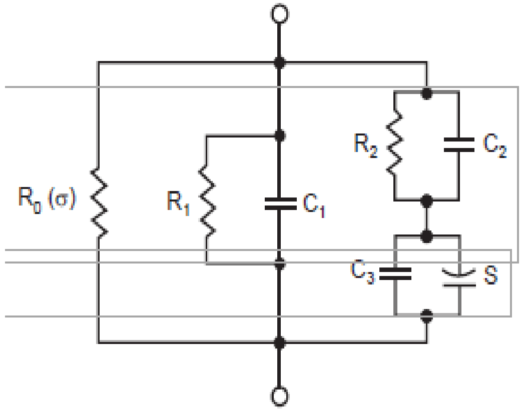


Fig. Equivalent circuit of a dielectric

Fig. shows an equivalent circuit of a dielectric with loss due to conduction, polarization and partial discharges. An ideal dielectric can be represented by a pure capacitor C1 and Conduction losses.

can be taken into account by a resistor R0 (σ) in parallel. Polarization losses produce a real component of the displacement current which is simulated by resistor R1. Pulse partial discharges are simulated by right hand branch. C3 is the capacitance of the void and S is the spark gap which fires during PD discharge and the repeated recharging of C_3 is effected either by a resistor R_2 or a capacitor C_2.

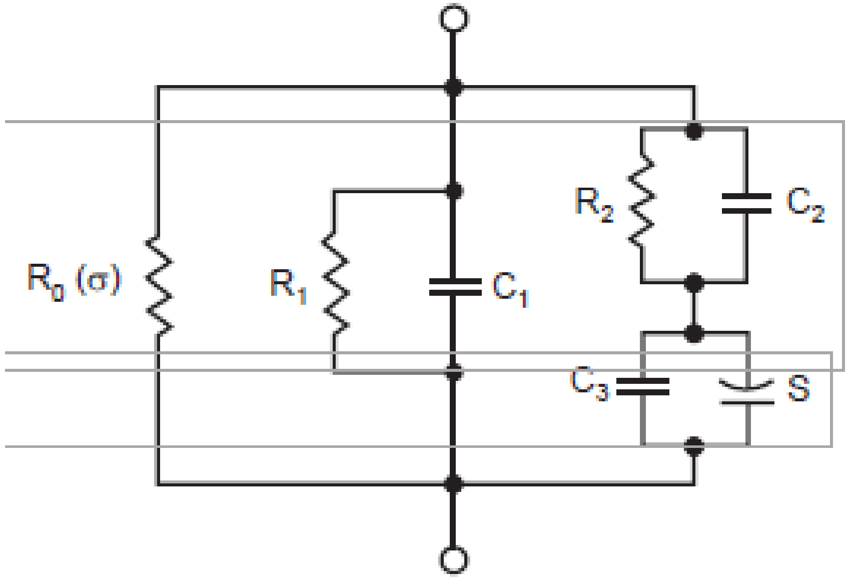


Fig. Equivalent circuit of a dielectric

MEASUREMENT OF DIELECTRIC CONSTANT AND LOSS FACTOR

Dielectric loss and equivalent circuit

In case of time varying electric fields, the current density J_c using Amperes law is given by

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

For harmonically varying fields

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

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

Therefore,

$$J_c = \sigma E + j\omega\varepsilon E$$
$$= (\sigma + j\omega\varepsilon)E$$

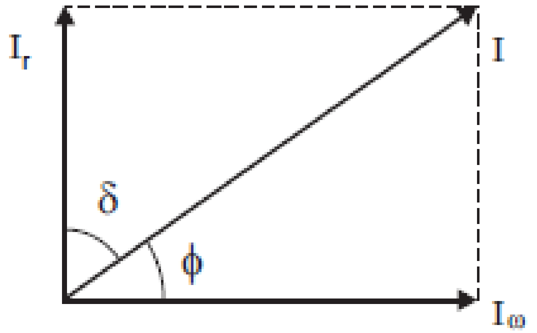


Fig. Phasor diagram for a real dielectric material

In general, in addition to conduction losses, ionization and polarization losses also occur and, therefore, the dielectric constant ε = ε0 εr is no longer a real quantity rather it is a complex quantity. By definition, the dissipation factor tan δ is the ratio of real component of current Iω to the reactive component Ir

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

Here δ is the angle between the reactive component of current and the total current flowing through the dielectric at fundamental frequency. When δ is very small tan δ = δ when δ is expressed in radians and tan δ = sin δ = sin (90 – φ) = cos φ i.e., tan δ then equals the power factor of the dielectric material.

As mentioned earlier, the dielectric loss consists of three components corresponding to the three loss mechanism.

Pdiel = Pc + Pp + Pi and for each of these an individual dissipation factor can be given such that

tan δ = tan δc + tan δp + tan δi

If only conduction losses occur then:-

$$P_{\text{diel}} = P_c = \sigma E^2 Ad = V^2 \omega C \tan \delta = \frac{V^2 \omega \varepsilon_0 \varepsilon_r A}{d} \tan \delta$$

$$\sigma E^2 = \frac{V^2}{d^2} \omega \varepsilon_0 \varepsilon_r \tan \delta = E^2 \omega \varepsilon_0 \varepsilon_r \tan \delta$$

$$\tan \delta = \frac{\sigma}{\omega \varepsilon_0 \varepsilon_r}$$

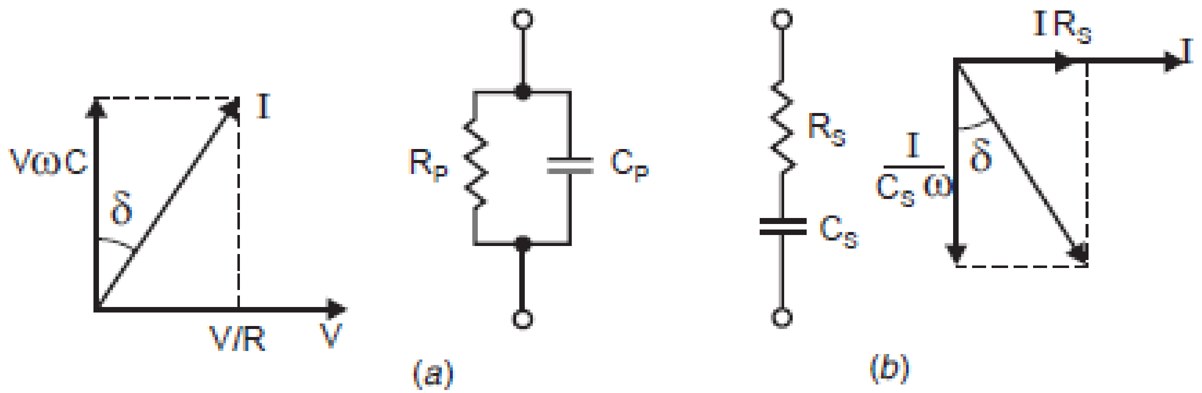


Fig. Equivalent circuits for an insulating material

Normally the angle between V and the total current in a pure capacitor is 90°. Due to losses, this angle is less than 90°. Therefore, δ is the angle by which the voltage and charging current fall short of the 90° displacement. For the parallel circuit the dissipation factor is given by

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

and for the series circuit

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

For a fixed frequency, both the equivalents hold good and one can be obtained from the other. However, the frequency dependence is just the opposite in the two cases and this shows the limited validity of these equivalent circuits.

The information obtained from the measurement of tan δ and complex permittivity is an indication of the quality of the insulating material.

(i) If tan δ varies and changes abruptly with the application of high voltage, it shows **inception of internal partial discharge**.

(ii) The **effect to frequency on the dielectric properties** can be studied and the band of frequencies where dispersion occurs i.e., where that permittivity reduces with rise in frequency can be obtained.

HIGH VOLTAGE SCHERING BRIDGE

The bridge 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 equipment have low capacitance and low loss factor. This bridge is then more suitable for measurement of such small capacitance equipment as the bridge uses either high voltage or high frequency supply. If measurements for such low capacity equipment is carried out at low voltage, the results so obtained are not accurate.

Fig. 6.5 shows a high voltage schering bridge where the specimen has been represented by a parallel combination of R_p and C_p.

The special features of the bridge are:

1] High voltage supply, consists of a high voltage transformer with regulation, protective circuitry and special screening. The input voltage is 220 volt and output continuously variable between 0 and 10 kV. The maximum current is 100 mA and it is of 1 kVA capacity.

2] Screened standard capacitor C_s of 100 PF ± 5%, **10 kV** max and dissipation factor tan $\delta = 10^{-5}$. It is a gas-filled capacitor having negligible loss factor over a wide range of frequency.

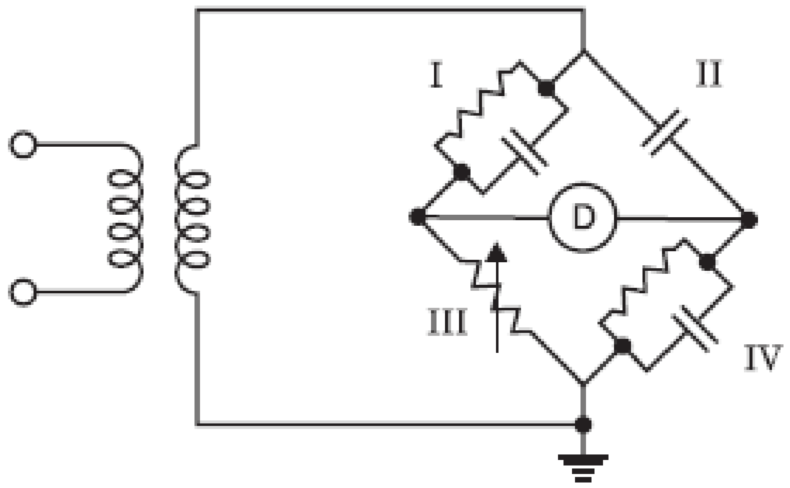


Fig. 6.5 Basic high voltage schering bridge

3]The impedances of arms I and II are very large and, therefore, current drawn by these arms is small from the source and a sensitive detector is required for obtaining balance. Also, since the impedance of arm I and II are very large as compared to III and IV, the detector and the impedances in arm III and IV are at a potential of only a few volts (10 to 20 volts) above earth even when the supply voltage is 10 kV, except of course, in case of breakdown of one of the capacitors of arm I or II in which case the potential will be that of supply voltage. Spark gaps are, therefore, provided to spark over whenever the voltage across arm III or IV exceeds 100 volt so as to provide personnel safety and safety for the null detector.

Balancing the Bridge

For ready reference Fig. is reproduced here and its phasor diagram under balanced condition is drawn in Fig. (b).

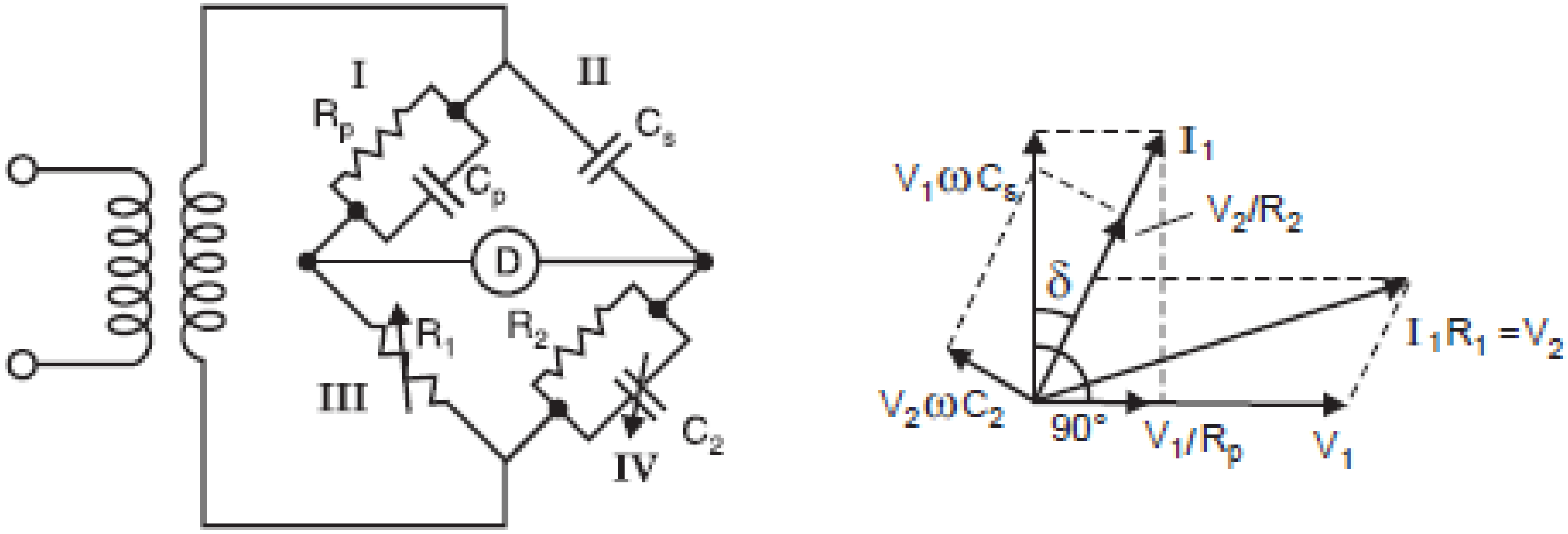


Fig. (*a*) Schering bridge (*b*) Phasor diagram

The bridge is balanced by successive variation of R_1 and C_2 until on the oscilloscope (Detector) a horizontal straight line is observed:

At balance $$\frac{Z_I}{Z_{II}} = \frac{Z_{III}}{Z_{IV}}$$

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

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

$$Z_{III} = R_1 \text{ and } Z_{IV} = \frac{R_2}{1 + j\,\omega\,C_2 R_2}$$

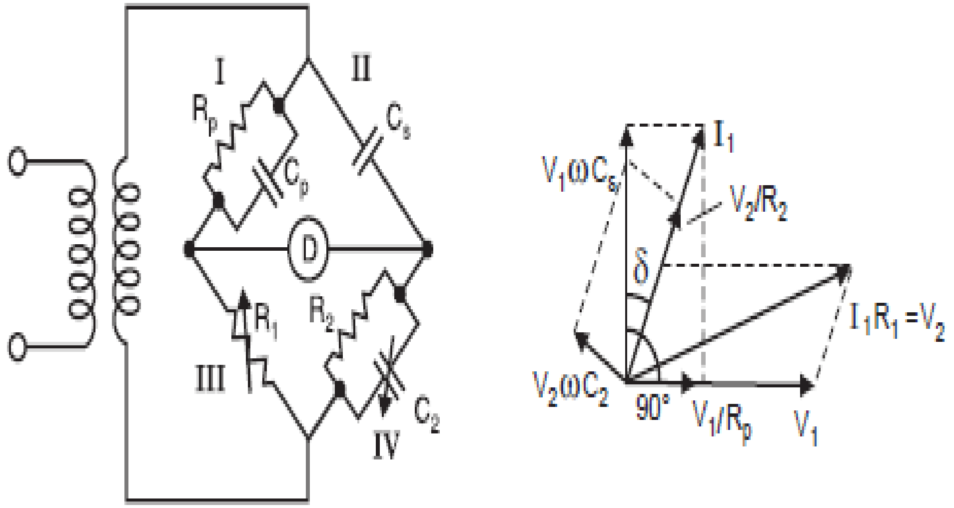


Fig (a) Schering bridge (b) Phasor diagram

Equating real part, we have

$$\frac{R_p}{R_1\left(1 + \omega^2 C_p^2 R_p^2\right)} = \frac{C_2}{C_s}$$

and equating imaginary part, we have

$$\frac{\omega\,C_p R_p^2}{R_1\left(1 + \omega^2\,C_p^2 R_p^2\right)} = \frac{1}{\omega C_s R_2}$$

Now tan δ from the phasor diagram

$$\tan\delta = \frac{V_1/R_p}{V_1\omega C_p} = \frac{1}{\omega C_p R_p} = \frac{V_2\ \omega\ C_2}{V_2/R_2} = \omega C_2 R_2$$

If, however, the specimen is replaced by *a* series equivalent circuit, then at balance

$$Z_I = R_s - \frac{j}{\omega C_s}$$

and the equation becomes

$$\frac{R_s - j/\omega C_s}{R_1} = \frac{1 + j\,\omega\, C_2 R_2}{j\,\omega\, C_s' R_2}$$

or $$\frac{R_s}{R_1} - \frac{j}{\omega\ C_s R_1} = -\frac{j}{\omega C_s{}'\,R_2} + \frac{C_2}{C_s{}'}$$

Equating real parts, we have

$$\frac{R_s}{R_1} = \frac{C_2}{C_s{}'}$$

or $$R_s = R_1\,\frac{C_2}{C_s{}'}$$

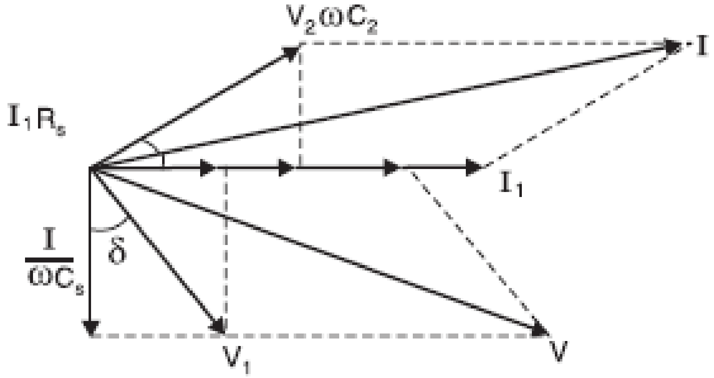


Fig. 6.11 Phasor diagram of S.B. for series equivalent of specimen

Similarly equating imaginary part, we have

$$\omega C_s R_1 = \omega C_s{}'\,R_2$$

$$C_s = C_s{}'\,\frac{R_2}{R_1}$$

To find out tan δ, we draw the phasor diagram of the bridge circuit (Fig. 6.11).

$$\tan \delta_s = \frac{I_1 R_s}{I_1/\omega C_s} = \omega C_s R_s$$

Partial Discharge Measurement and Test Circuits

- Partial discharge is defined as localized discharge process in which the distance between two electrodes is only partially bridged i.e., the insulation between the electrodes is partially punctured.
- Partial discharges may originate directly at one of the electrodes or occur in a cavity in the dielectric.
- Some of the typical partial discharges are:

(i) Corona or gas discharge. These occur due to non-uniform field on sharp edges of the conductor subjected to high voltage especially when the insulation provided is air or gas or liquid Fig. 6.18 (a).

