HIGH VOLTAGE ENGINEERING

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Department: Electrical and Electronics Engineering

Batch/Year: 2017-2021 **Subject code : EE8701**

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SYLLABUS

EE8701 HIGH VOLTAGE ENGINEERING **L T P C**

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OBJECTIVES:

To impart knowledge on the following Topics

- Various types of over voltages in power system and protection methods.
- Generation of over voltages in laboratories.
- Measurement of over voltages.
- Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.
- Testing of power apparatus and insulation coordination

UNIT I OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS 9

Causes of over voltages and its effects on power system – Lightning, switching surges and temporary over voltages, Corona and its effects – Bewley lattice diagram- Protection against over voltages.

UNIT II DIELECTRIC BREAKDOWN 9

Properties of Dielectric materials - Gaseous breakdown in uniform and non-uniform fields – Corona discharges – Vacuum breakdown – Conduction and breakdown in pure and commercial liquids, Maintenance of oil Quality – Breakdown mechanisms in solid and composite dielectrics- Applications of insulating materials in electrical equipments.

UNIT III GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

Generation of High DC voltage: Rectifiers, voltage multipliers, vandigraff generator: generation of high impulse voltage: single and multistage Marx circuits – generation of high AC voltages: cascaded transformers, resonant transformer and tesla coil- generation of switching surges – generation of impulse currents - Triggering and control of impulse generators.

UNIT IV MEASUREMENT OF HIGH VOLTAGES AND HIGH CURRENTS

High Resistance with series ammeter – Dividers, Resistance, Capacitance and Mixed dividers - Peak Voltmeter, Generating Voltmeters - Capacitance Voltage Transformers, Electrostatic Voltmeters – Sphere Gaps - High current shunts- Digital techniques in high voltage measurement.

UNIT V HIGH VOLTAGE TESTING & INSULATION COORDINATION 9

High voltage testing of electrical power apparatus as per International and Indian standards – Power frequency, impulse voltage and DC testing of Insulators, circuit breakers, bushing, isolators and transformers- Insulation Coordination& testing of cabilitys.

TOTAL : 45 PERIODS

UNIT -1

OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS

1. Causes of Over Voltages

Lightning

Lightning has been a source of wonder to mankind for thousands of years. Schonland points out that Any real scientific search for the first time was made into the phenomenon of lightning by Franklin in 18th century. Before going into the various theories explaining the charge formation in a thunder cloud and the mechanism of lightning, it is desirable to review some of the accepted facts concerning the thunder cloud and the associated phenomenon.

1. The height of the cloud base above the surrounding ground level may vary from 160 to 9,500 m. The charged centres which are responsible for lightning are in the range of 300 to 1500 m.
2. The maximum charge on a cloud is of the order of 10 coulombs which is built up exponentially over a period of perhaps many seconds or even minutes.
3. The maximum potential of a cloud lies approximately within the range of 10 MV to 100 MV.
4. The energy in a lightning stroke may be of the order of 250 kWhr.
5. Raindrops:

   (*a*) Raindrops elongate and become unstable under an electric field, the limiting diameter being 0.3 cm in a field of 100 kV/cm.

   (*b*) A free falling raindrop attains a constant velocity with respect to the air depending upon its size. This velocity is 800 cms/sec. for drops of the size 0.25 cm dia. and is zero for spray. This means that in case the air currents are moving upwards with a velocity greater than 800 cm/sec, no rain drop can fall.

   (*c*) Falling raindrops greater than 0.5 cm in dia become unstable and break up into Smaller drops.

   (*d*) When a drop is broken up by air currents, the water particles become positively charged and the air negatively charged.

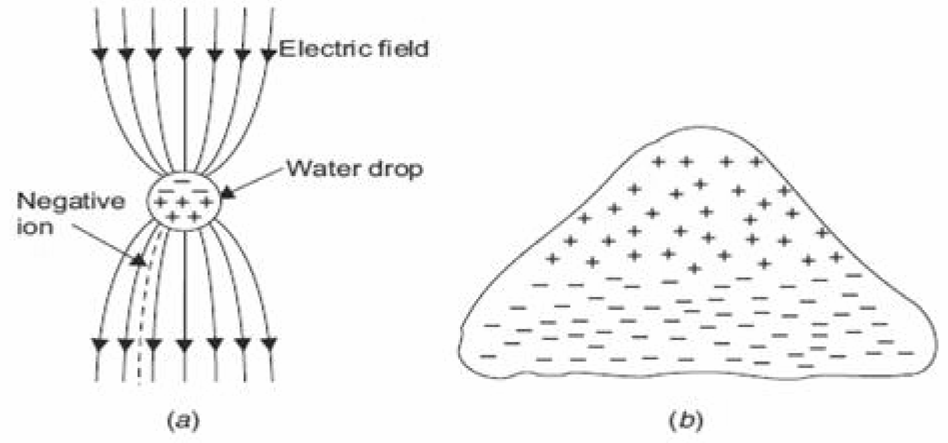
   (*e*) When an ice crystal strikes with air currents, the ice crystal is negatively charged and the air positively charged.

Wilson's Theory of Charge Separation

Wilson's theory is based on the assumption that a large number of ions are present in the atmosphere. Many of these ions attach themselves to small dust particles and water particles. It also assumes that an electric field exists in the earth's atmosphere during fair weather which is directed downwards towards the earth. The intensity of the field is approximately 1 volt/cm at the surface of the earth and decreases gradually with height so that at 9,500 m it is only about 0.02 V/cm.

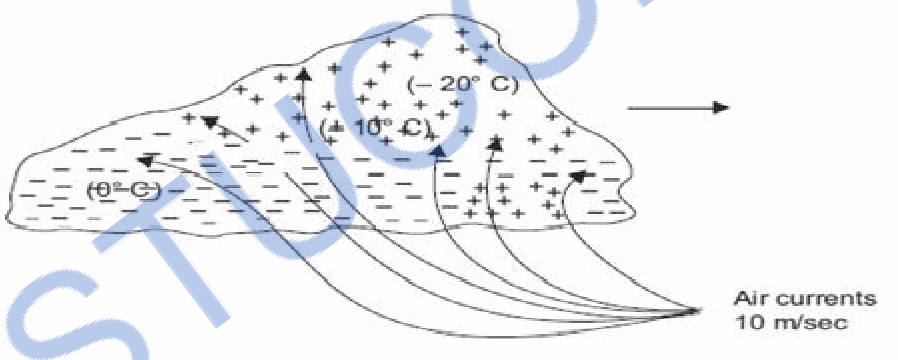
A relatively large raindrop (0.1 cm radius) falling in this field becomes polarized, the upper side acquires a negative charge and the lower side a positive charge. Subsequently, the lower part of the drop attracts –ve charges from the atmosphere which are available in abundance in the atmosphere leaving a preponderance of positive charges in the Air.

The upwards motion of air currents tends to carry up the top of the cloud, the +ve air and smaller drops that the wind can blow against gravity. Meanwhile the falling heavier raindrops which are negatively charged settle on the base of the cloud. It is to be noted that the selective action of capturing –ve charges from the atmosphere by the lower surface of the drop is Possible. No such selective action occurs at the upper surface. Thus in the original system, both the positive and negative charges which were mixed up, producing essentially a neutral space charge, are now separated. Thus according to Wilson's theory since larger negatively charged drops settle on the base of the cloud and smaller positively charged drops settle on the upper positions of the cloud, the lower base of the cloud is negatively charged and the upper region is positively charged.



Simpson's and Scarse Theory

Simpson's theory is based on the temperature variations in the various regions of the cloud. When water droplets are broken due to air currents, water droplets acquire positive charges whereas the air is negatively charged. Also when ice crystals strike with air, the air is positively charged and the crystals negatively charged. The theory is explained with the help of Fig

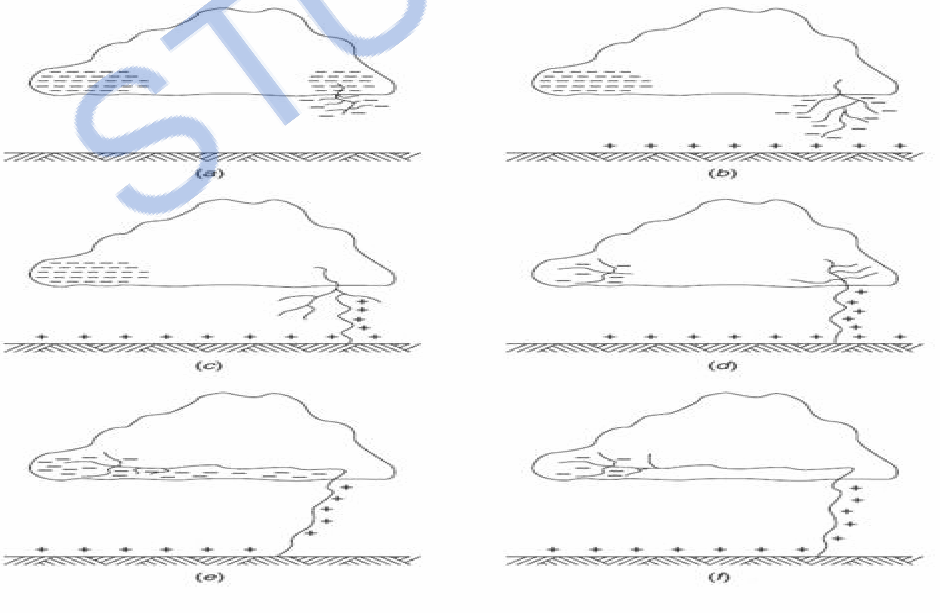


Let the cloud move in the direction from left to right as shown by the arrow. The air currents are also shown in the diagram. If the velocity of the air currents is about 10 m/sec in the base of the cloud, these air currents when collide with the water particles in the base of the cloud, the water drops are broken and carried upwards unless they combine together and fall down in a pocket as shown by a pocket of positive charges (right bottom region in Fig.)

With the collision of water particles we know the air is negatively charged and the water particles positively charged. These negative charges in the air are immediately absorbed by the cloud particles which are carried away upwards with the air currents. The air currents go still higher in the cloud where the moisture freezes into ice crystals. The air currents when collide with ice crystals the air is positively charged and it goes in the upper region of cloud whereas the negatively charged ice crystals drift gently down in the lower region of the cloud. This is how the charge is separated in a thundercloud. Once the charge separation is complete, the conditions are now set for a lightning stroke.

Mechanism of Lightning Stroke

Lightning phenomenon is the discharge of the cloud to the ground. The cloud and the ground form two plates of a gigantic capacitor and the dielectric medium is air. Since the lower part of the cloud is negatively charged, the earth is positively charged by induction. Lightning discharge will require the puncture of the air between the cloud and the earth. For breakdown of air at STP condition the electric field required is 30 kV/cm peak. But in a cloud where the moisture content in the air is large and also because of the high altitude (lower pressure) it is seen that for breakdown of air the electric field required is only 10 kV/cm. The mechanism of lightning discharge is best explained with the help of Fig.



After a gradient of approximately 10 kV/cm is set up in the cloud, the air surrounding gets Ionized. At this a streamer (Fig. (*a*)) starts from the cloud towards the earth which cannot be detected with the naked eye; only a spot travelling is detected. The current in the streamer is of the order of 100 amperes and the speed of the streamer is 0.16 m/μ sec. This streamer is known as pilot streamer because this leads to the lightning phenomenon. Depending upon the state of ionization of the air surrounding the streamer, it is branched to several paths and this is known as stepped leader (Fig. (*b*)). The leader steps are of the order of 50 m in length and are accomplished in about a microsecond. The charge is brought from the cloud through the already ionized path to these pauses. The air surrounding these pauses is again ionized and the leader in this way reaches the earth (Fig. (*c*)).