(ii) Surface discharges and discharges in laminated materials on the inter-faces of different dielectric material such as gas/solid interface as gas gets over stressed εr times the stress on the solid material (where εr is the relative permittivity of solid material) and ionization of gas results Fig. 6.18 (b) and (c).

(iii) Cavity discharges: When cavities are formed in solid or liquid insulating materials the gas in the cavity is over stressed and discharges are formed Fig. 6.18 (d)

(iv) Treeing Channels: High intensity fields are produced in an insulating material at its sharp edges and this deteriorates the insulating material. The continuous partial discharges so produced are known as Treeing Channels Fig. 6.18 (e).

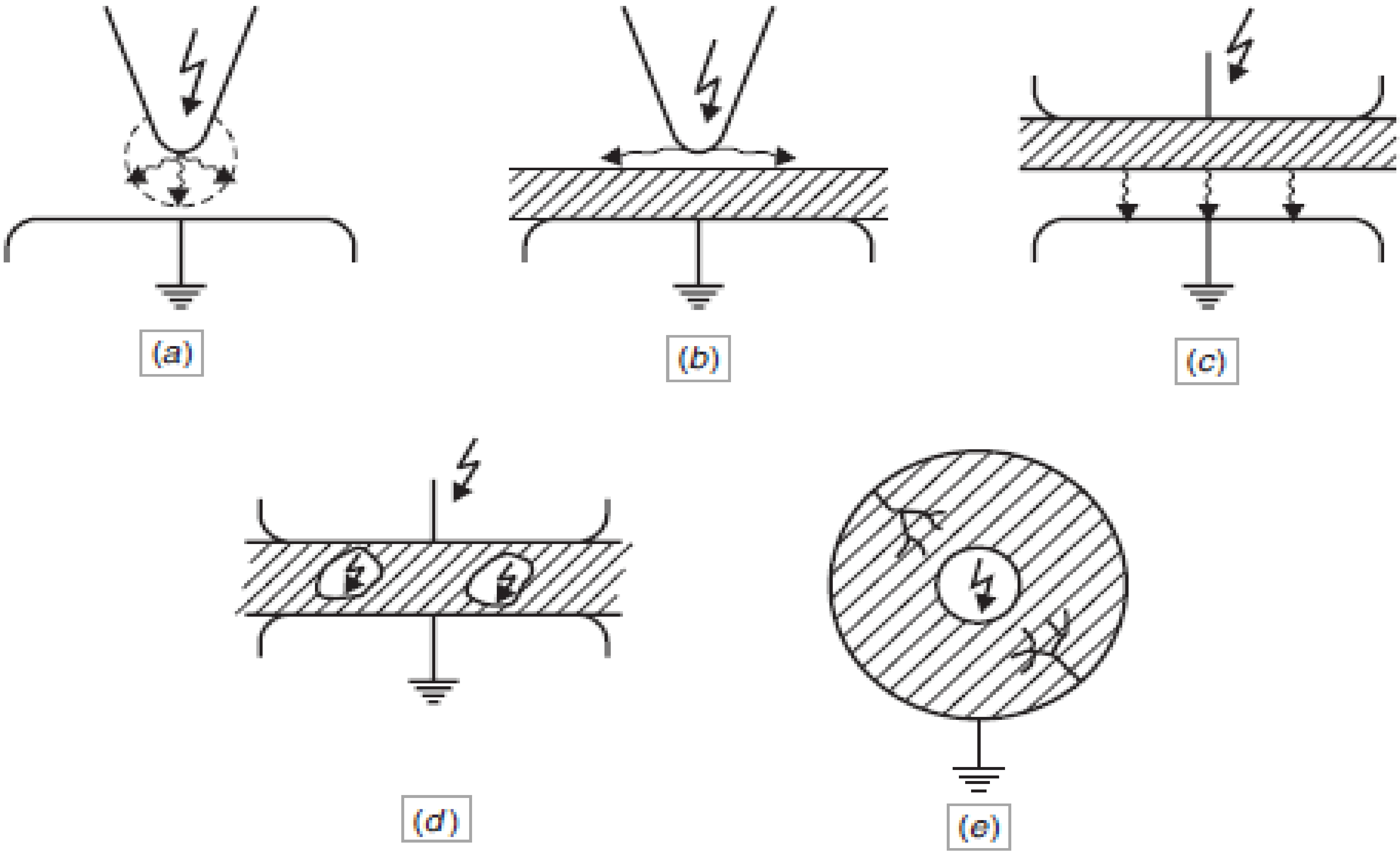


Fig Various partial discharges

External Partial Discharge

External partial discharge is the process which occurs external to the equipment e.g. on overhead lines, on armature etc.

Internal Partial Discharge

- Internal partial 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 external discharges can be nicely distinguished from internal discharges.
- Partial discharge used to assess the life expectancy of insulating materials. Even though no well defined relationship of the insulating properties of the material.
- Partial discharges on insulation not only by electrical methods but by optical, acoustic and chemical method also.
- The principles are based on energy conversion process associated with electrical discharges such as emission of electromagnetic waves, light, noise or formation of chemical compounds.
- The oldest and simplest method of listening to hissing sound coming out of partial discharge.
- A **high value** of loss factor **tan δ** is an indication of occurrence of partial discharge in the material.
- Optical methods are used only for those materials which are transparent not applicable for all materials.
- Acoustic detection methods using ultrasonic transducers have, however, been used with some success.
- The most modern and the most accurate methods are the electrical methods. The main objective here is to separate impulse currents associated with PD from any other phenomenon.

The Partial Discharge Equivalent Circuit

If there are any partial discharges in a dielectric material, these can be measured only across its terminal. Fig. 6.19 shows a simple capacitor arrangement in which a gas filled void is present. The partial discharge in the void will take place as the electric stress in the void is εr times the stress in the rest of the material where εr is the relative permittivity of the material. Due to geometry of the material, various capacitances are formed as shown in Fig. 6.19 (a). Flux lines starting from electrode and termi-nating at the void will form one capacitance Cb1 and similarly Cb2 between electrode B and the cavity. Cc is the capacitance of the void. Similarly Ca1 and Ca2 are the capacitance of healthy portions of the dielectric on the two sides of the void. Fig. 6.19 (b) shows the equivalent of 6.19 (a) where Ca = Ca1+ Ca2, and Cb = Cb1Cb2/(Cb1 + Cb2) and Cc is the cavity capacitance. In general Ca >> Cb >> Cc.

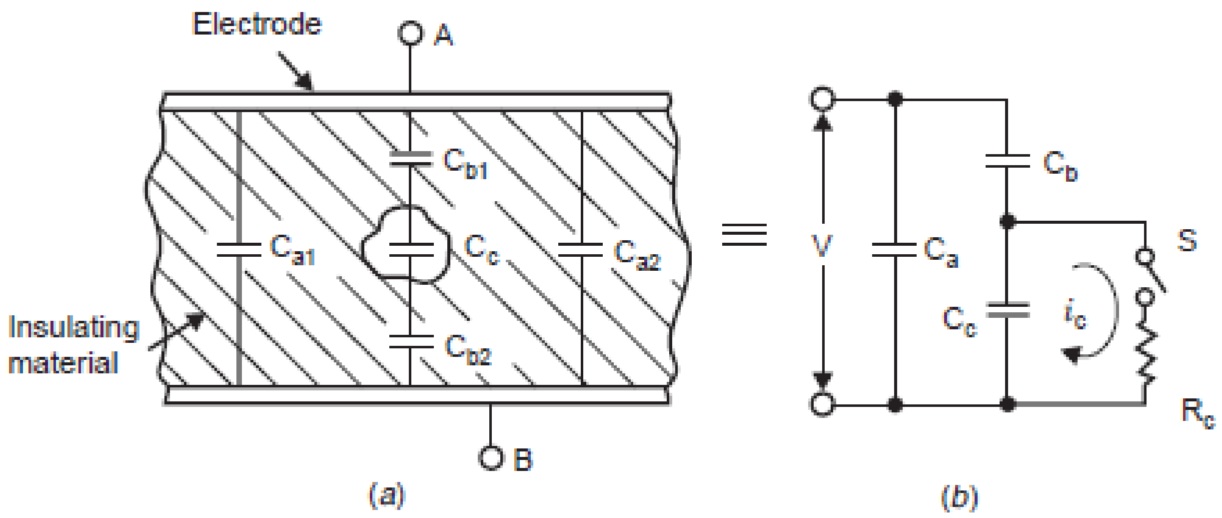


Fig. 6.19. (a) Dielectric material with a cavity (b) Equivalent circuit

Closing of switch S is equivalent to simulating partial discharge in the void as the voltage Vc across the void reaches breakdown voltage. The discharge results into a current ic(t) to flow. Resistor Rc simulates the finite value of current ic(t).

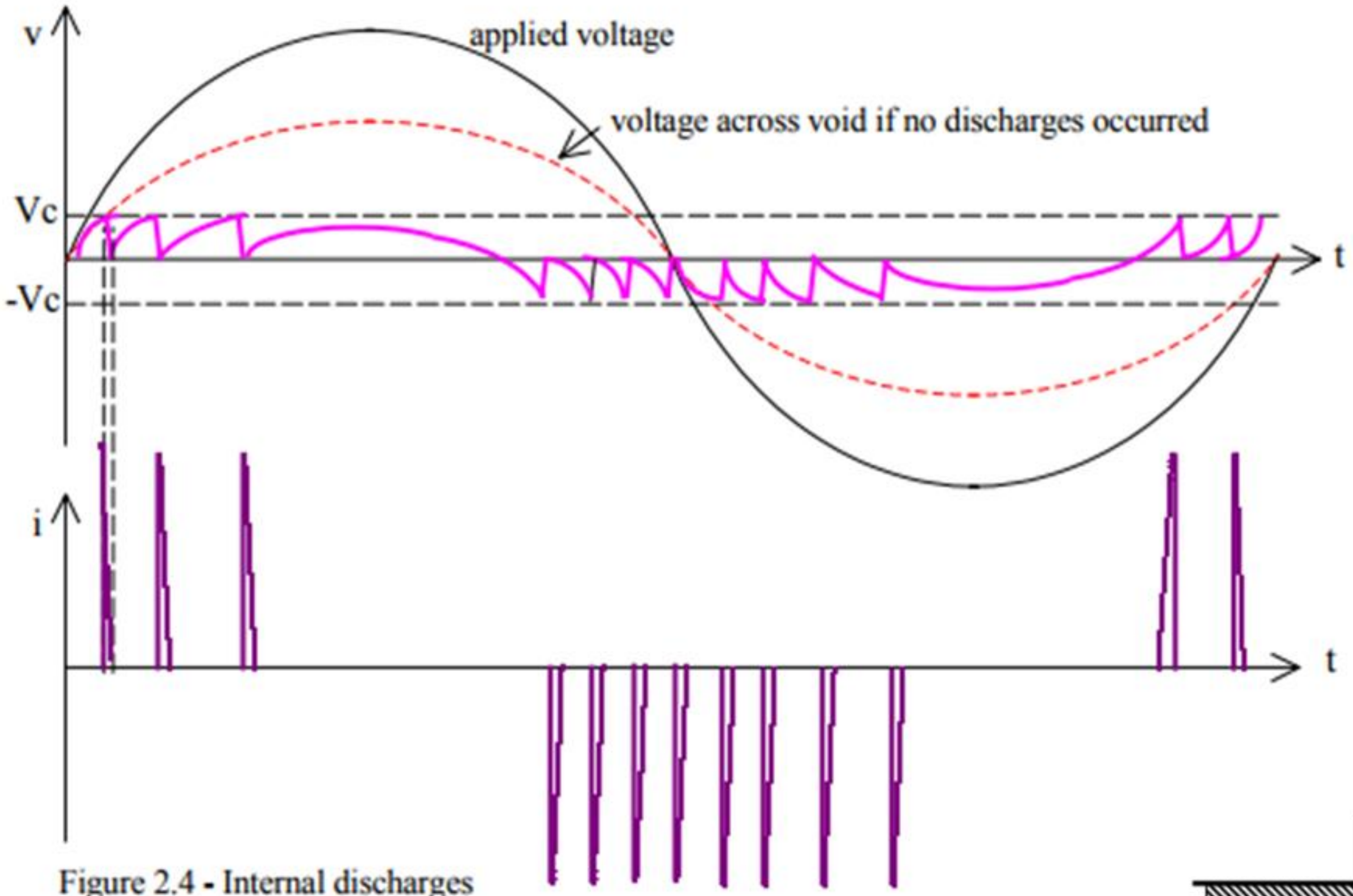


Figure 2.4 - Internal discharges

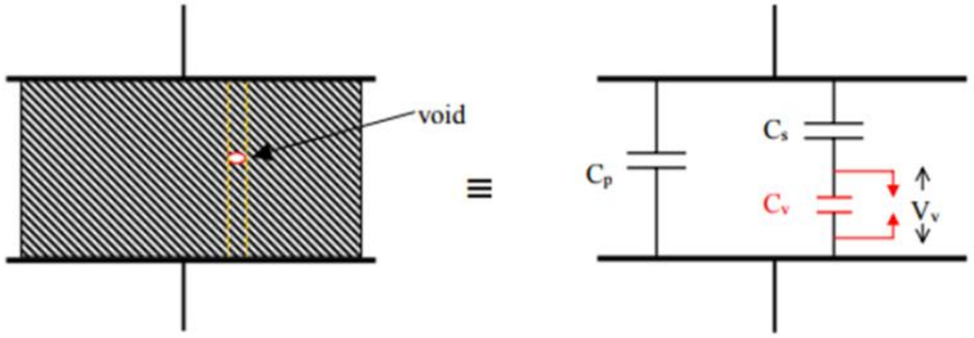


Figure 2.3 - Equivalent circuit of dielectric with void

The measurement of PD current pulses provides important information concerning the discharge processes in a test specimen. The time response of an electric discharge depends mainly on the nature of fault and design of insulating material. The shape of the circular current is an indication of the physical discharge process at the fault location in the test object. The principle of measurement of PD current is shown in Fig. 6.23.

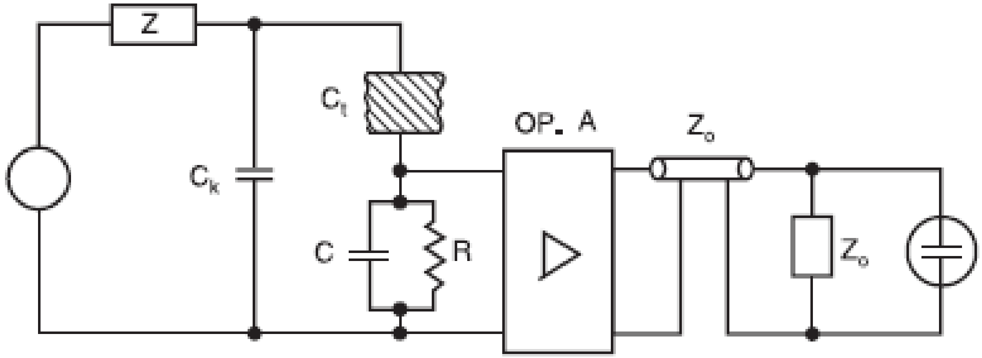


Fig. 6.23 Principle of pulse current measurement

Here C indicates the stray capacitance between the lead of Ct and the earth, the input capaci-tance of the amplifier and other stray capacitances. The function of the high pass amplifier is to sup-press the power frequency displacement current ik(t) and Ic(t) and to further amplify the short duration current pulses. Thus the delay cable is electrically disconnected from the resistance R. Suppose during a partial discharge a short duration pulse current δ (t) is produced and results in apparent charge q on Ct which will be redistributed between Ct, C and Ck . The circuit for the same is given in Fig. 6.24.