Once the stepped leader has made contact with the earth it is believed that a power return stroke (Fig. 7.24(*c*)) moves very fast up towards the cloud through the already ionized path by the leader. This streamer is very intense where the current varies between 1000 amps and 200,000 amps and the speed is about 10% that of light. It is here where the –ve charge of the cloud is being neutralized by the positive induced charge on the earth (Fig. 7.24(*d*)). It is this instant which gives rise to lightning flash which we observe with our naked eye. There may be another cell of charges in the cloud near the neutralized charged cell. This charged cell will try to neutralize through this ionised path. This streamer is known as dart leader (Fig. 7.24(*e*)). The velocity of the dart leader is about 3% of the velocity of light. The effect of the dart leader is much more severe than that of the return stroke.

The discharge current in the return streamer is relatively very large but as it lasts only for a few microseconds the energy contained in the streamer is small and hence this streamer is known as cold lightning stroke whereas the dart leader is known as hot lightning stroke because even though the current in this leader is relatively smaller but it lasts for some milliseconds and therefore the energy contained in this leader is relatively larger. It is found that each thunder cloud may contain as many as 40 charged cells and a heavy lightning stroke may occur. This is known as multiple strokes.

Mathematical Model for Lightning

During the charge formation process, the cloud may be considered to be a non conductor. Hence, various potentials may be assumed at different parts of the cloud. If the charging process is continued, it is probable that the gradient at certain parts of the charged region exceeds the breakdown strength of the air or moist air in the cloud. Hence, local breakdown takes place within the cloud. This local discharge may finally lead to a situation wherein a large reservoir of charges involving a considerable mass of cloud hangs over the ground, with the air between the cloud and the ground as a dielectric. When a streamer discharge occurs to ground by first a leader stroke, followed by main strokes with considerable currents flowing, the lightning stroke may be thought to be a current source of value /Q with a source impedance Z0 discharging to earth. If the stroke strikes an object of impedance Z, the voltage built across it may b e taken as

$$V = IZ$$

$$= I_0 \frac{Z\,Z_0}{Z + Z_0}$$

$$= I_0 \frac{Z}{1+\frac{Z}{Z_0}}$$

The source impedance of the lightning channels are not known exactly, but it is estimated to be about 1000 to 3000 Ω. The objects of interest to electrical engineers, namely, transmission line, etc. have surge impedances less than 500 Ω (overhead lines 300 to 5OO Ω , ground wires 100 to 150 Ω, towers 10 to 50 Ω, etc.). Therefore, the value Z/Z0 will usually be less than 0.1 and hence can be neglected. Hence, the voltage rise of lines, etc. may be taken to be approximately $V = I_0 Z$, *where* I_0 *is the* lightning stroke current and Z the line surge impedance.

Switching surges

Origin of Switching Surges The making and breaking of electric circuits with switchgear may result in abnormal over voltages in power systems having large inductances and capacitances. The over voltages 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 .The wave shapes 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,

(i v) Sudden switching off of loads.

(v) Short circuits and fault clearances.

(w) Resonance phenomenon like ferro-resonance, arcing grounds, etc

Bewley Lattice Diagram :
Successive reflections and lattice diagrams

In many problems involving short cable lengths, or lines tapped at intervals, the travelling waves encounter successive reflections at the transition point.

Bewley has given the lattice or time-space diagrams from which the motion of reflected and transmitted waves and their positions at every instant can be obtained. The principles observed in the lattice diagrams are as follows:

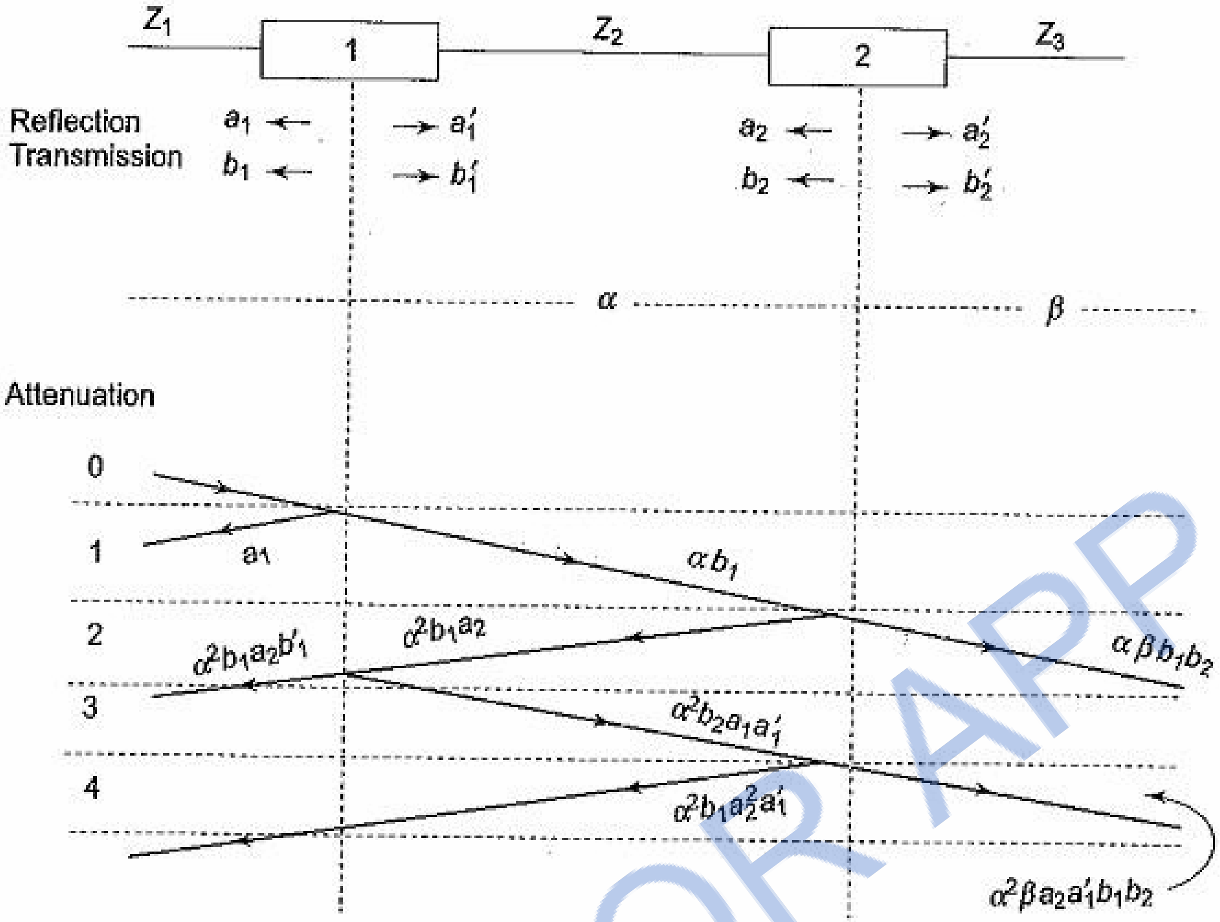
(1) All waves travel downhill, i.e. into the positive time

(2) The position of the wave at any instant is given by means of the time scale at the left of the lattice diagram

(3) The total potential at any instant of time is the superposition of all the waves which arrive at that point until that instant of time, displaced in position from each other by time intervals equal to the time differences of their arrival

(4) Attenuation is included so that the amount by which a wave is reduced is taken care of and the previous history of the wave, if desired can be easily traced. If the computation is to be carried out at a point where the operations cannot be directly placed on the lattice diagram, the arms can be numbered and the quantity can be tabulated and computed arms are as follows:

In the arrangement shown in the figure, there are two junctions 1 and 2. The travel times for the waves are different through Z1, Z2, and Z3. The lines with surge impedances Z1, Z2, and Z3 are connected on either side of the junctions. Let α and β be the attenuation coefficients for the two sections Z2 and Z$. Let a and a' be the reflection coefficients for the waves approaching from the left and the right at junction1, and a2 and a2’ be the corresponding reflection coefficients at junction 2



Similarly, let *b and b' be the transmission coefficients for the waves that approach from the* left and the right at junction 1, and the corresponding coefficients be b2 and b2' at junction 2. To construct the lattice diagram, the position O is taken when the wave coming from Z1 reaches junction 1. Junction 2 is taken to scale at the time in equal to the travel time through the line Z2 between the junctions 1 and 2.

The diagram is drawn by choosing a suitable time scale. The reflection and the transmission factors are marked as shown in the figure. The process of calculation is indicated on the slope of the lines in the diagram. The process can be continued for up to the required time interval.

Bewley's Lattice Diagram

Whenever there is an abrupt change in the parameters of a transmission line, such as an open circuit or a termination, the travelling wave undergoes a transition, pan of the wave is reflected or sent back and only a portion is transmitted forward. At the transition point, the voltage or current wave may attain a value which can vary from zero to two times its initial value. The incoming wave is called the incident wave and the other waves are called the reflected and transmitted waves at the transition point. Such waves are formed according to the KirchhofFs laws and they satisfy the line differential equations.