Potential across C_t $= \dfrac{q}{C_t + \dfrac{CC_k}{C + C_k}}$

Therefore, voltage across C will be

$$v = \frac{q}{C_t + \dfrac{CC_k}{C + C_k}} \cdot \frac{C_k}{C + C_k} = \frac{q}{C_t(C + C_k) + CC_k} \cdot C_k$$

$$= \frac{qC_k}{CC_t + C_kC_t + CC_k} = \frac{q}{C + C_t\left(1 + \dfrac{C}{C_k}\right)}$$

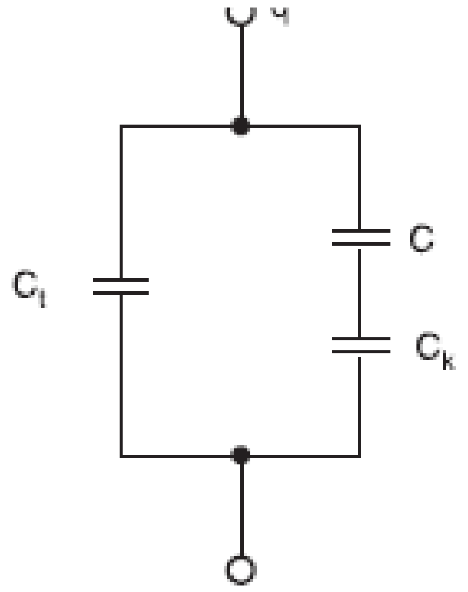


Fig. 6.24 Equivalent of 6.23 after discharge

and because of resistance R the expression for voltage across R will be

$$v(t) = \frac{q}{C + C_t\left(1 + \dfrac{C}{C_k}\right)} e^{-t/\tau}$$

where $$\tau = \left(C + \frac{C_t C_k}{C_t + C_k}\right) R$$

High Voltage Power Cable Topics - 4

High Voltage Power Cables

- Classification of Cables
- Typical Construction and Cross-Sections of Cables
- Dependence of Power Rating of Cable in Different Environments
- Electrical Characteristics of EHV Cables
- Belted Cables and its Capacitance Measurement
- Super Tension Cables: H-type, Separate Lead (S.L) type and H.S.L type cables
- Pressurized High Voltage Cables
- Oil-pressure cables, Gas-pressure cables(External and Internal Pressure cables)
- Materials used for Insulation in HV cables: Oil filled, XLPE
- Methods for Laying Underground Cables

High Voltage Cables –Why ?

- High Voltage Cables are used when underground transmission is required. These cables are laid in ducts or may be buried in the ground. Unlike in overhead lines, air does not form part of the insulation, and the conductor must be completely insulated. Thus cables are much more costly than overhead lines. Also, unlike for overhead lines where tapping can easily given, cables must be connected through cable boxes which provide the necessary insulation for the joint.
- Cables have a much lower inductance than overhead lines due to the lower spacing between conductor and earth, but have a correspondingly higher capacitance, and hence a much higher charging current. High **voltage cables are generally single cored**, and hence have their separate insulation and mechanical protection by sheaths. In the older paper insulated cables, the sheath was of extruded lead.
- The presence of the sheath introduces certain difficulties as currents are induced in the sheath as well. This is due to fact that the sheaths of the conductors cross the magnetic fields set up by the conductor currents. At all points along the cable, the magnetic field is not the same, Hence different voltages are induced at different points on the sheath. This causes eddy currents to flow in the sheaths. These eddy currents depend mainly on

(a) the frequency of operation,
(b) the distance between cables,
(c) the mean radius of the sheath, and
(d) the resistivity of the sheath material.

Power loss in the Cable

Power loss in the cable can occur due to a variety of reasons (Figure 5.2). They may be caused by the conductor current passing through the resistance of the conductor - **conductor loss** (also sometimes called the copper loss on account of the fact that conductors were mainly made out of copper), **dielectric losses** caused by the voltage across the insulation, **sheath losses** caused by the induced currents in the sheath, and **intersheath losses** caused by circulating currents in loops formed between sheaths of different phases. The dielectric loss is voltage dependant, while the rest is current dependant.

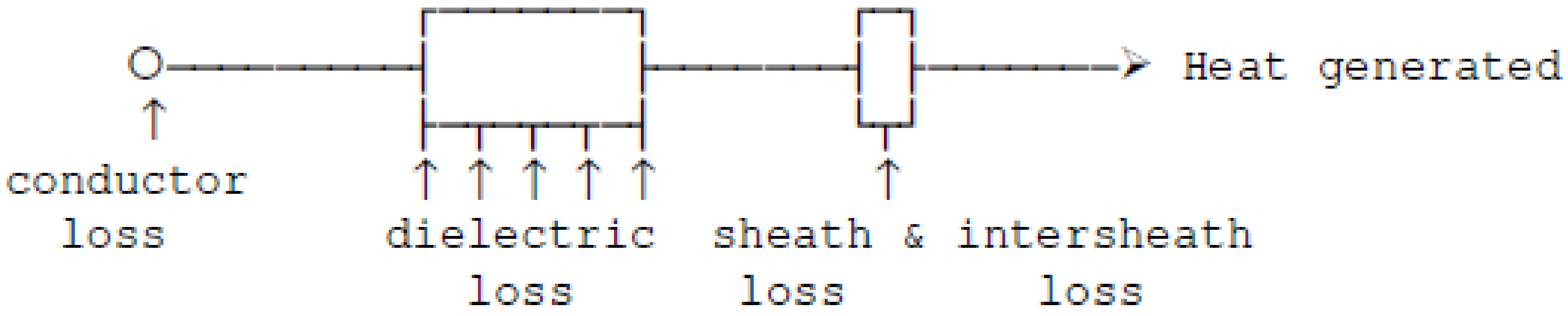


Figure 5.2 - Heat Transfer in a cable due to losses

Underground Cables

An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover. Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must fulfil the following necessary requirements :

(i) The conductor used in cables should be tinned stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

(ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.

(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

(iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.

(v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

Construction of Cables

Fig. 11.1 shows the general construction of a 3-conductor cable. The various parts are :

(i) Cores or Conductors. A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3-conductor cable shown in Fig. 11.1 is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

(ii) Insulatian. Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

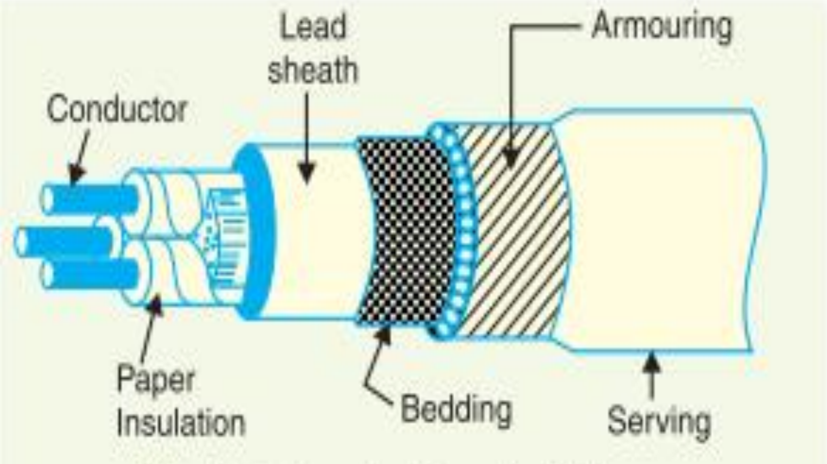


Fig. 11.1 Construction of a Cable

(iii) Metallic sheath. In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig. 11.1

(iv) Bedding. Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

(v) **Armouring.** Over the bedding, armouring is provided which consists of one or two layers of galvanized steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

(vi) **Serving**. In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as serving.

It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury

Insulating Materials for Cables

The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance. In general, the insulating materials used in cables should have the following properties :

(i) High insulation resistance to avoid leakage current.

(ii) High dielectric strength to avoid electrical breakdown of the cable.

(iii) High mechanical strength to withstand the mechanical handling of cables.

(iv) Non-hygroscopic i.e., it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.

(v) Non-inflammable.

(vi) Low cost so as to make the underground system a viable proposition.

(vii) Unaffected by acids and alkalies to avoid any chemical action.

No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at.The principal insulating materials used in cables are rubber, vulcanised India rubber, impregnated paper, varnished cambric and polyvinyl chloride.

1. **Rubber**. Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is 1017Ω cm. Although pure rubber has reasonably high insulating properties, it suffers form some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38ºC), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

2. **Vulcanised India Rubber (V.I.R.).** It is prepared by mixing pure rubber with mineral matter such as zine oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150ºC. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

3. **Impregnated paper**. It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or napthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance.

The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed. If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar. Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a *few joints. For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus. However, for smaller installations, where the lengths are small and joints are required at a number of places, VIR cables will be cheaper and durable than paper insulated cables.

4. Varnished cambric. It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as empire tape. The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent. As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.

5. Polyvinyl chloride (PVC). This insulating material is a synthetic compound. It is obtained from the polymerisation of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gell and renders the material plastic over the desired range of temperature

.Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over VIR in extreme enviormental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations

Classification of Cables

Cables for underground service may be classified in two ways according to

(i) the type of insulating material used in their manufacture

(ii) the voltage for which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups :

(iii) Low-tension (L.T.) cables — upto 1000 V

(ii) High-tension (H.T.) cables — upto 11,000 V

(iii) Super-tension (S.T.) cables — from 22 kV to 33 kV

(iv) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

(v) Extra super voltage cables — beyond 132 kV

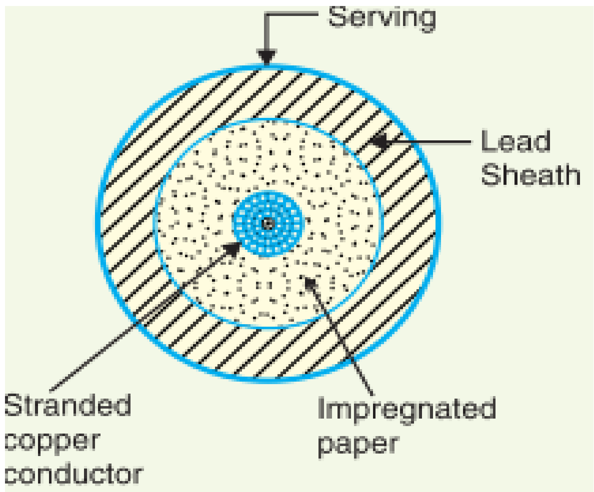


Fig. 11.2

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be (i) single-core (ii) two-core (iii) three-core (iv) four-core etc. For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.

Fig. 11.2 shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (upto 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts.

In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

Cables for 3-Phase Service

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or *three single core cables may be used. For voltages upto 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used.

The following types of cables are generally used for 3-phase service :

1. Belted cables — upto 11 kV
2. Screened cables — from 22 kV to 66 kV
3. Pressure cables — beyond 66 kV.

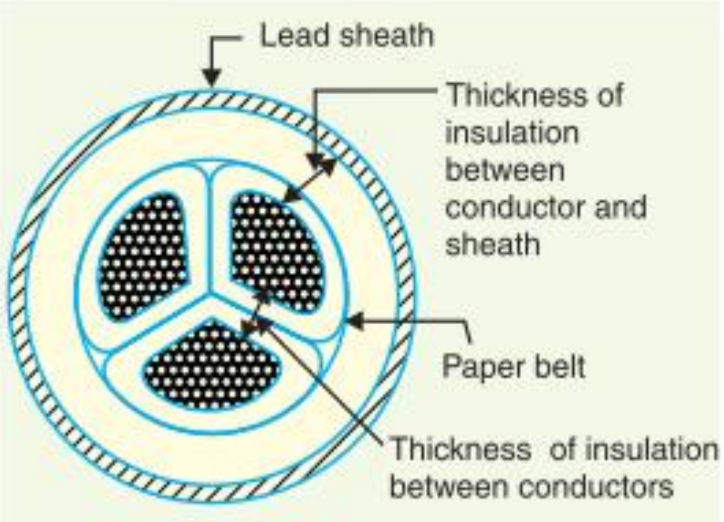


Fig. 11.3

Belted cables.

These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV. Fig. 11.3 shows the constructional details of a 3-core belted cable. The cores are insulated from each other by layers of impregnated paper. Another layer of impregnated paper tape, called paper belt is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of noncircular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure).

The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial i.e., across the insulation. However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation. As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up **leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment. In order to overcome this difficulty, screened cables are used where leakage currents are conducted to earth through metallic screens.

Screened cables.

These cables are meant for use upto 33 kV, but in particular cases their use may be extended to operating voltages upto 66 kV. Two principal types of screened cables are H type cables and S.L. type cables.

(i) <u>H-type cables.</u>

This type of cable was first designed by H. Hochstadter and hence the name. Fig. 11.4 shows the constructional details of a typical 3-core, H-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminium foil. The cores are laid in such a way that metallic screens make contact with one another. An additional conducting belt (copper woven fabric tape) is wrapped round the three cores. The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at †earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced. Two principal advantages are claimed for H-type cables. Firstly, the perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation. Secondly, the metallic screens increase the heat dissipating power of the cable.

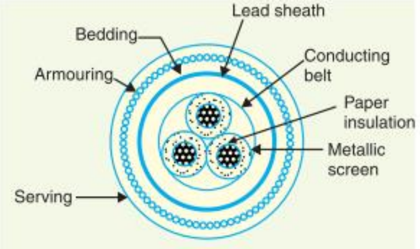


Fig. 11.4

(ii) **S.L. type cables.**

Fig. 11.5 shows the constructional details of a 3-core *S.L. (separate lead) type cable. It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over H-type cables. Firstly, the separate sheaths minimise the possibility of core-to-core breakdown. Secondly, bending of cables becomes easy due to the elimination of overall lead sheath. However, the disadvantage is that the three lead sheaths of S.L. cable are much thinner than the single sheath of H-cable and, therefore, call for greater care in manufacture.

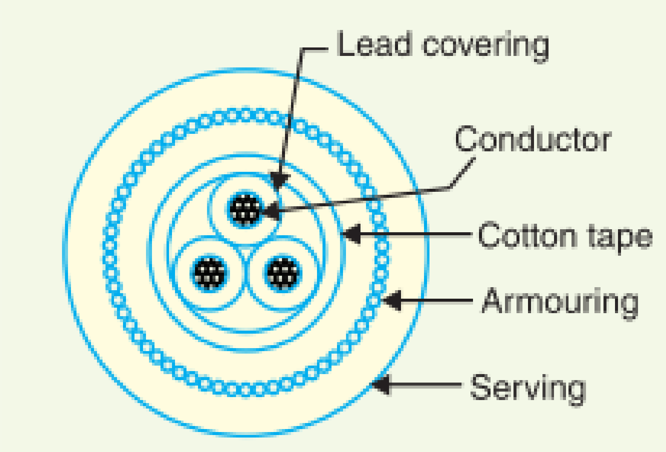


Fig. 11.5

Limitations of solid type cables.

All the cables of above construction are referred to as solid type cables because solid insulation is used and no gas or oil circulates in the cable sheath. The voltage limit for solid type cables is 66 kV due to the following reasons :

(a) As a solid cable carries the load, its conductor temperature increases and the cable compound (i.e., insulating compound over paper) expands. This action stretches the lead sheath which may be damaged.

(b) When the load on the cable decreases, the conductor cools and a partial vacuum is formed within the cable sheath. If the pinholes are present in the lead sheath, moist air may be drawn into the cable. The moisture reduces the dielectric strength of insulation and may eventually cause the breakdown of the cable.

(c) In practice, †voids are always present in the insulation of a cable. Modern techniques of manufacturing have resulted in void free cables. However, under operating conditions, the voids are formed as a result of the differential expansion and contraction of the sheath and impregnated compound. The breakdown strength of voids is considerably less than that of the insulation. If the void is small enough, the electrostatic stress across it may cause its breakdown. The voids nearest to the conductor are the first to break down, the chemical and thermal effects of ionisation causing permanent damage to the paper insulation.

3. Pressure cables

For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids. When the operating voltages are greater than 66 kV, pressure cables are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables viz oil-filled cables and gas pressure cables are commonly used.

(i) **Oil-filled cables.** In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the cable. Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers. Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV upto 230 kV. Oil-filled cables are of three types viz., single-core conductor channel, single-core sheath channel and three-core filler-space channels. Fig. 11.6 shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the centre by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation. The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir. However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel.

The disadvantage of this type of cable is that the channel is at the middle of the cable and is at full voltage w.r.t. earth, so that a very complicated system of joints is necessary. Fig. 11.7 shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown. In the 3-core oil-filler cable shown in Fig. 11.8, the oil ducts are located in the filler spaces. These channels are composed of perforated metal-ribbon tubing and are at earth potential.

The oil-filled cables have three principal advantages. Firstly, formation of voids and ionisation are avoided. Secondly, allowable temperature range and dielectric strength are increased. Thirdly, if there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased. However, their major disadvantages are the high initial cost and complicated system of laying.

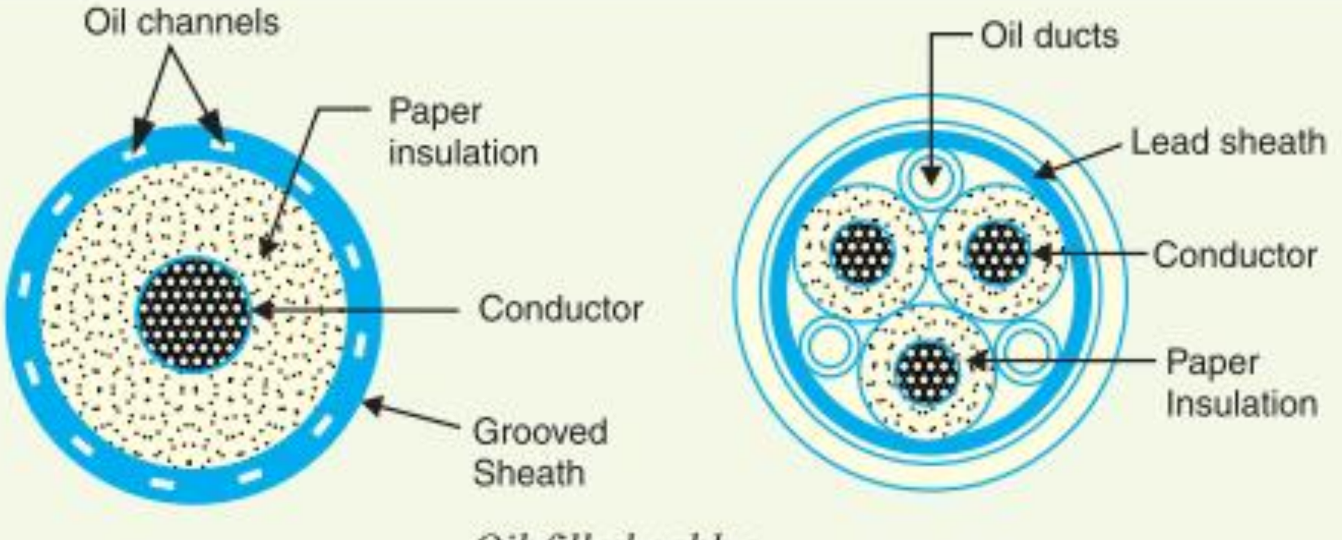


Fig. 11.7 *Oil-filled cables* **Fig. 11.8**

(ii) Gas pressure cables.