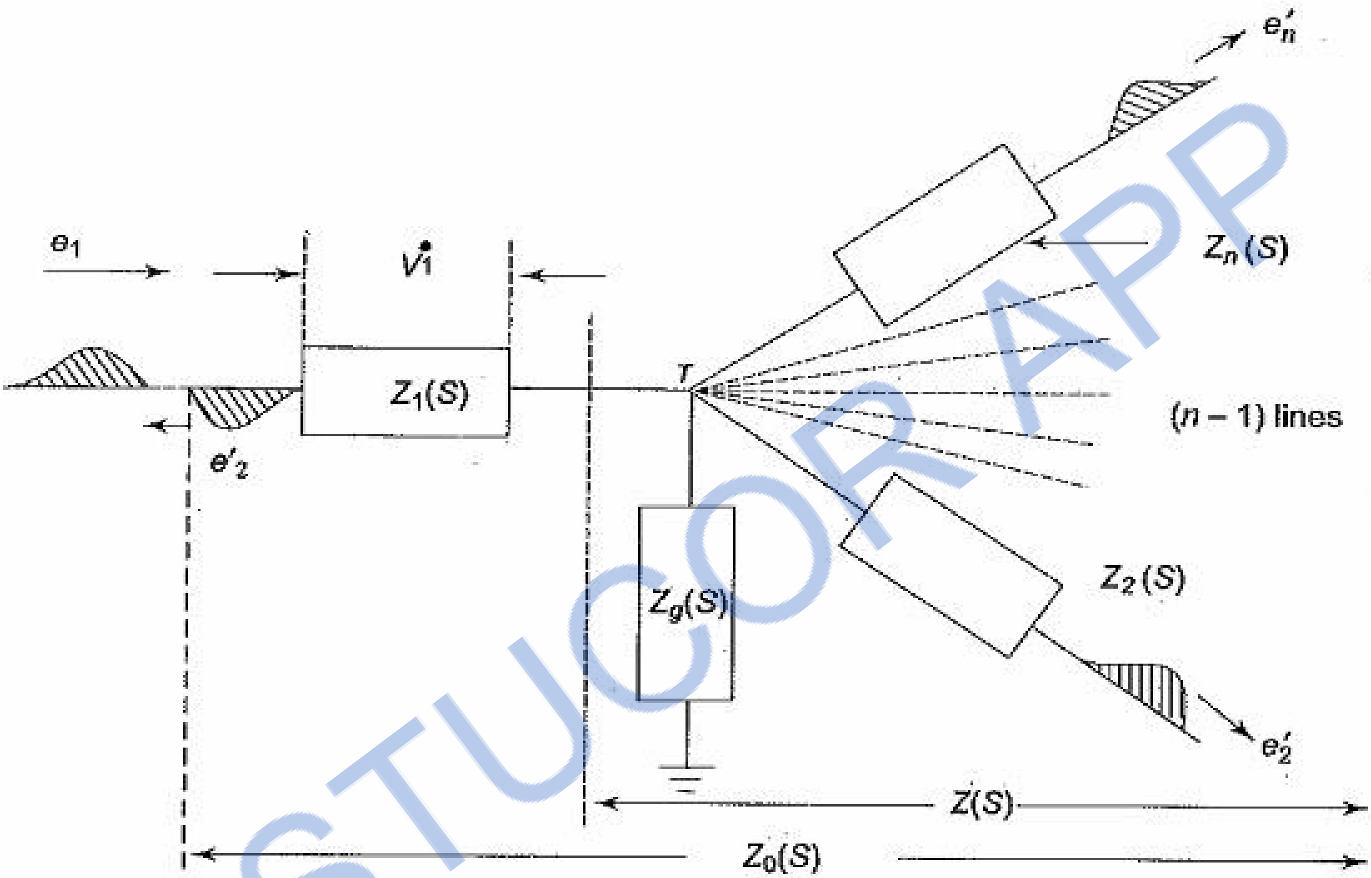


Fig. 8.15 *Transition point (T) and the propagation of the wave at the transition point*

In short cable lengths, or lines tapped at intervals, the travelling waves encounter successive reflections at the transition point. It is extremely difficult to calculate the multiplicity of these reflections. ***Bewley*** has given the lattice or time-space diagrams from which the motion of reflected and transmitted waves and their positions at every instant can be obtained.

The principles observed in the lattice diagrams are as follows:

(a) all waves travel downhill, i.e. into the positive time
(b) the position of the wave at any instant is given by means of the time scale at the left of the lattice diagram
(c) the total potential at any instant of time is the superposition of all the waves which arrive at that point until that instant of time, displaced in position from each other by time intervals equal to the time differences of their arrival
(d) attenuation is included so that the amount by which a wave is reduced is taken care of and
(e) the previous history of the wave, if desired can be easily traced. If the computation is to be carried out at a point where the operations cannot be directly placed on the lattice diagram, the arms can be numbered and the quantity can be tabulated and computed.

Attenuation Factor

Attenuation factor α to be defined corresponding to the length of a particular line i.e.

$$\alpha = e^{-\text{attenuation constant x length of the line}}$$

Propagation constant $\gamma = \sqrt{zy}$

Surge impedance and Velocity of Propagation

Let L be the inductance,
Let C be the capacitance,

Surge impedance $(Z_C) = \sqrt{\frac{L}{C}}$

Velocity of Propagation constant, $v = \frac{1}{\sqrt{LC}}$ m/sec

where, $L = 2X10^{-7} ln\left(\frac{d}{r}\right)$

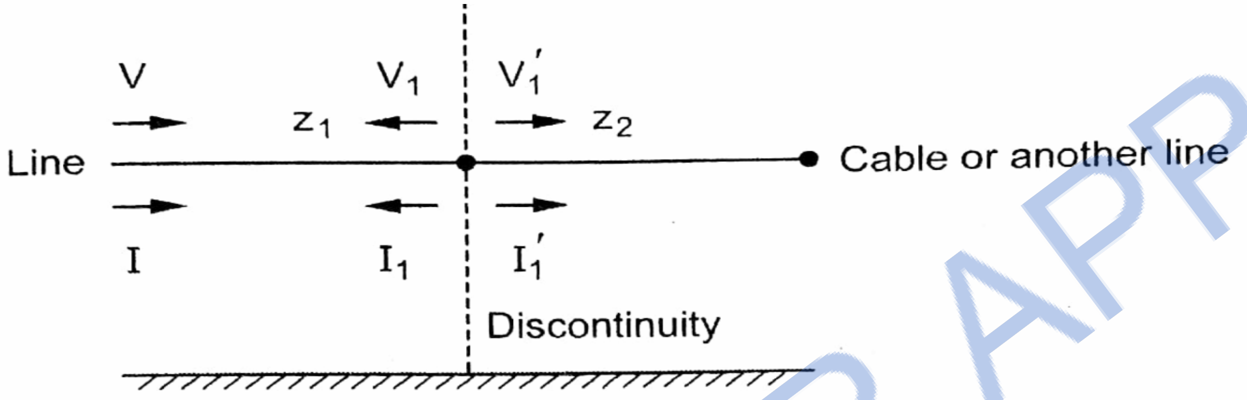
$$C = \frac{2\pi\epsilon_0}{ln\left(\frac{d}{r}\right)}$$

Reflection and Refraction Coefficient

There is a proportionality between the voltage and current. Consider the junction between the lines or between the line and a cable of characteristics impedances Z_1 and Z_2.

Let the incoming voltage wave or step function surge of amplitude be V.
Let the incoming current wave be I.

Let the reflected voltage at the point of discontinuity be V_1,
Let the reflected current at the point of discontinuity be I_1,
Let the transmitted or refracted voltage at the point of discontinuity be V_1',
Let the transmitted or refracted current at the point of discontinuity be I_1',



At the point of discontinuity between the lines or cables having an surge impedance are Z_1 and Z_2.