The voltage required to set up ionisation inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionisation can be altogether eliminated. At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables. Fig. 11.9 shows the section of external pressure cable designed by Hochstadter, Vogal and Bowden. The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable. The triangular section reduces the weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane. The sheath is protected by a thin metal tape. The cable is laid in a gas-tight steel pipe. The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres. The gas pressure produces radial compression and closes the voids that may have formed between the layers of paper insulation. Such cables can carry more load current and operate at higher voltages than a normal cable. Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. However, it has the disadvantage that the overall cost is very high

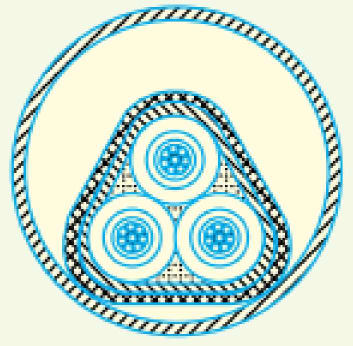


Fig. 11.9

Laying of Underground Cables

The reliability of underground cable network depends to a considerable extent upon the proper laying and attachment of fittings i.e., cable end boxes, joints, branch connectors etc. There are three main methods of laying underground cables viz., **direct laying**, **draw-in system** and the **solid system**.

1. Direct laying.

This method of laying underground cables is simple and cheap and is much favoured in modern practice. In this method, a trench of about 1·5 metres deep and 45 cm wide is dug. The trench is covered with a layer of fine sand (of about 10 cm thickness) and the cable is laid over this sand bed. The sand prevents the entry of moisture from the ground and thus protects the cable from decay. After the cable has been laid in the trench, it is covered with another layer of sand of about 10 cm thickness.

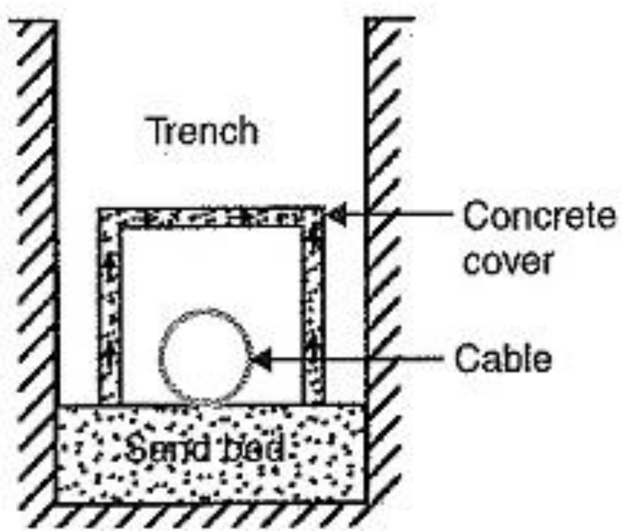
The trench is then covered with bricks and other materials in order to protect the cable from mechanical injury. When more than one cable is to be laid in the same trench, a horizontal or vertical interaxial spacing of atleast 30 cm is provided in order to reduce the effect of mutual heating and also to ensure that a fault occurring on one cable does not damage the adjacent cable. Cables to be laid in this way must have serving of bituminised paper and hessian tape so as to provide protection against corrosion and electorlysis.

Advantages

(i) It is a simple and less costly method.
(ii) It gives the best conditions for dissipating the heat generated in the cables.
(iii) It is a clean and safe method as the cable is invisible and free from external disturbances.

Disadvantages

(i) The extension of load is possible only by a completely new excavation which may cost as much as the original work.
(ii) The alterations in the cable network cannot be made easily.
(iii) The maintenance cost is very high.
(iv) Localization of fault is difficult.
(v) It cannot be used in congested areas where excavation is expensive and inconvenient.



Draw In System

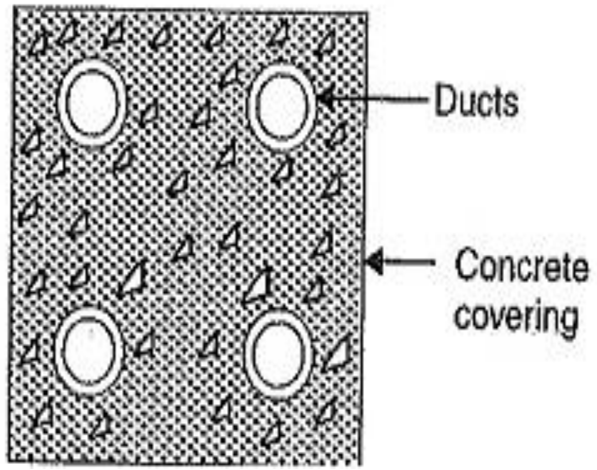
- In congested Area direct system is unfeasible.
- In this system single or multiple pipes will be used at under ground and the cable will be puled inside it.
- Man hole will be used at intermediate location which makes the maintenance easy.
- Features of the systems:-
  - Separate pipes or duct will be used.
  - This system is suitable only for the short route or crossing like highway, railway, city area etc.
  - The cable will be used of sufficient strength due to underground pull.

Advantages

Repairs, alterations or additions to the cable network can be made without opening the ground surface.

As the cables are not armoured, therefore, joints become simpler and maintenance cost is reduced considerably.

There are very less chances of fault occurrence due to strong mechanical protection provided by the system.



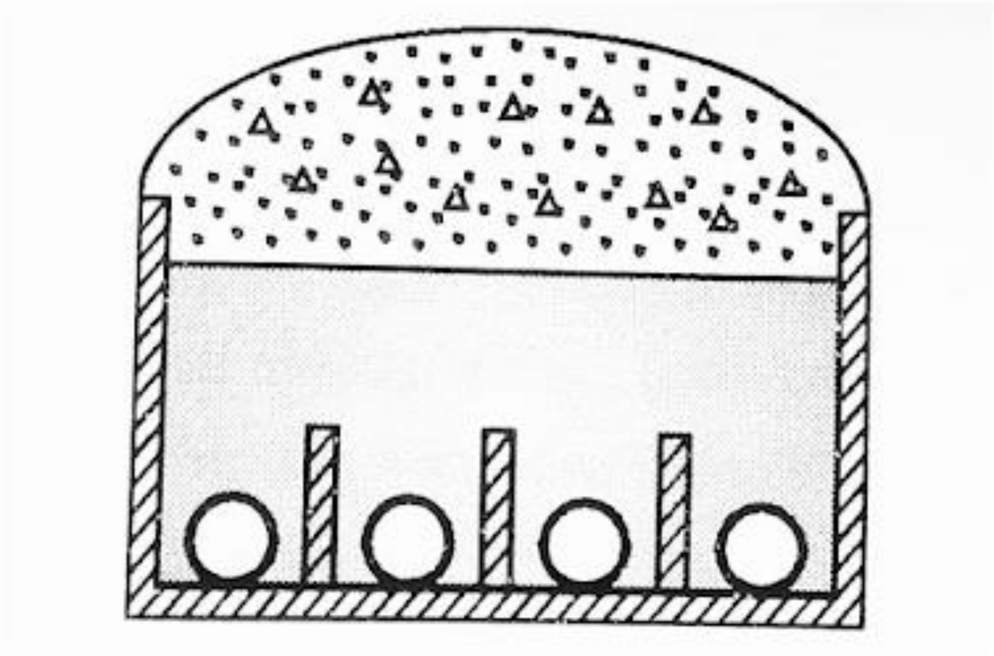
Disadvantages

The initial cost is very high.

The current carrying capacity of the cables is reduced due to the close grouping of cables and unfavorable conditions for dissipation of heat.

Solid system:

In this method of laying, the cable is laid in open pipes or troughs dug out in earth along the cable mule. The troughing is of cast iron, stoneware, asphalt or treated wood. After the cable is laid in position, the troughing is filled with a bituminous or asphaltic compound and covered over. Cables laid in this manner an usually plain lead covered because troughing affords good mechanical protection.



Solid System Method

<u>Disadvantages</u>

It is more expensive than direct laid system.

It requires skilled labour and favourable weather conditions.

Due to poor heat dissipation facilities, the current carrying capacity of the cable is reduced.

In view of these disadvantages, this method of Laying of Underground Cables is rarely used now-a-days.

Capacitance of a Single-Core Cable

A single-core cable can be considered to be equivalent to two long co-axial cylinders. The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential. Consider a single core cable with conductor diameter d and inner sheath diameter D (Fig. 11.13). Let the charge per metre axial length of the cable be Q coulombs and ε be the permittivity of the insulation material between core and lead sheath. Obviously *$\varepsilon = \varepsilon_0\ \varepsilon_r$ where εr is the relative permittivity of the insulation. Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is = 2 π x × 1 = 2 π x m^2.

Electric flux density at any point P on the considered cylinder is

Dx = Q 2 π x C/m2

Electric intensity at point P, Ex = Dx ε = Q 2 π ε x = Q x r 2 0 π εε volts/m

The work done in moving a unit positive charge from point P through a distance dx in the direction of electric field is Ex dx. Hence, the work done in moving a unit positive charge from conductor to sheath, which is the potential difference V between conductor and sheath, is given by :

$$V = \int_{d/2}^{D/2} E_x\,dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r}\,dx = \frac{Q}{2\pi\varepsilon_0\,\varepsilon_r}\log_e\frac{D}{d}$$

Capacitance of the cable is

$$C = \frac{Q}{V} = \frac{Q}{\dfrac{Q}{2\pi\,\varepsilon_0\varepsilon_r}\log_e\dfrac{D}{d}} \text{ F/m}$$

$$= \frac{2\pi\,\varepsilon_o\varepsilon_r}{\log_e(D/d)} \text{ F/m}$$

$$= \frac{2\pi \times 8\cdot854 \times 10^{-12} \times \varepsilon_r}{2\cdot303\,\log_{10}(D/d)} \text{ F/m}$$

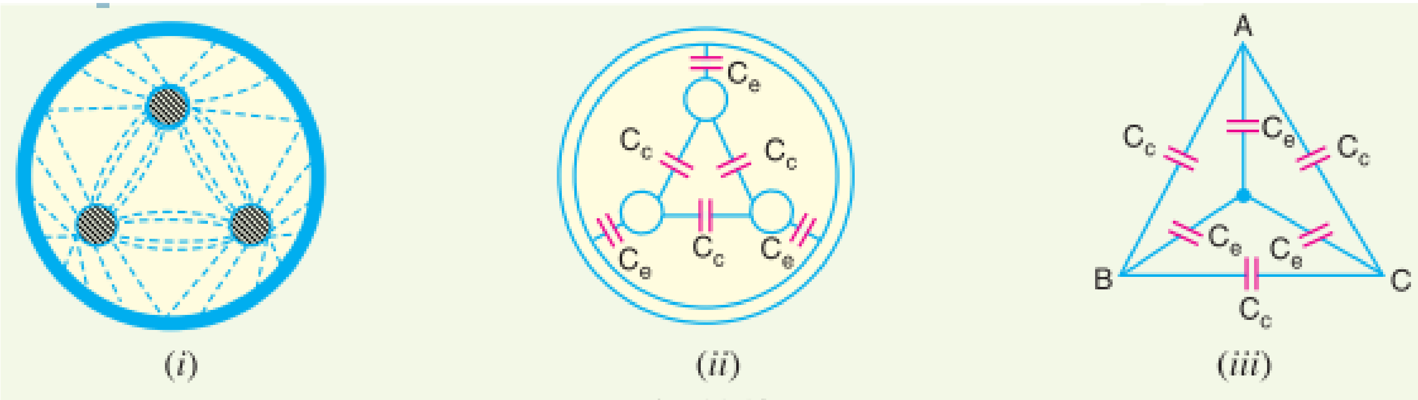
$$= \frac{\varepsilon_r}{41\cdot4\,\log_{10}(D/d)} \times 10^{-9} \text{ F/m}$$

If the cable has a length of l metres, then capacitance of the cable is

$$C = \frac{\varepsilon_r\ l}{41\cdot4\,\log_{10}\dfrac{D}{d}} \times 10^{-9} \text{ F}$$

Capacitance of 3-Core Cables

The capacitance of a cable system is much more important than that of overhead line because in cables (i) conductors are nearer to each other and to the earthed sheath (ii) they are separated by a dielectric of permittivity much greater than that of air. Fig. 11.18 shows a system of capacitances in a 3-core belted cable used for 3-phase system. Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig. 11.18 (i). These electrostatic fields give rise to core-core capacitances Cc and conductor-earth capacitances Ce as shown in Fig. 11.18 (ii). The three Cc are delta connected whereas the three Ce are star connected, the sheath forming the star point [See Fig. 11.18 (iii)].



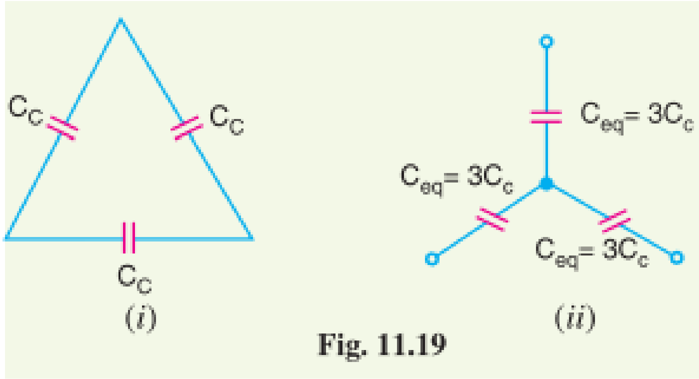


Fig. 11.19

They lay of a belted cable makes it reasonable to assume equality of each Cc and each Ce . The three delta connected capacitances Cc [See Fig. 11.19 (i)] can be converted into equivalent star connected capacitances as shown in Fig. 11.19 (ii). It can be easily *shown that equivalent star capacitance Ceq is equal to three times the delta capacitance Cc i.e. Ceq = 3Cc .

The system of capacitances shown in Fig. 11.18 (iii) reduces to the equivalent circuit shown in Fig. 11.20 (i). Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance [See Fig. 11.20 (ii)],

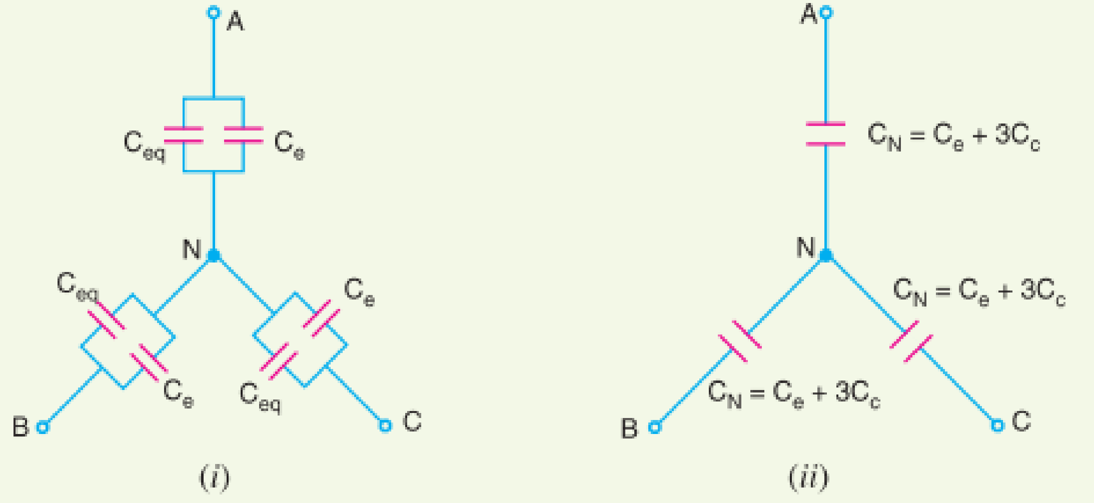


Fig. 11.20

$$C_N = C_e + C_{eq}$$
$$= C_e + 3C_c$$

If V_{ph} is the phase voltage, then charging current I_C is given by ;

$$I_C = \frac{V_{ph}}{\text{Capacitive reactance per phase}}$$
$$= 2\,\pi f\, V_{ph}\, C_N$$
$$= 2\,\pi f\, V_{ph}\,(C_e + 3C_c)$$

Measurements of Ce and Cc

Although core-core capacitance Cc and core-earth capacitance Ce can be obtained from the empirical formulas for belted cables, their values can also be determined by measurements. For this purpose, the following two measurements are required :

(i) In the first measurement, the three cores are bunched together (i.e. commoned) and the capacitance is measured between the bunched cores and the sheath. The bunching eliminates all the three capacitors Cc, leaving the three capacitors Ce in parallel. Therefore, if C1 is the measured capacitance, this test yields :

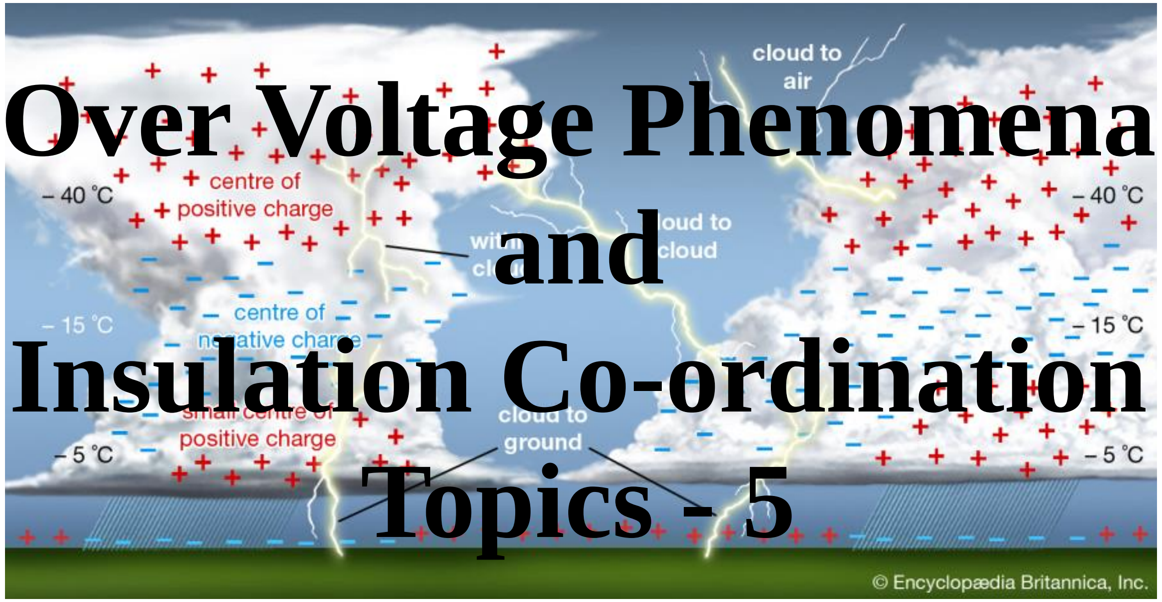
C1 = 3 Ce or Ce = C1 / 3. Knowing the value of C1, the value of Ce can be determined.

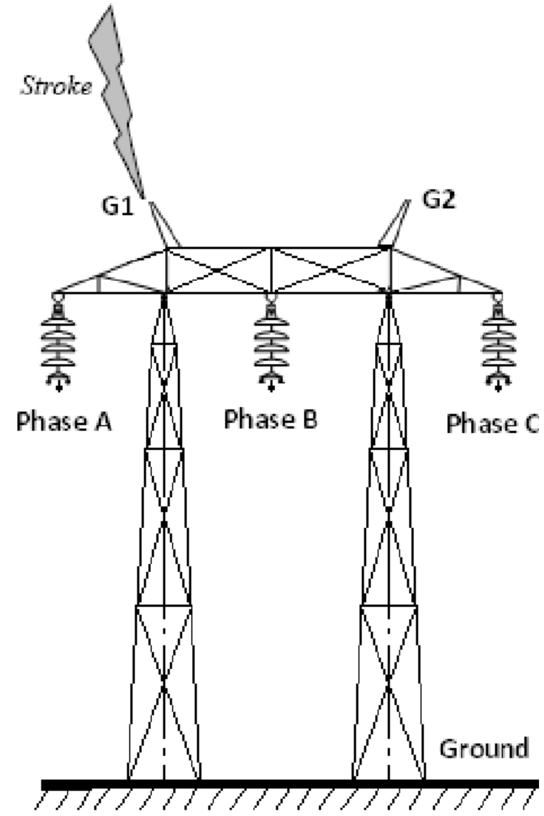
(ii) In the second measurement, two cores are bunched with the sheath and capacitance is measured between them and the third core. This test yields 2Cc + Ce. If C2 is the measured capacitance, then,

C2 = 2Cc + Ce As the value of Ce is known from first test and C2 is found experminentally, therefore, value of Cc can be determined. It may be noted here that if value of CN (= Ce + 3Cc) is desired, it can be found directly by another test. In this test, the capacitance between two cores or lines is measured with the third core free or connected to the sheath. This eliminates one of the capacitors Ce so that if C3 is the measured capacitance, then,

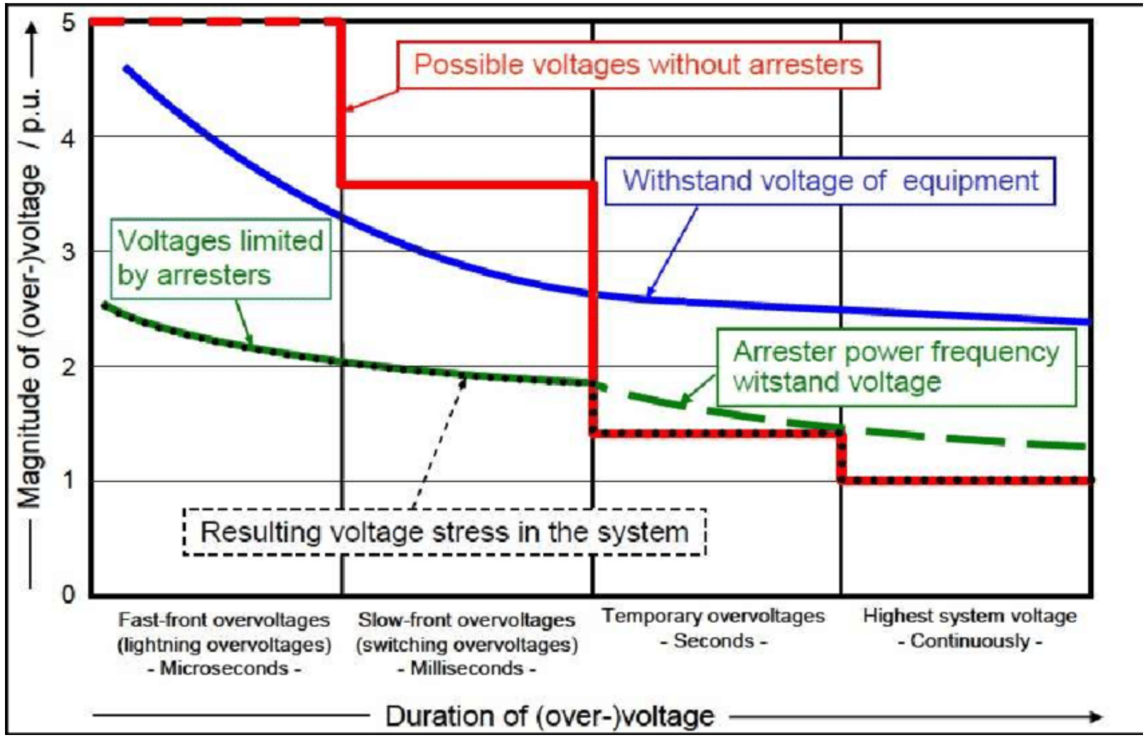
$$\begin{aligned} C_3 &= C_c + \frac{C_c}{2} + \frac{C_e}{2} \\ &= \frac{1}{2}(C_e + 3C_c) \\ &= \frac{1}{2} C_N \end{aligned}$$

Over Voltage Phenomena
and
Insulation Co-ordination
Topics - 5





)0 kV transmission line tower



Over Voltage Phenomena and Insulation Co-ordination

Overvoltage due to Lighting and Switching Surges

Power Frequency Overvoltage

Insulation Co-ordination

Necessity of Insulation Co-ordination

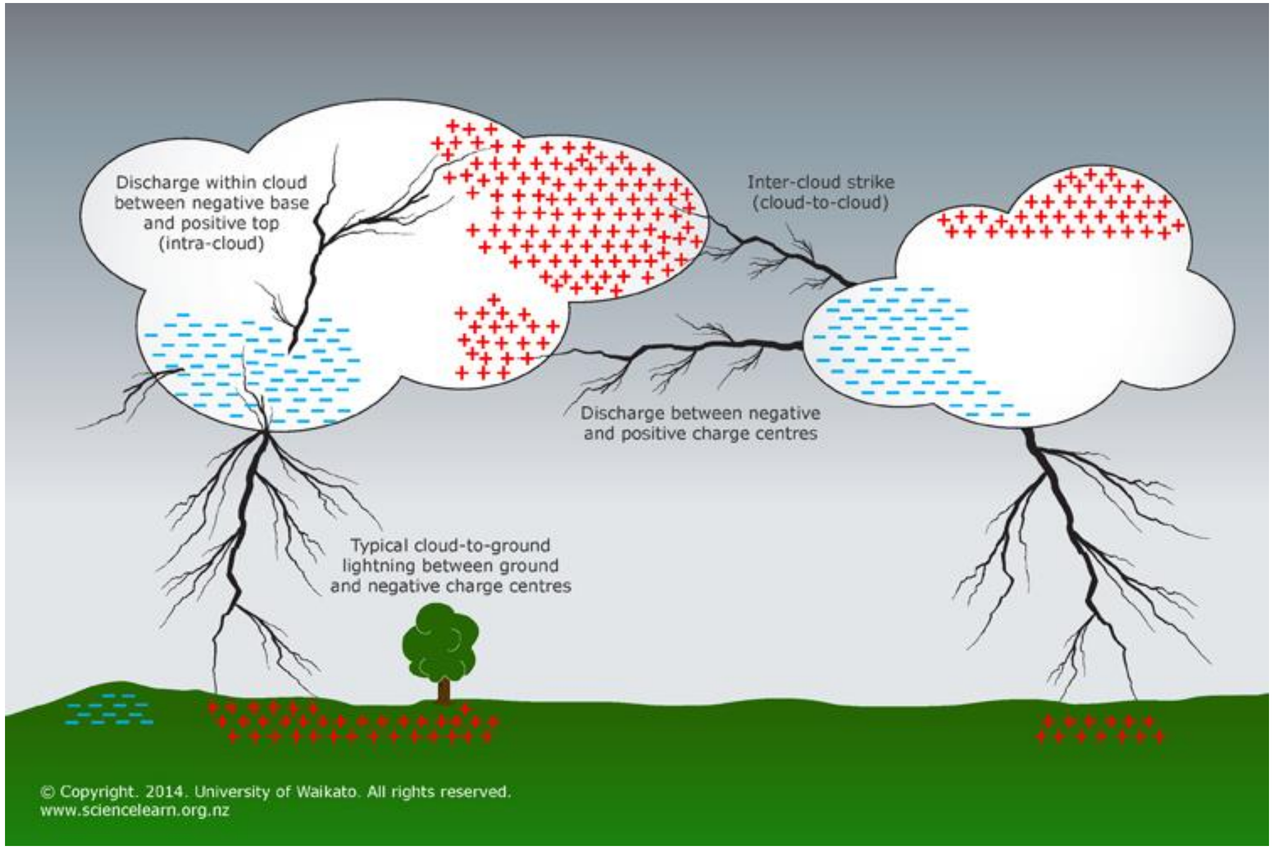
Equipment Insulation level

Insulation Co-ordination and volt-time characteristics

Standards for Insulation Co-ordination: IEC 71

Insulation Co-ordination in EHV and UHV systems

Surge arrestor sizing



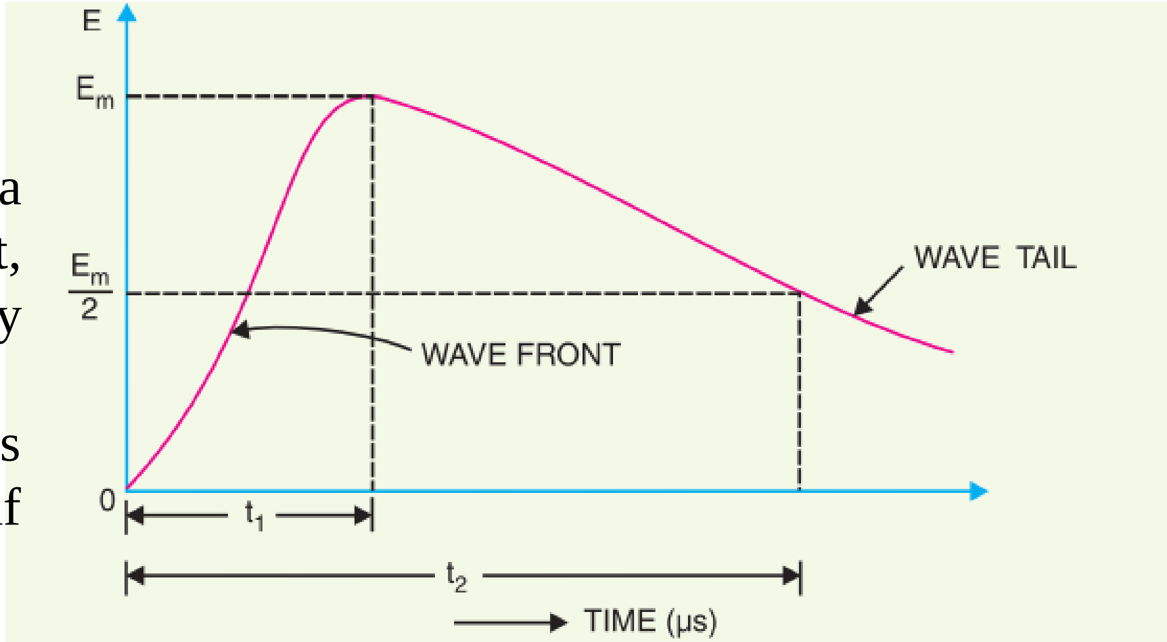
Overvoltage due to Lighting and Switching Surges

- There are several instances when the elements of a power system (e.g. generators, transformers, transmission lines, insulators etc.) are subjected to overvoltages i.e. voltages greater than the normal value.
- These overvoltages on the power system may be caused due to many reasons such as lightning, the opening of a circuit breaker, the grounding of a conductor etc.
- Most of the overvoltages are not of large magnitude but may still be important because of their effect on the performance of circuit interrupting equipment and protective devices. An appreciable number of these overvoltages are of sufficient magnitude to cause insulation breakdown of the equipment in the power system. Therefore, power system engineers always device ways and means to limit the magnitude of the overvoltages produced and to control their effects on the operating equipment.
- Here we shall confine our attention to the various causes of overvoltages on the power system with special emphasis on the protective devices used for the purpose.

Voltage Surge

- ❖ A sudden rise in voltage for a very short durastion on the power system is known as a voltage surge or transient voltage. Transients or surges are of temporary nature and exist for a very short duration (a few hundred μs) but they cause overvoltages on the power system.
- ❖ They originate from switching and from other causes but by far the most important transients are those caused by lightning striking a transmission line.
- ❖ When lightning strikes a line, the surge rushes along the line like flood of water damaging retaining wall of a reservoir at its head suddenly gives way.
- ❖ In most of the cases, such surges may cause the line insulators (near the point where lightning has struck) to flash over and may also damage the nearby transformers, generators or other equipment connected to the line if the equipment is not suitably protected.

- ✓ The wave-form of a typical lightning surge.
- ✓ It may be seen that lightning introduces a steep-fronted wave. The steeper the wave front, the more rapid is the build-up of voltage at any point in the network.
- ✓ Voltage surges are generally specified in terms of *rise time t1 and the time t 2 to decay to half of the peak value.



Causes of Overvoltages

The overvoltages on a power system may be broadly divided into two main categories viz.

1. Internal causes

(i) Switching surges
(ii) Insulation failure
(iii) Arcing ground
(iv) Resonance

2. External causes i.e. lightning Internal causes do not produce surges of large magnitude.

- The surges due to internal causes hardly increase the system voltage to twice the normal value.
- Surges due to internal causes are taken care of by providing proper insulation to the equipment in the power system.
- However, surges due to lightning are very severe and may increase the system voltage to several times the normal value. If the equipment in the power system is not protected against lightning surges, these surges may cause considerable damage. In fact, in a power system, the protective devices provided against overvoltages mainly take care of lightning surges.

Internal Causes of Overvoltages

- ❖ Internal causes of overvoltages on the power system are primarily due to oscillations set up by the sudden changes in the circuit conditions. This circuit change may be a normal switching operation such as opening of a circuit breaker, or it may be the fault condition such as grounding of a line conductor.
- ❖ In practice, the normal system insulation is suitably designed to withstand such surges.

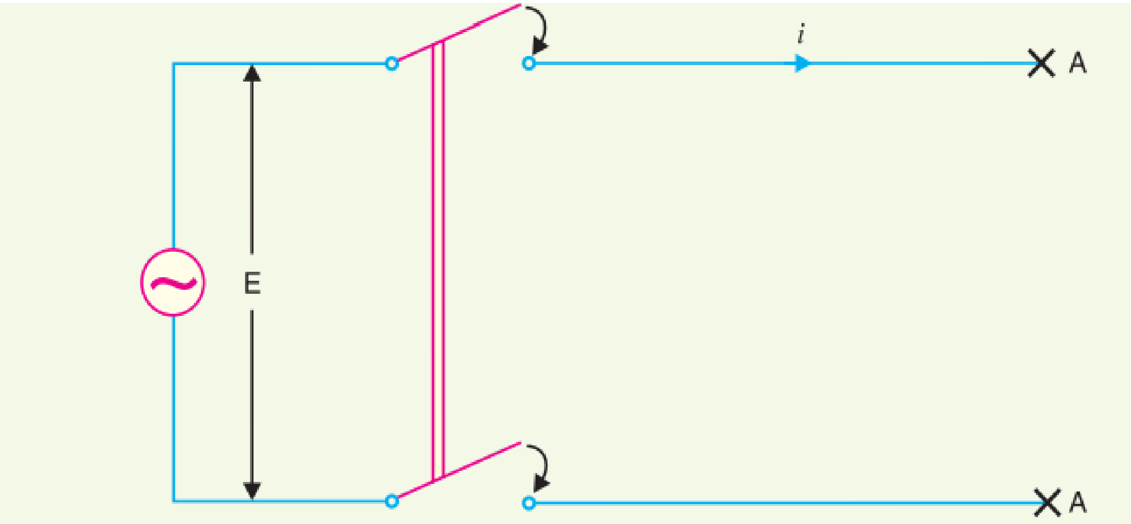
1. Switching Surges.