(i) Determine reflected voltage V_1 in terms of a:

Applying KVL and KCL, we have

$V_1' = V + V_1$ & $I_1' = I - I_1$
[∵ the reflected wave has negative sign]

$$\frac{V_1'}{Z_2} = \frac{V}{Z_1} - \frac{V_1}{Z_1}$$

Substituting V_1',

$$\frac{V+V_1}{z_2} = \frac{V-V_1}{z_1}$$

$$V_1\left(\frac{1}{Z_2} + \frac{1}{Z_1}\right) = V\left(\frac{1}{Z_1} - \frac{1}{Z_2}\right)$$

$$V_1\left(\frac{Z_1+Z_2}{Z_2Z_1}\right) = V\left(\frac{Z_2-Z_1}{Z_1Z_2}\right)$$

$$V_1 = \left(\frac{Z_2-Z_1}{Z_1+Z_2}\right)V = \text{aV}$$

where, a = Reflection coefficient

(i) Determine transmitted voltage V_1' in terms of b

$$V_1' = V + V_1$$

$$V_1 = V_1' - V$$

$$I_1' = I - I_1$$

$$\frac{V_1'}{Z_2} = \frac{V}{Z_1} - \frac{V_1}{Z_1} = \frac{V}{Z_1} - \left[\frac{V_1' - V}{Z_1}\right]$$

$$\frac{V_1'}{Z_2} = \frac{2V - V_1'}{Z_1}$$

$$V_1'\left[\frac{1}{Z_2} + \frac{1}{Z_1}\right] =$$

$$V_1'\left[\frac{Z_1 + Z_2}{Z_1 Z_2}\right] = \frac{2V}{Z_1}$$

$$V_1' = \frac{2Z_1Z_2}{(Z_1+Z_2)Z_1}V = \frac{2Z_2}{Z_1 + Z_2}.V$$

$$V_1' = b.V$$

where, b = Refraction coefficient

iii) Relation between a and b:

$$1 + a = 1 + \frac{Z_2 - Z_1}{Z_1 + Z_2}$$

$$= \frac{Z_1 + Z_2 + Z_2 - Z_1}{Z_1 + Z_2} = \frac{2Z_2}{Z_1 + Z_2} = b$$

iv) Transmitted or refracted current:

$$I_1' = I - I_1 = \frac{V}{Z_1} - \frac{V_1}{Z_1}$$

Substituting the value of V_1, we get

$$= \frac{V}{Z_1} - \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)\frac{V}{Z_1} = V$$

$$= \frac{2Z_1}{Z_1 + Z_2}\left(\frac{V}{Z_1}\right) = \frac{2Z_1}{Z_1 + Z_2}.I$$

iv) Transmitted or refracted current:

$$I_1' = I - I_1 = \frac{V}{Z_1} - \frac{V_1}{Z_1}$$

Substituting the value of V_1, we get

$$= \frac{V}{Z_1} - \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)\frac{V}{Z_1} = V\left\{\frac{Z_1 + Z_2 - Z_2 + Z_1}{(Z_1 + Z_2)Z_1}\right\}$$

$$= \frac{2Z_1}{Z_1 + Z_2}\left(\frac{V}{Z_1}\right) = \frac{2Z_1}{Z_1 + Z_2}.I$$

v) Reflected current:

$$I_1 = \frac{-V_1}{Z_1}$$

Substituting V_1, we get $I_1 = -a.\left[\frac{V}{Z_1}\right] = -aI$

Important Relation: $Z_c = \sqrt{\frac{L}{C}}$

$$v = \frac{1}{\sqrt{LC}}$$

1 + a = b

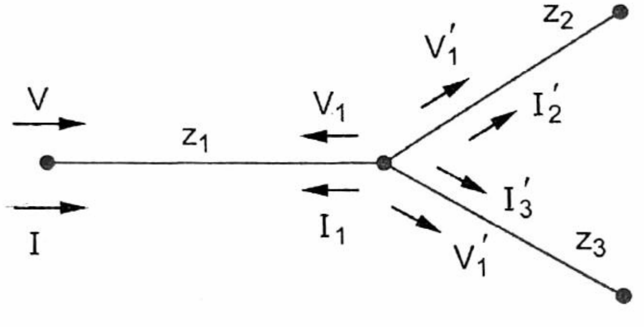
V_1 = a.V, V_1' = b V

I_1 = -a. I, $I_1' = \frac{2Z_1}{Z_1+Z_2}.I$

where, $a = \frac{Z_2 - Z_1}{Z_1 + Z_2}$, $b = \frac{2Z_2}{Z_1 + Z_2}$

Reflection and Refraction or Transmission at a T-Junction

Consider a line with natural impedance Z_1 connected to two different lines with surge impedances Z_2 and Z_3 as shown in fig.



Applying KCL and KVL, we get

$$V_1' = V + V_1$$

$$I - I_1 = I_2' + I_3'$$

$$\frac{V}{Z_1} - \frac{V_1}{Z_1} = \frac{V_1'}{Z_2} + \frac{V_1'}{Z_3}$$

$$\frac{V}{Z_1} - \left[\frac{V_1' - V}{Z_1}\right] = \frac{V_1'}{Z_2} + \frac{V_1'}{Z_3}$$

$$V_1'\left[\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}\right] = 2\frac{V}{Z_1}$$

Refracted transmitted voltage,

$$V_1' = 2\frac{V}{Z_1\left[\frac{1}{Z_1}+\frac{1}{Z_2}+\frac{1}{Z_3}\right]}$$

The refracted or transmitted currents are

$$I_2' = \frac{V_1'}{Z_2} = 2\frac{V}{Z_2 Z_1\left[\frac{1}{Z_1}+\frac{1}{Z_2}+\frac{1}{Z_3}\right]}$$

$$I_3' = \frac{V_1'}{Z_3} = 2\frac{V}{Z_3 Z_1\left[\frac{1}{Z_1}+\frac{1}{Z_2}+\frac{1}{Z_3}\right]}$$

Open ended transmission line of surge impedance Z

$Z_1 = Z$, $Z_2 = \infty$

Reflection coefficient at the receiving end

$$a = \frac{Z_2 - Z_1}{Z_1 + Z_2} = \frac{1 - \frac{Z_1}{Z_2}}{1 + \frac{Z_1}{Z_2}}$$

$Z_2 = \infty$, $a = \frac{1 - \frac{Z}{\infty}}{1 + \frac{1}{\infty}} = 1$

Reflection coefficient at the sending end

$$a' = \frac{0 - Z}{0 + z} = 1$$

Procedure

Assume T is the time taken for a wave to travel from on end to the end of line and ɑ is the attenuation factor. Assume amplitude is unity.