The overvoltages produced on the power system due to switching operations are known as switching surges.

A few cases will be discussed by way of illustration :

(i) Case of an open line. During switching operations of an unloaded line, travelling waves are set up which produce overvoltages on the line. As an illustration, consider an unloaded line being connected to a voltage source as shown in Fig.

When the unloaded line is connected to the voltage source, a voltage wave is set up which travels along the line. On reaching the terminal point A, it is reflected back to the supply end without change of sign. This causes voltage doubling i.e. voltage on the line becomes twice the normal value. If Er.m.s. is the supply voltage, then instantaneous voltage which the line will have to withstand will be $2\sqrt{2}$ E .



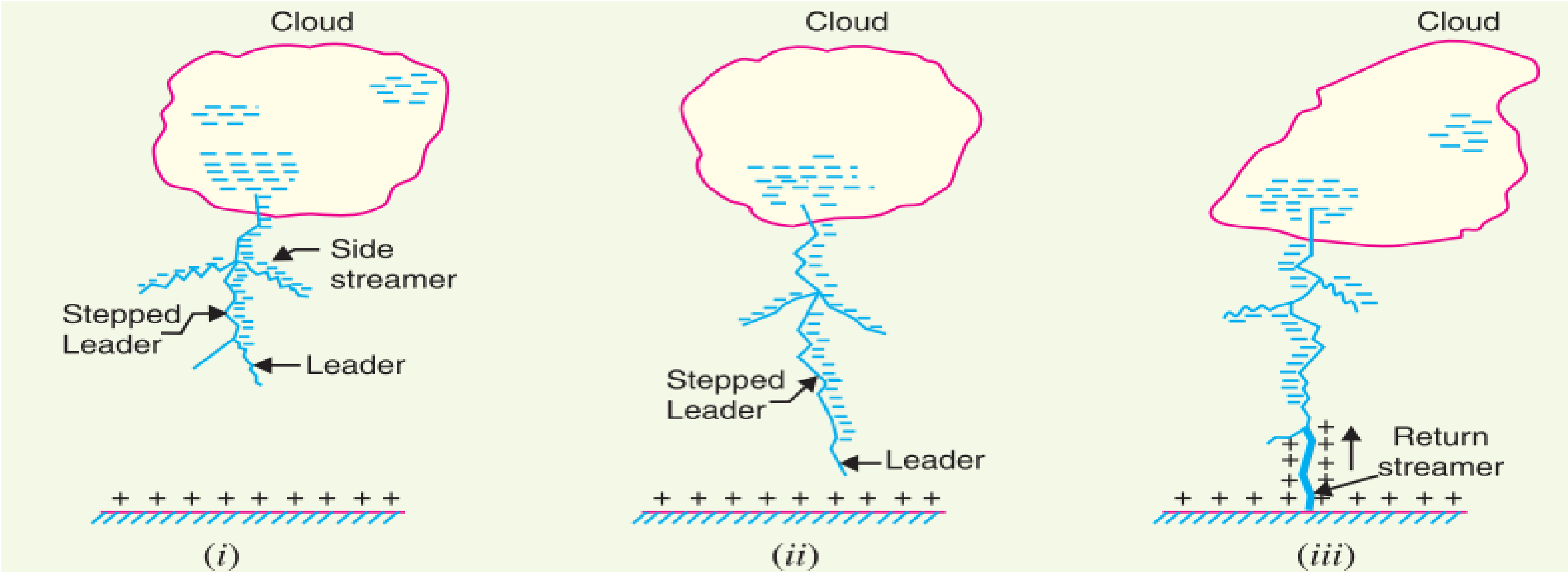
This overvoltage is of temporary nature. It is because the line losses attenuate the wave and in a very short time, the line settles down to its normal supply voltage E. Similarly, if an unloaded line is switched off, the line will attain a voltage of 2 √2 E for a moment before settling down to the normal value.

Case of a loaded line.

Overvoltages will also be produced during the switching operations of a loaded line. Suppose a loaded line is suddenly interrupted. This will set up a voltage of 2 Zn i across the break (i.e. switch) where i is the instantaneous value of current at the time of opening of line and *Zn is the natural impedance of the line. For example, suppose the line having Zn = 1000 Ω carries a current of 100 A (r.m.s.) and the break occurs at the moment when current is maximum. The voltage across the breaker (i.e. switch) = 2 X√2 X 100 X 1000/1000 = 282·8 kV. If V m is the peak value of voltage in kV, the maximum voltage to which the line may be subjected is = (V m + 282·8) kV.

Lightning

- An electric discharge between cloud and earth, between clouds or between the charge centres of the same cloud is known as lightning.
- Lightning is a huge spark and takes place when clouds are charged to such a high potential (+ve or −ve) with respect to earth or a neighbouring cloud that the dielectric strength of neighbouring medium (air) is destroyed. There are several theories which exist to explain how the clouds acquire charge. The most accepted one is that during the uprush of warm moist air from earth, the friction



Why Lightning Study Needed?

It is essential for electrical power engineers to reduce the number of outages and preserve the continuity of service and electric supply. Therefore, it is necessary to direct special attention towards the protection of transmission lines and power apparatus from the chief causes of overvoltages in electric systems, namely **lightning overvoltages and switching overvoltages**. Lightining overvoltage is a natural phenomenon, while switching overvoltages originate in the system itself by the connection and disconnection of circuit breaker contacts or due to initiation or interruption of faults. Switching overvoltages are highly damped short duration overvoltages. They are "temporary overvoltages" of power frequency or its harmonic frequency either sustained or weakly damped and originate in switching and fault clearing processes in power systems. Although both switching and power frequency over voltages have no common origin, they may occur together, and their combined effect is important in insulation design. Probability of lightning and switching overvoltages coinciding together is very small and hence can be neglected. The magnitude of lightning voltages appearing on transmission lines does not depend on line design and hence lightning performance tends to improve with increasing insulation level, that is with system voltage. On the other hand, switching overvoltages are proportional to operating voltage. Hence, there is a system operating voltage at which the emphasis changes from lightning.to switching surge design, this being important above 500 kV. In the range of 300 kV to 765 kV; both switching overvoltages and lightning overvoltages have to be considered, while for ultra high voltages (> 700 kV), perhaps switching surges may be the chief condition for design considerations.

For the study of overvoltages a basic knowledge of the origin of overvoltages, surge phenomenon, and its propagation is desirable. The present chapter is therefore devoted to a summary of the above topics.

NATURAL CAUSES FOR OVERVOLTAGES - LIGHTNING PHENOMENON

Lightning phenomenon is a peak discharge in which charge accumulated in the clouds discharges into a neighbouring cloud or to the ground. The electrode separation, i.e. cloud-to-cloud or cloud-to-ground is very large, perhaps 10 km or more. The mechanism of charge formation in the clouds and their discharges is quite a complicated and uncertain process. Nevertheless, a lot of information has been collected since the last fifty years and several theories have been put forth for explaining the phenomenon. A summary of the various processes and theories is presented in this section.

Mechanism of Lightning Strokes

When the electric field intensity at some point in the charge concentrated cloud exceeds the breakdown value of the moist ionized air (• 10 kV/cm), an electric streamer with plasma starts towards the ground with a velocity of about 1/10 times that of the light, but may progress only about 50 m or so before it comes to a halt emitting a bright flash of light. The halt may be due to insufficient build-up of electric charge at its head and not sufficient to maintain the necessary field gradient for further progress of the streamer. But after a short interval of about 100μs, the streamer again starts out repeating its performance. The total time required for such a stepped leader to reach the ground may be 20 ms. The path may be quite lustrous, depending on the local conditions in air as well as the electric field gradients. Branches from the initial leader may also be Conned. Since the progress of this leader stroke is by a series of jumps, it is referred as stepped leader. The picture of a typical leader stroke taken with a Boy's camera is shown in Fig. 8.3.

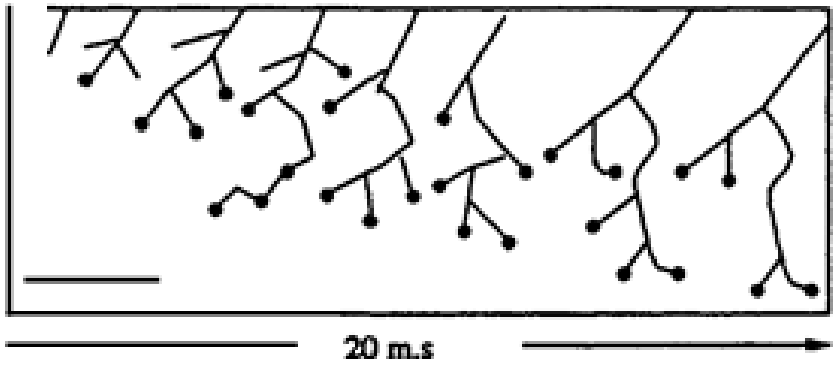


Fig. Propagation of a stepped leader stroke from a cloud
(• Brighttips recorded)

The lightning stroke and the electrical discharges due to lightning are explained based on the "streamer" or "kanel" theory for spark discharges in long gaps with non-unifonn electric fields. The lightning consists of few separate discharges starting from a leader discharge and culminates in return strokes or main discharges. The velocity of the leader stroke of the first discharge may be 1.5 x 10^7 cm/s, of the succeeding leader strokes about 108 cm/s, and of the return strokes may be 1.5 *x* W^9 to 1.5 x 10^{10} cm/s (about 0.05 to 0.5 times the velocity of light).

After the leader touches the ground. the return stroke follows. As the leader moves towards the ground. positive charge is directly accumulated under the head of the stroke or canal. By the time the stroke reaches the ground or comes sufficiently near the ground. the electrical field intensity on the ground side is sufficiently large to build up the path. Hence. the positive charge returns to the cloud neutralizing the negative charge. and hence a heavy current flows through the path. The velocity of the return or main stroke ranges from 0.05 to 0.5 times the velocity of light. and currents will be of the order of 1000 to 250.000 A. The return strokes vanish before they reached the cloud. suggesting that the charge involved is that conferred to the stroke itself. The duration of the main or return stroke is about 100 µs or more. The diameters of the return strokes were estimated to be about I to 2 cm but the corona envelop may be approximately 50 cm. The return strokes also may develop branches but the charges in the branches are neutralized in succession so that their further progress is arrested. A Boy'scamera picture of return stroke is shown in Fig.

Fig. ` | Development of the main or return stroke

Parameters and Characteristics of the Lightning Strokes

The parameters and characteristics of lightning include the amplitude of the currents, the rate of rise, the probability distribution of the above, and the wave shapes of the lightning voltages and currents.

Typical oscillograms of the lightning current and voltage waveshapes on a transmission line are shown in Figs. 8.11 and

8.12. The lightning current oscillograms indicate an initial high current portion which is characterized by short front times up to 10μs.The high current peak may last for some tens of microseconds followed by a long duration low current portion lasting for several milliseconds. This last portion is normally responsible for damages (thermal damage). Lightning currents are usually measured either directly from high towers or buildings or from the transmission tower legs. The former gives high values and does not represent typical currents that occur on electrical transmission lines, and the latter gives inaccurate values due to non-uniform division of current in legs and the presence of ground wires and adjacent towers. Measurements made by several investigators and committees indicated the large strokes of currents (> 100 kA) are possible (Fig. 8.7). It was shown earlier that tall objects attract a large portion of high current strokes, and this would explain the shift of the frequency distribution curves towards higher currents.

Other important characteristics are time to peak value and its rate of rise. From the field data, it was indicated that 50% of lightning stroke currents have a rate of rise greater than 7.5 kA/μ s, and for 10% strokes it exceeded 25 kA/μ s. The duration of the stroke currents above half the value is more than 30 μs.

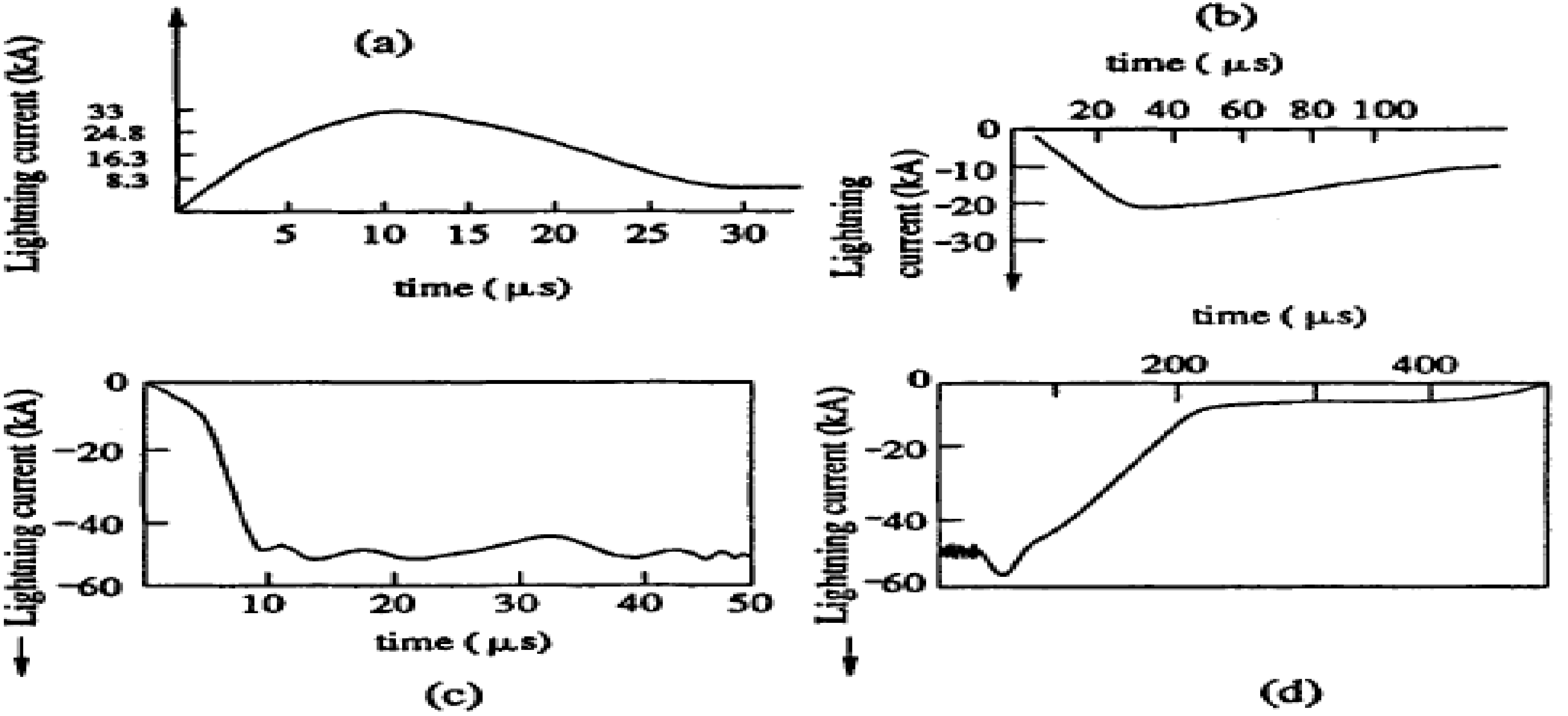


Fig. 8.11 Typical lightning current oscillograms

(a) to a capacitive balloon (CIGRE)
(b) on Empire State Building (McEachron)
(c) and (d) on transmission line tower (Berger)
ref: Westinghouse T and D reference book

OVERVOLTAGE DUE TO SWITCHING SURGES, SYSTEM FAULTS AND OTHER ABNORMAL CONDITIONS

Till the time when the transmission voltages were about 220 kV and below, over voltages due to lightning were of very high order and over voltages generated inside lhe system were not of much consequence. In later years, with increase in transmission voltages, (400 kV and above) the overvoltages generated inside the system reached the same order of magnitude as those of lightning over voltages, or higher. Secondly, the overvoltages thus generated last for longer durations and therefore are severe and more dangerous to the system. Unlike the lightning overvoltages, the switching and other types of overvoltages depend on the normal voltage of the system and hence increase with increased system voltage. In insulation co-ordination, where the protective level of any particular kind of surge diverter is proportional to the maxim um voltage, the insulation level and the cost of the equipment depends on the magnitudes of these ovcr vollages. In the EHV range, it is the switching surge and other types of overvoltages that determine the insulation level of the lines and other equipment and consequenlty, they also determine their dimensions and costs.

Origin of Switching Surges

The making and breaking of electric circuits with switchgear may result in abnormal overvoltages in power systems having large inductances and capacitances. The overvoltages may go as high as six times the normal power frequency voltage. In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated restriking of the arc between *the* contacts of a circuit breaker, thereby causing destruction of the circuit breaker contacts. The switching surges may include high natural frequencies of the system, a damped normal frequency voltage component, or the restriking and recovery voltage of the system with successive reflected waves from terminations.

Characteristics of Switching Surges

The waveshapes of switching surges are quite different and may have origin from any of the following sources.

i) De-energizing of transmission lines, cables, shunt capacitor, banks, etc.

(ii) Disconnection of unloaded transformers, reactors, etc.

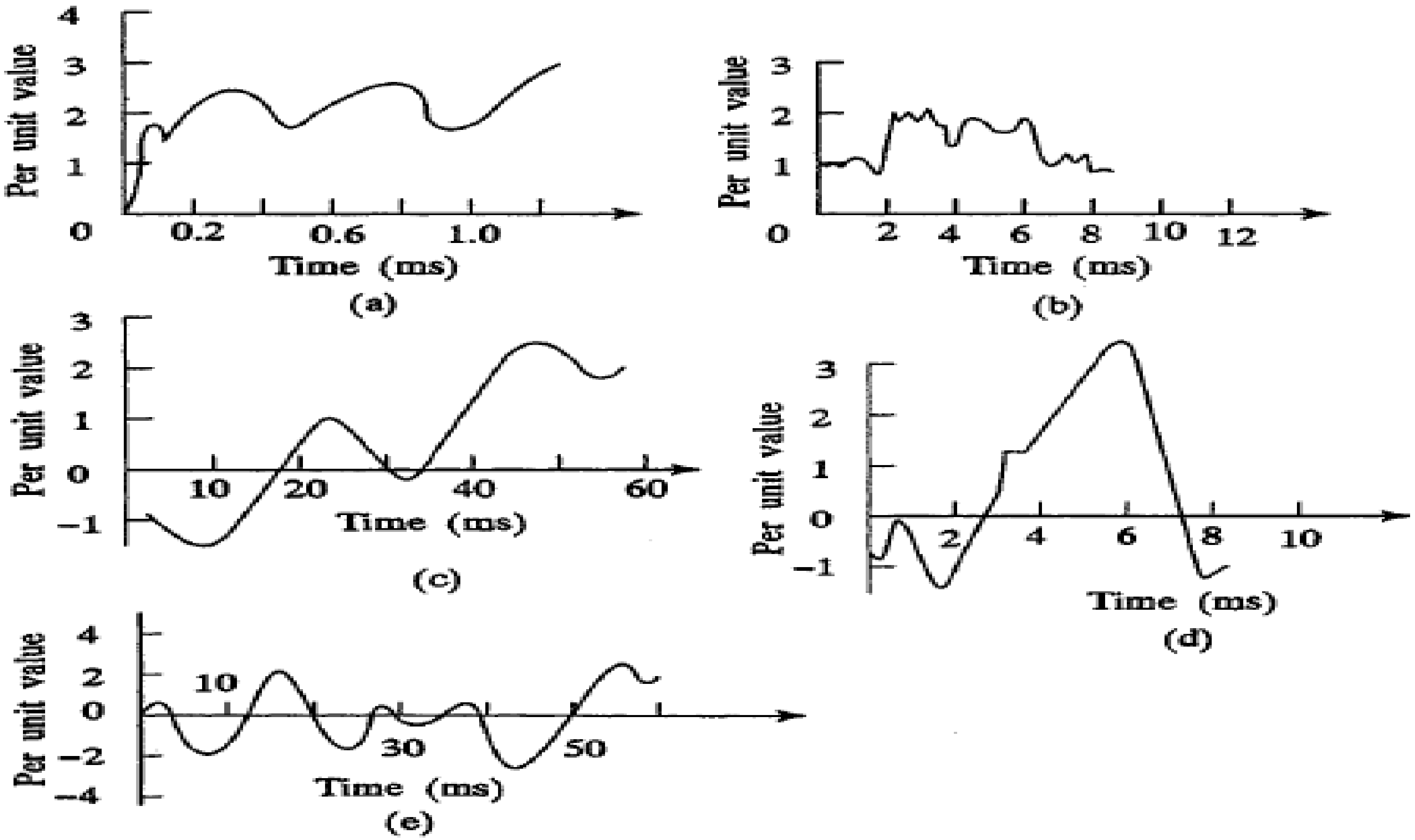
(iii) Energization or reclosing of lines and reactive loads.

(iv) Sudden switching off of loads.

(v) Short circuits and fault clearances.

(vi) Resonance phenomenon like ferro-resonance, arcing grounds, etc. Typical waveshapes of the switching surges are given in Figs. 8.16a to (e).

From the figures of the switching surges it is clear that the overvoltages are irregular (oscillatory or unipolar) and can be of high frequency or power frequency with its harmonics. The relative magnitudes of the overvoltages may be about 2.4 p.u. in the case of transformer energizing and 1.4 to 2.0 p.u. in switching transmission lines.



(a) Recovery voltage after fault clearing
(b) Fault initiation
(c) Overvoltage at the line end after fault clearing
(d) Energization of long transmission line
(e) Overvoltage at line end during (d)

Fig. 8.16 Typical waveshapes of switching surge voltages

Energization of long EHV or UHV lines.

Transient overvoltages in the above cases can be of iite order of 2.0 to 3.3 p.u. and will have magnitudes of the order of 1200 kV to 2000 kV on 750 kV systems. The duration of these overvoltages varies from 1 to 10 ms depending on the circuit parameters. It is seen that these are of comparable magnitude or are even higher than those that occur due to lightning. Sometimes the overvoltages may last for several cycles. The other situations of switching that give rise to switching overvoltages of shorter duration (0.5 to 5 ms) and lower magnitudes (2.0 to 2.5 p.u.) are:

(a) single pole closing of circuit breaker

(b) interruption of fault current when the L-G or L-L fault is cleared

resistance switching used in circuit breakers

switching lines terminated by transformers

series capacitor compensated lines

(f) sparking of the surge diverter located at the receiving end of the line to limit the lightning overvoltages.

It is necessary in EHV and UHV systems to control the switching surges to a safe value of less than 2.5 p.u. or preferably to 2.0 p.u. or even less. The measures taken to control or reduce the overvoltages are

(i) one step or multi-step energisation of lines by preinsertion of resistors,

(ii) phase controlled closing of circuit breakers with proper sensors,

(iii) drainage of trapped charges on long lines before the rcclosing of the lines, and

(iv) limiting the overvoltages by using surge diverters.

The first three methods, if used properly will limit the switching overvoltages to 1.5 to 2.0 p.u.

In Table 8.1,a summary of the extent of overvoltages that can be developed under various conditions of switching is given.

Table 8.1 Overvoltages due to Switching Operations Under Different Conditions

Maximum value of the system line-to-ground voltage = 1.0 p.u.

Sl. no.		Type of operation	Overvoltage (p.u.)
1		Switching an open ended line with:	
	(a)	infinite bus as source with trapped charges on line	4.1
	(b)	infinite bus as source without trapped charges	2.6
	(c)	de-energising an unfaulted line with a restrike in the circuit breaker	2.7
	(d)	de-energising an unfaulted line with a line to ground fault (about 270 km in length)	1.3
2	(a)	switching a 500 kV line through an auto-transformer, 220 kV/500 from the L.V. side	2.0
	(b)	switching a transformer terminated line	2.2
	(c)	series capacitor compensated line with 50% compensation	2.2
	(d)	series capacitor compensated line with shunt reactor compensation	2.6
3		High speed reclosing of line after fault clearance	3.6

Power Frequency Overvoltages In Power Systems

Thepower frequency ovcrvoltages occur in large power systems and they are of much concern in EHV systems, i.e. systems of 400 kV and above. The main causes for power frequency and its harmonic overvoltages are

(a) sudden loss of loads,

(b) disconnection of inductive loads or connection of capacitive loads,

(c) Ferranti effect. unsymmetrical faults, and

(d) saturation in transformers, etc.

Overvoltages of power frequency harmonics and voltages with frequencies nearer to the operating frequency are caused during tap changing operations, by magnetic or ferroresonance phenomenon in large power transformers, and by resonating over voltages due to series capacitors with shunt reactors or transformers.

The duration of these overvoltages may be from one to two cycles to a few seconds depending on the overvoltage protection employed.

Sudden Load Rejection

Sudden load rejection on large power systems causes the speeding up of generator prime movers. The speed governors and automatic voltage regulators will intervene to restore normal conditions. But initially both the frequency and voltage increase. The approximate voltage rise, neglecting losses. etc. may be taken as

$$v = \frac{f}{f_0} E' \left[\left(1 - \frac{f}{f_0} \right) \frac{x_s}{x_c} \right]$$

where *Xs* is the reactance of the generator (= the sum of the transient reactances of the generator and the transformer), *Xe* is the capacitive reactance of the line at open end at increased frequency, *E'* the voltage generated before the over-speeding and load rejection,/is the instantaneous increased frequency. and/o is the normal frequency.

This increase in voltage may go to as high as 2.0 per unit (p.u.) value with 400 kV lines. The voltage at the sending end is affected by the line length, short circuit MVA at sending end bus, and reactive power generation of the line (due to line capacitive reactance and any shunt or series capacitors). Shunt reactors may reduce the voltage to 1.2 to 1.4 p.u.

Ferranti Effect

Long uncompensated transmission lines exhibit voltage rise at the receiving end. The voltage rise al the receiving end *V2* is approximately given by

$$V_2 = \frac{V_1}{\cos \beta l}$$

where, V_1 = sending end voltage,

l = length of the line,

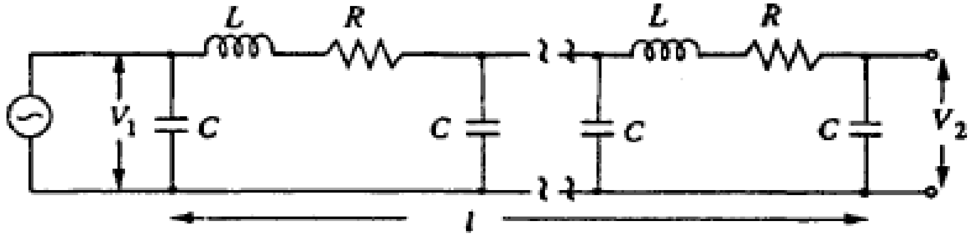
β = phase constant of the line

$$\approx \left[\frac{(R + j\omega L)(G + j\omega C)}{LC}\right]^{1/2}$$

$\approx$ about 6° per 100 km line at 50 Hz frequency.

R, L, G, and C are as defined in Sec. 8.1.5, and

ω = angular frequency for a line shown in Fig. 8.17.



L, R and C — Inductance, resistance and capacitance per unit length of the line

l — Length of the line

Fig. 8.17 Typical uncompensated long transmission line

Considering that the line capacitance is concentrated at the middle of the line, under open circuit conditions at the receiving end, the line charging current

$$I_C \approx j\omega C V_1 = \frac{V_1}{X_C}$$

and the voltage $V_2 \approx V_1 \left[1 - \frac{X_L}{2X_C}\right]$

where, X_L = line inductive reactance, and

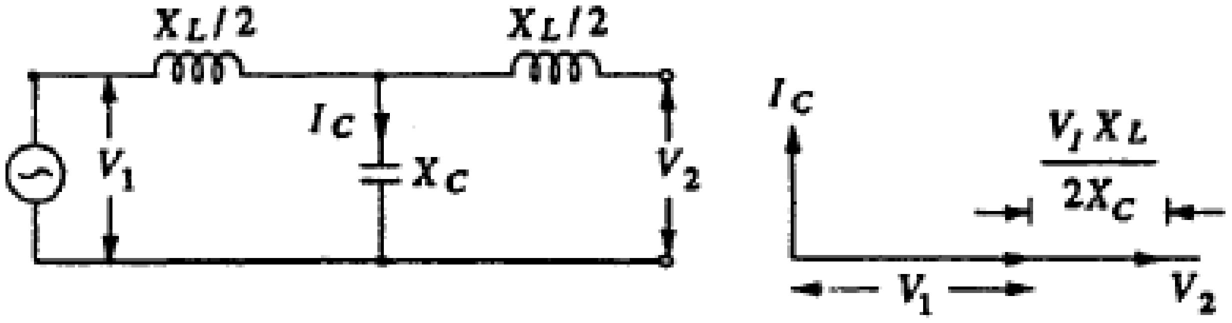
X_C = line capacitive reactance.

Ground Faults and Their Effects

Single line to ground faults cause rise in voltages in other healthy phases. Usually, with solidly grounded systems, the increases in voltage (phase to ground value) will be less than the line-to-line voltage. With effectively grounded systems, i.e. with

$$\frac{X_0}{X_1} \leq 3.0 \text{ and } \frac{R_0}{X_1} \leq 1.0$$

(where, *Ro* and Xo are zero sequence resistance and reactance and *X* 1 is the positive sequence reactance of the system), the rise in voltage of the healthy phases does not usually exceed 1.4 per unit.



Transmission line approximation for line in Fig. 8.17.

Fig. 8.18 Vector (phase) diagram of an open circuited uncompensated line showing Ferranti effect

Saturation Effects

When voltages above the rated value are applied to transformers, their magnetizing currents (no load currents also) increase rapidly and may be about the full rated current for 50% overvoltage. These magnetizing currents are not sinusoidal in nature but are of a peaky waveform. The third, fifth, and seventh harmonic contents may be 65%, 35%, and 25% of the exciting current of the fundamental frequency corresponding to an overvoltage of 1.2 p.u. For third and its multiple harmonics, zero sequence impedance values are effective, and delta connected windings suppress them. But the shunt connected capacitors and line capacitances can form resonant circuits and cause high third harmonic overvoltages. When such overvoltages are added, the voltage rise in the lines may be significant. For higher harmonics a series resonance between the transformer inductance and the line capacitance can occur which may produce even higher voltages.

Protection of Transmission Lines against Overvoltages

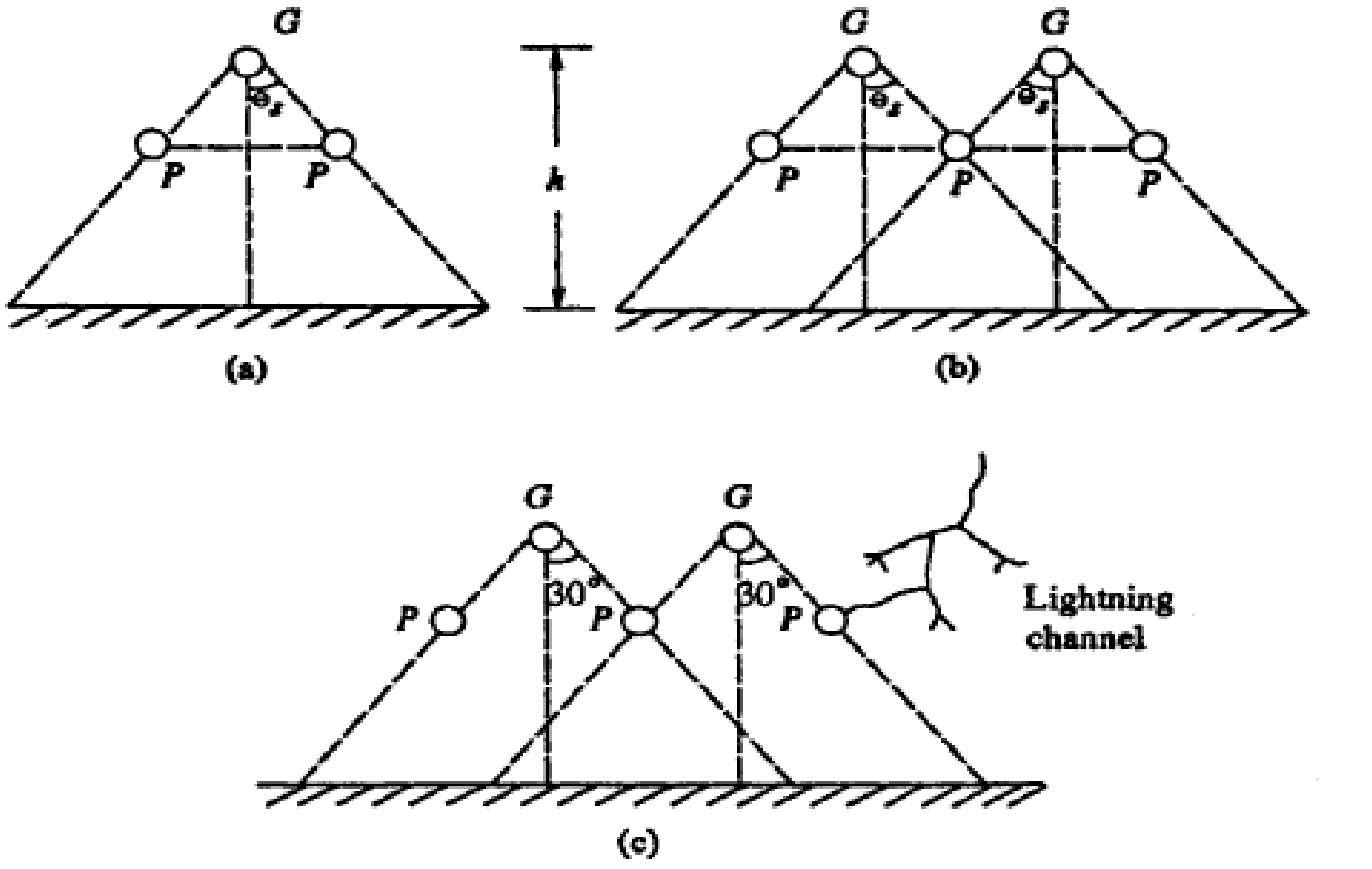
Protection of transmission lines against natural or lighting ovcrvoltages and minimizing the lightning overvoltages are done by **suitable line designs**, **providing guard** and **ground wires**, and using **surge diverters**. Switching surges and power frequency overvoltages are accounted for by providing greater insulation levels and with proper insulation co-ordination. Hence, the above two protection schemes are dealt.