At time t=0, the magnitude is +1. The wave is attenuated and reaches at T with magnitude +1 x ɑ = +ɑ

At time T, the wave is reflected and the amplitude is +ɑ x a = +ɑ and the wave is again attenuated and reaches at 2T with magnitude $+ɑ^2$

At time 2T, the wave is reflected and the amplitude is $+ɑ^2$x-a=$-ɑ^2$ and the wave is again attenuated and reaches at 3T with magnitude $-ɑ^3$

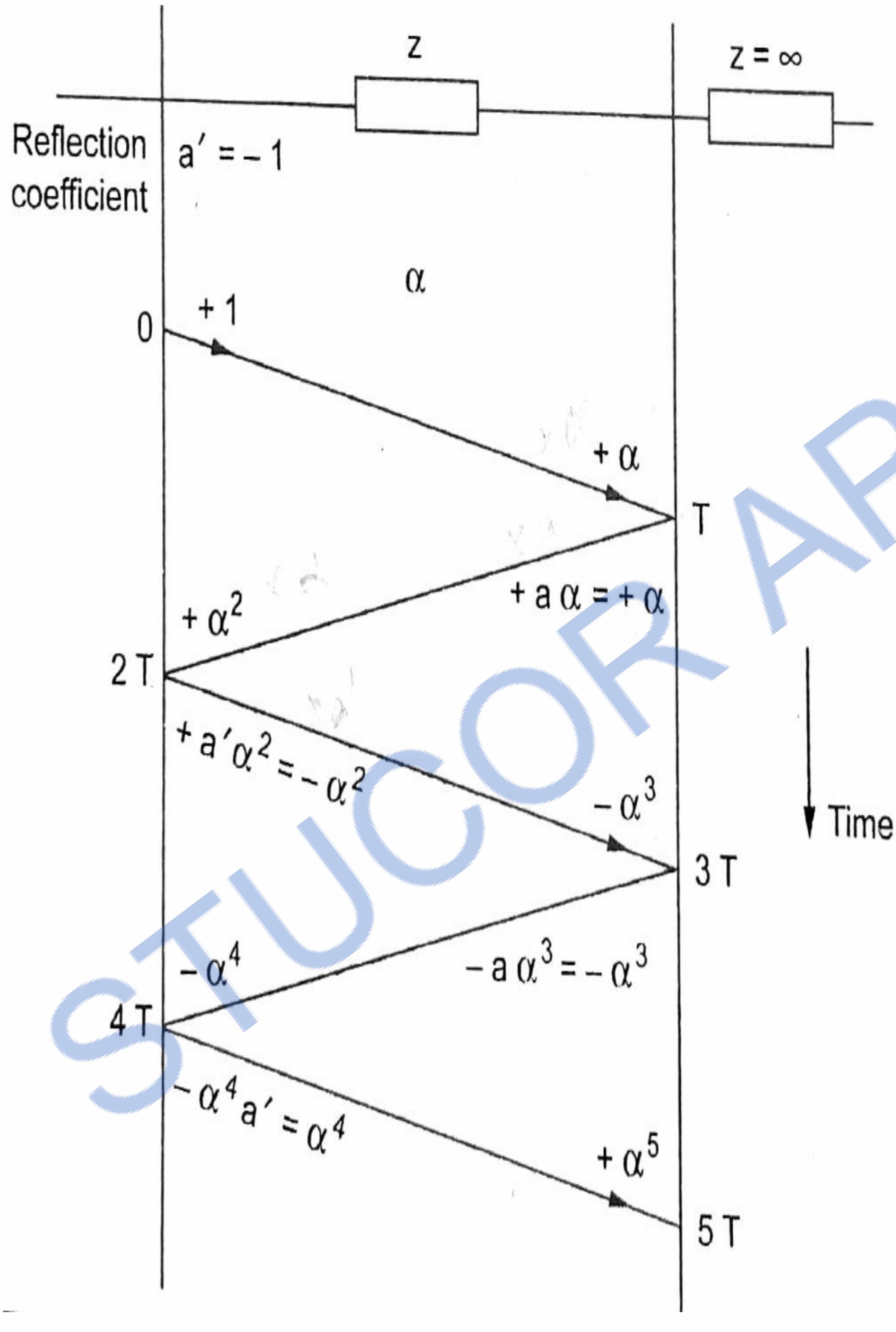
At time 3T, the wave is reflected and the amplitude is $-ɑ^3$ x a = $-ɑ^3$ and the wave is attenuated and reaches at 4T with magnitude $-ɑ^4$ and so on.

Voltage at the receiving end = 2 [ɑ – $ɑ^3$ + $ɑ^5$ + ……..+ $ɑ^2$n-1] u(t)