Lightning Protection Using Shielded Wires or Ground Wires

Ground wire is a conductor run parallel to the main conductor of the transmission line supported on the same tower and earthed at every equally and regularly spaced towers. It is run above the main conductor of the line. The ground wire shields the transmission line conductor from induced charges, from clouds as well as from a lightning discharge. The arrangements of ground wires over the line conductor is shown in' Fig. 8.19.

The mechanism by which the line is protected may be explained as follows. If a positively charged cloud is assumed to be above the line, it induces a negative charge on the portion below it, of the transmission line. With the ground wire present, both the ground wire and the line conductor get the induced charge. But the ground wire is earthed at regular intervals, and as such the induced charge is drained to the earth potential only; the potential difference between the ground wire and the cloud and that between the ground wire and the transmission line wire will be in the inverse ratio of their respective capacitanc [assuming the cloud to be a perfect conductor and the atmospheric medium (air) a dielectric]. As the ground wire is nearer to the line wire, the induced charge on it will be much less and hence the potential rise will be quite small. The effective protection or shielding given by the ground wire depends on the height of the ground wire above the ground (h) and the protection or shielding angle $Ø_s$ (usually 30°) as shown in Fig. 8.19.

The shielding angle $Ø_s$ = 30° was considered adequate for tower heights of 30 m or less. The shielding wires may be one or more depending on the type of the towers used. But for EHV lines, the tower heights may be up to 50 m, and the lightning strokes sometimes occur directly to the line wires as shown in Fig. 8.19. The present trend in fixing the tower heights and shielding angles is by considering the "flashover rates" and failure probabilities.



G — Ground wire
P-P — Phase wires
θ_s — Shielding angle
h — Height of the ground wire from the earth surface

Fig. 8.19 Shielding arrangement of overhead lines by ground wires

Protection Using Ground Rods and Counter-Poise Wires

When a line is shielded, the Lightning strikes either the tower or the ground wire. The path for drainage of the charge and lightning current is (a) through the tower frame to ground, (b) through the ground line in opposite directions from the point of striking. Thus the ground wire reduces the instantaneous potential to which the tower top rises considerably, as the current path is in three directions. The instantaneous potential to which tower top can rise is

$$V_T = \frac{I_0 Z_T}{\left(1 + \frac{Z_T}{Z_S}\right)}$$

where,

Z_T = surge impedance of the tower, and

Z_S = surge impedance of the ground wire.

If the surge impedance of the tower, which is the effective tower footing resistance, is reduced, the surge voltage developed is also reduced considerably. This is accomplished by providing driven ground rods and counter-poise wires connected to tower Jegs at the tower foundation.

Ground rods are a number of rods about 15mm diameter and 2.5 to 3m long driven into the ground. In hard soils the rods may be much longer and can be driven to a depth of, say, 50 m. They are usually made of galvanized iron or copper bearing steel. The spacings of the rods, the number of rods, and the depth to which they are driven depend on the desired tower footing resistance. With 10 rods of 4 m long and spaced 5 m apart, connected to the legs of the tower, the dynamic or effective resistance may be reduced to 10 n.

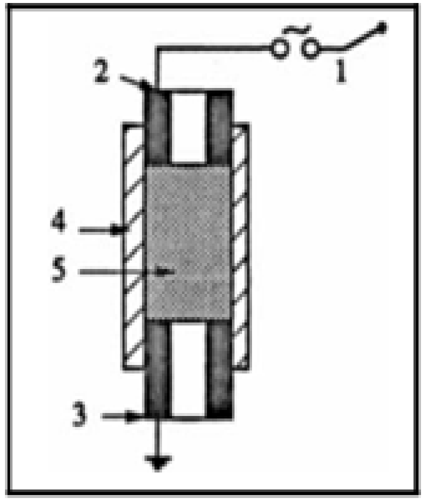
The above effect is alternatively achieved by using counterpoise wires. Counter poise wires are wires buried in the ground at a depth of 0.5 to 1.0 m, running parallel to the transmission line conductors and connected to the tower legs. These wires may be 50 to 100 m long. These are found to be more effective than driven rods and the surge impedance of the tower may be reduced to as low as 25 n. The depth does not materially affect the resistance of the counterpoise, and it is only necessary to bury it to a depth enough to prevent theft It is desirable to use a larger number of parallel wires than a single wire. But it is difficult to lay counter-poise wires compared to ground or driven rods.

Protective Devices

In regions where lightning strokes are intensive or heavy, the overhead lines within these zones are fitted with shunt protected devices. On the line itself two devices known as expulsion gaps and protector tubes are used. Line terminations, junctions of lines, and sub-stations are usually fitted with surge diverters.

Expulsion gaps

Expulsion gap is a device which consists of a spark gap together with an arc quenching device which extinguishes the current arc when the gaps breakover due to over voltages. A typical such arrangement is shown in Fig. 8.20a. This essentially consists of arod gap in air in series with a second gap enclosed within a fibre tube. In the event of an overvoltage, both the spark gaps preakdown simultaneously. The current due to the overvoltage is limited only by the tower footing resistance and the surge imped ance of the ground wires. The internal arc in the fibre tube due to lightning current vapourizes a small portion of the fibre material. The gas thus produced, being a mixture of water vapour and the decomposed fibre product, drive away the arc products and ionized air. When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, and the normal conditions are estab lished. The lightning and follow-up power frequency currents together can last for 2 to 3 half cycles only. Therefore, generally no disturbance in the network is produced. For 132 or 220 kV lines, the maximum current rating may be about 7,500 A.

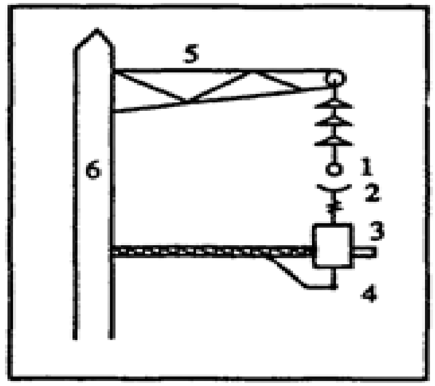


1. External series gap
2. Upper electrode
3. Ground electrode
4. Fibretube
5. Hollow space

Fig. 8.20a. Expulsion gap

Protector tubes

A protector tube is similar to the expulsion gap in, construction and principle. It also consists of a rod or spark gap in air formed by the line conductor and its high voltage terminal. It is mounted underneath the line conductor on a tower. The arrangement is shown in Fig. 8.20b. The hollow gap in the expulsion tube is replaced by a nonlinear element which offers a very high impedance at low currents but has low impedance for high or lightning currents. When an overvoltage occurs and the spark gap breaksdown, the current is limited both by its own resistance and the tower footing resis tance. The ovcrvohage on the line is reduced to the voltage drop across the protector tube. After the surge current is diverted and discharged to the ground, the follow-on normal power frequency current will be limited by its high resistance. After the current zero of power frequency, the spark gap recovers the insulation . strength quickly. Usually, the flashover voltage of the protector tube is less than that vf the line insulation, and hence it can discharge the lightning overvoltage effectively.



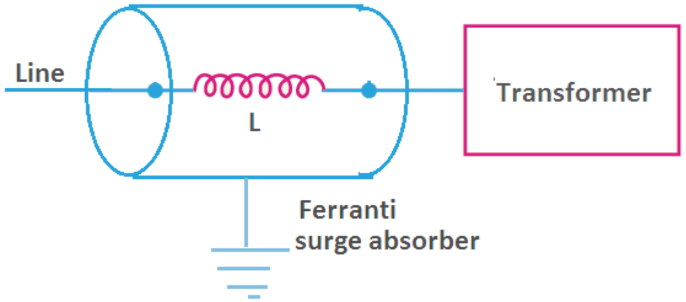
1. Line conductor on string insulator
2. Series gap
3. Protector tube
4. Ground connection
5. Cross arm
6. Tower body

ïg.8.20b Protector tube mounting

Surge Absorber

A surge absorber is a protective device that absorbs the high voltage surges and reduces the steepness of the surge wavefronts. The traveling waves set up by the surges on the transmission lines caused due to lightning and electrostatic induction possess an amplitude of 10 to 15kV, which has the ability to damage the equipment connected to that line. The damage caused depends not only on the amplitude of the traveling wave but also on the steepness of the wave. More the steepness in the traveling wave, damage caused to the equipment will be more. Thus in order to reduce the steepness of the surge wavefronts a surge absorber is used, thereby minimizing the danger caused due to overvoltages. Though the surge diverter and surge absorber eliminate the surge, the operation behind it is different. The surge diverter diverts the surge voltage to the earth by restricting it from entering the equipment, while the surge absorber absorbs energy contained in the surge voltage.

In this type of absorber, an inductor is connected in series with the line as shown in figure (a) below. The inductor is air-cored and insulated with a metallic sheet that is grounded. This insulated metal sheet acts as a dissipater. This type of setup is equivalent to the transformer whose secondary is earthed i.e., short-circuited. Its primary winding is formed by the inductor and secondary winding is formed by the dissipater. We know that a huge amount of energy is generated during surge formation and the energy is utilized for the transformer action. Even during the surge formation, the energy obtained is utilized efficiently and prevents the winding from damage.



Rod gaps

A much simpler and effective protective device is a rod-gap. However, it does not meet the complete requirement The sparkover voltage of a rod gap depends on the atmospheric conditions. A typical volt-time characteristic of a 67 cm-rod gap is shown in Fig. 8.21, with its protective margin. There is no current limiting device provided so as to limit the current after sparkover, and hence a series resistance is often used. Without a series resistance, the sparking current may be very high and the applied impulse voltage suddenly collapses to zero thus creating a steep step voltage, which sometimes proves to be very dangerous to the apparatus to be protected, such as transformer or the machine windings. Nevertheless, rod gaps do provide efficient protection where thunderstonn activity is less and the lines are protected by ground wires.

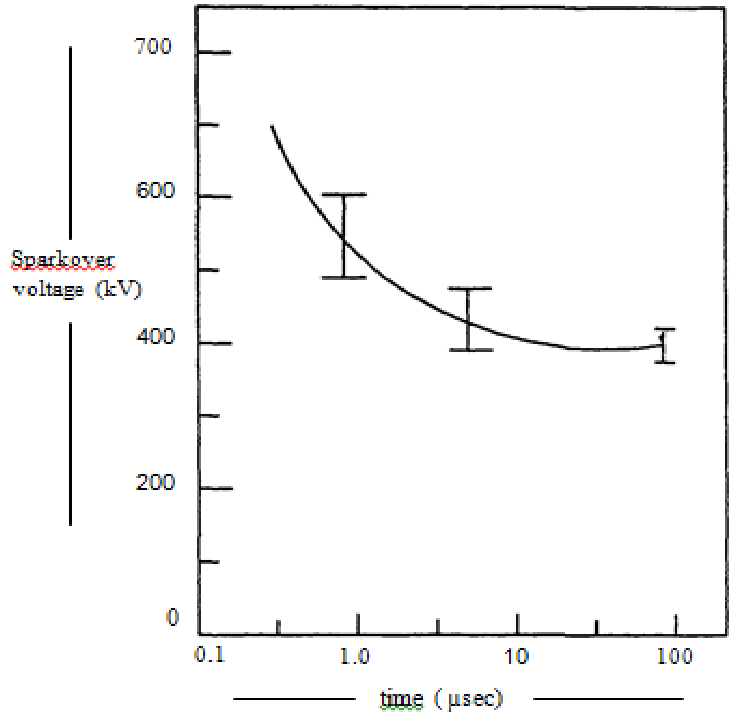


Fig. 8.21 Volt-time characteristic of a standard rod-rod gap

Surge diverters or lightning arresters

Surge diverters or lightning arresters are devices used at sub-stations and at line terminations to discharge the lightning overvoltages and short duration switching surges. These are usually mounted at the line end at the nearest point to the substation. They have a flashover voltage power than that of any other insulation or apparatus at the sub-station. These are capable of discharging 10 to 20 kA of long duration surges (8/20 µs) and 100 to 250 kA of the short duration surge currents (1/5 µs).

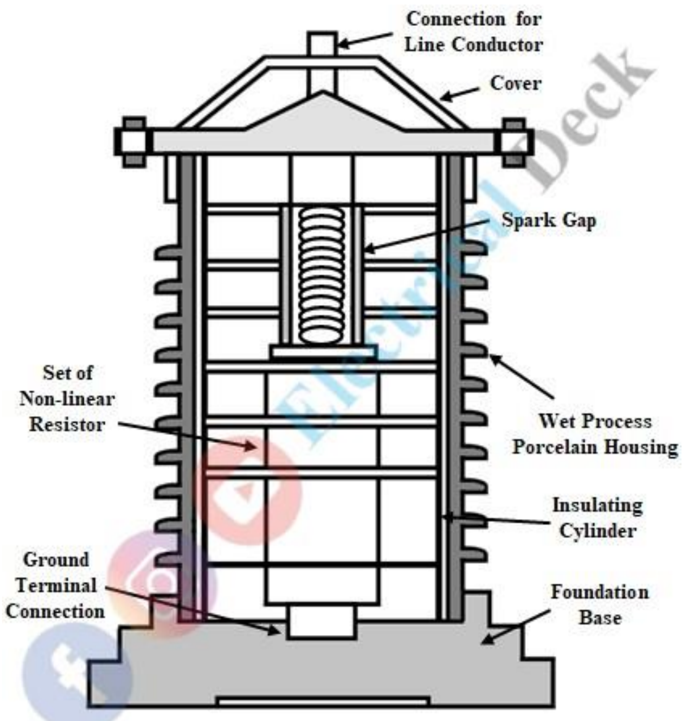
Lighting Arrester are the devices used at the substation and at the line termination to the divert the switching and lighting surges towards the earth. By diverting such high voltage towards earth it protect the line from the surge voltages. Lighting Arrester /Surge Arrester are the non linear resistor type equipment. The resistor unit is housed in porcelain enclosure. The non linear resistors are made of the specific materials such as silicon-carbide or zinc oxide. The volt-Amp characteristic of the resistor element is given by the following :-

$$\mathbf{I = KV^x}$$

Where, I= discharge Current /V= Applied Voltage across the element / K & x = the constant depending upon the materials and dimension of the element

Valve Type lightning Arresters

- Gapless and Gap-Type Lightning Arrester is called Valve type LA.
- As its name Valve type, so contains Valve elements as-Thyrites, Metal oxide etc.
- More expensive however mostly used.
- It contains cylindrical hollow porcelain insulator within which number of non-linear resistance unit, coil unit and valve element etc.
- The non-linear resistance is generally made of Silicon carbide. The construction of this type is shown as in fig.
- The circular disc are 90mm in dia. And 15mm thick.Disc are made up of the Silicon Carbide.



Valve Type Lightning Arrester

Characteristics:-

The characteristics of valve type LA is usually expressed as –

$$I=KV^{x}$$

X = 2 to 6 for Gap type LA

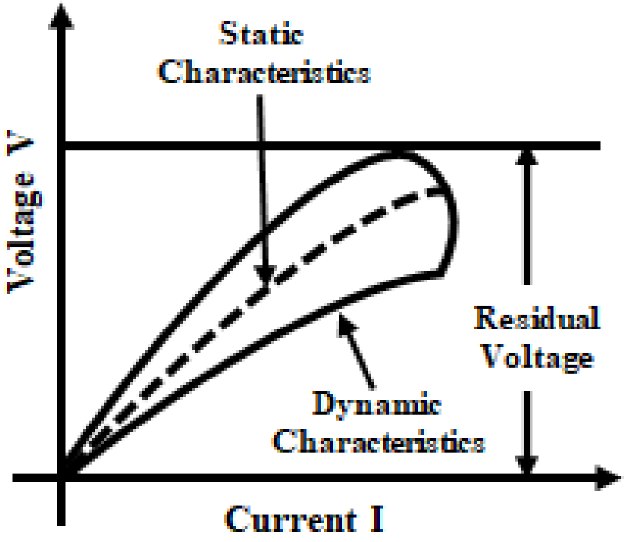
K=constant depends on geometry and dimensions of the resistor

X=40 for Gapless

I=discharge current

V=Operating voltage.

The above equation can be represented by V-I characteristic curve.



At a normal system voltage, the valve arrester works like an insulator i.e., it does not cause the breakdown of air gap assembly. During overvoltage conditions, the series spark gap breakdown. And the nonlinear resistors offer a low resistance due to a high surge current. As a result, the surge goes to earth instead of the line. The nonlinear resistors attain a high resistance to cease the flow of current when there is no surge. The volt-ampere characteristics of a nonlinear resistor are shown in the figure

The static and dynamic characteristics are represented by a dotted line and a dark line respectively. A horizontal tangent is drawn to the dynamic characteristic whose intercept gives the residual voltage. Residual voltage is the peak value of the voltage which occurs between the terminals of the surge diverter.

This occurs when the surge current discharges through the diverter. The voltage lies between 3 kV and 6 kV depending on the type of current discharge and rate of change of current. These arresters operate very fast and are effective in providing protection for devices like cables and transformers.

Metal Oxide lightning Arresters

- ✓ The constructional dwgs. is shown as –
- ✓ These types of LA are made up of with Metal oxide that are enclosed within column type porcelain insulator.
- ✓ The oxides that are used are – ZnO, Bismuth Oxide , Cobalt Oxide
- ✓