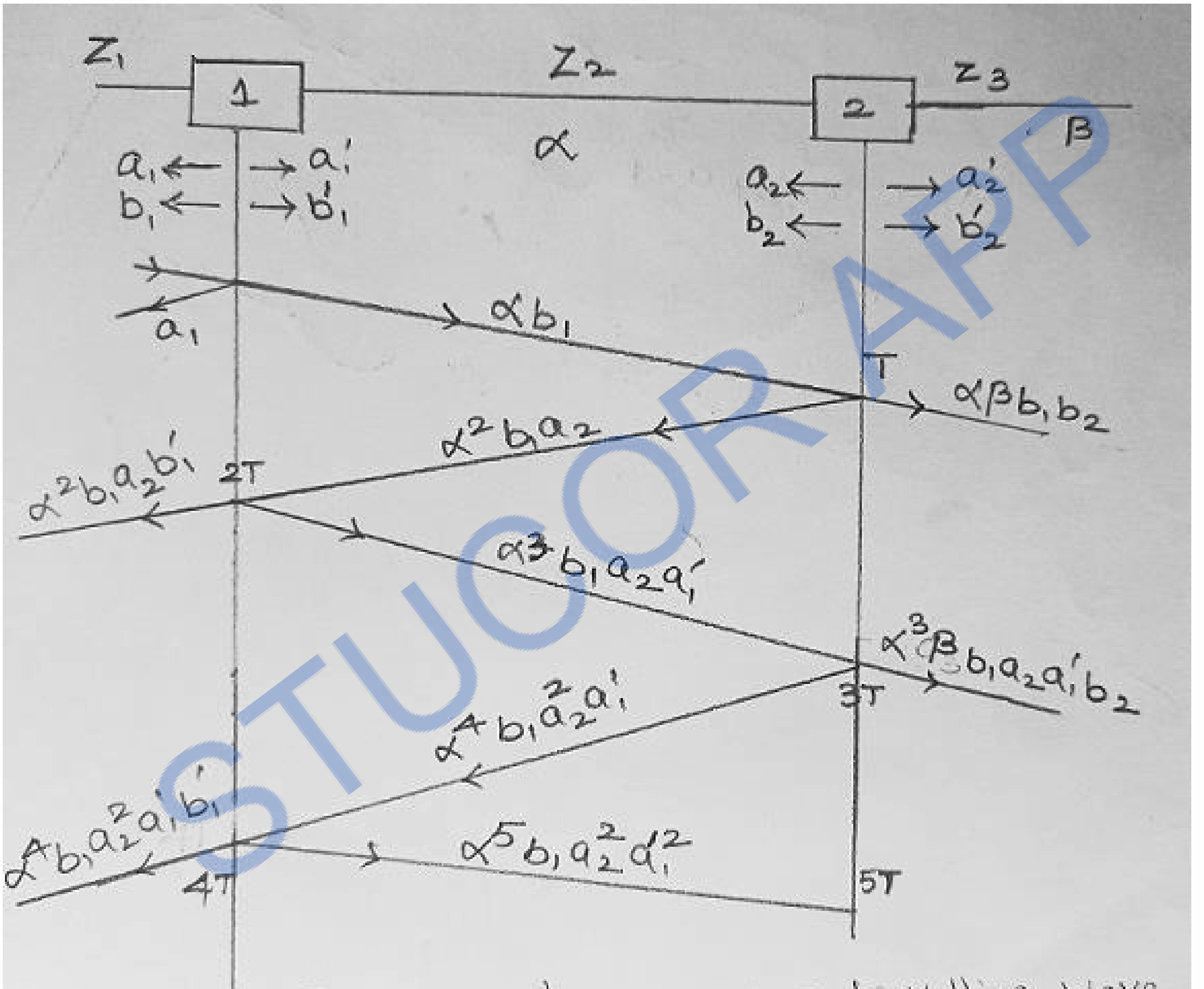
$$= 2\alpha \frac{[1-\alpha^{4(n+1)}]}{[1+\alpha^2]} . u(t)$$

At t = ∞, $V\infty = \frac{2\alpha}{1+\alpha^2}\, u(t)$

Current at the receiving end , $I_\alpha = \frac{V_\alpha}{Z}$



Open ended transmission line of surge impedance Z



Reflection lattice of a travelling wave.

Problem No:1

A transmission line of surge impedance 250Ω and is connected to a cable of surge impedance 50Ω at the other end, if a surge of 400kV travels along the line to the junction point, find the voltage build at the junction.

Solution:

Z1 = 250Ω, Z2 = 50Ω, V= 400kV

$$V1 = \frac{Z_2 - Z_1}{Z_2 + Z_1}\, x\, V = \frac{50 - 250}{50 + 250}\, x\, 400 = -266.67kV$$

Voltage build at the junction = V - V_1

= 400 – (-266.67) = 666.67kV

Problem No:2

A long trnsmission line is energised by a unit step voltage 1.0V at the sending end and is open circuited at the receiving end. Construct the Bewley lattice diagram and obtain the value of the voltage at the receiving end after a long time. Take the attenuation α=0.9.

Solution: For the open circuited at the receiving end,

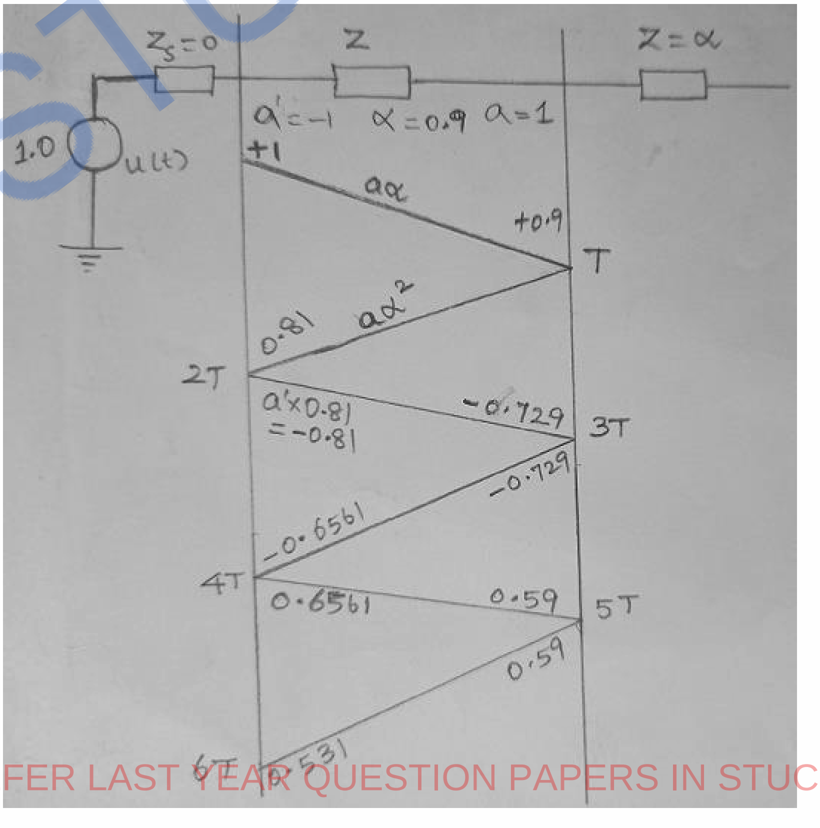
Let the time of travel be 1unit.
At the receiving end,

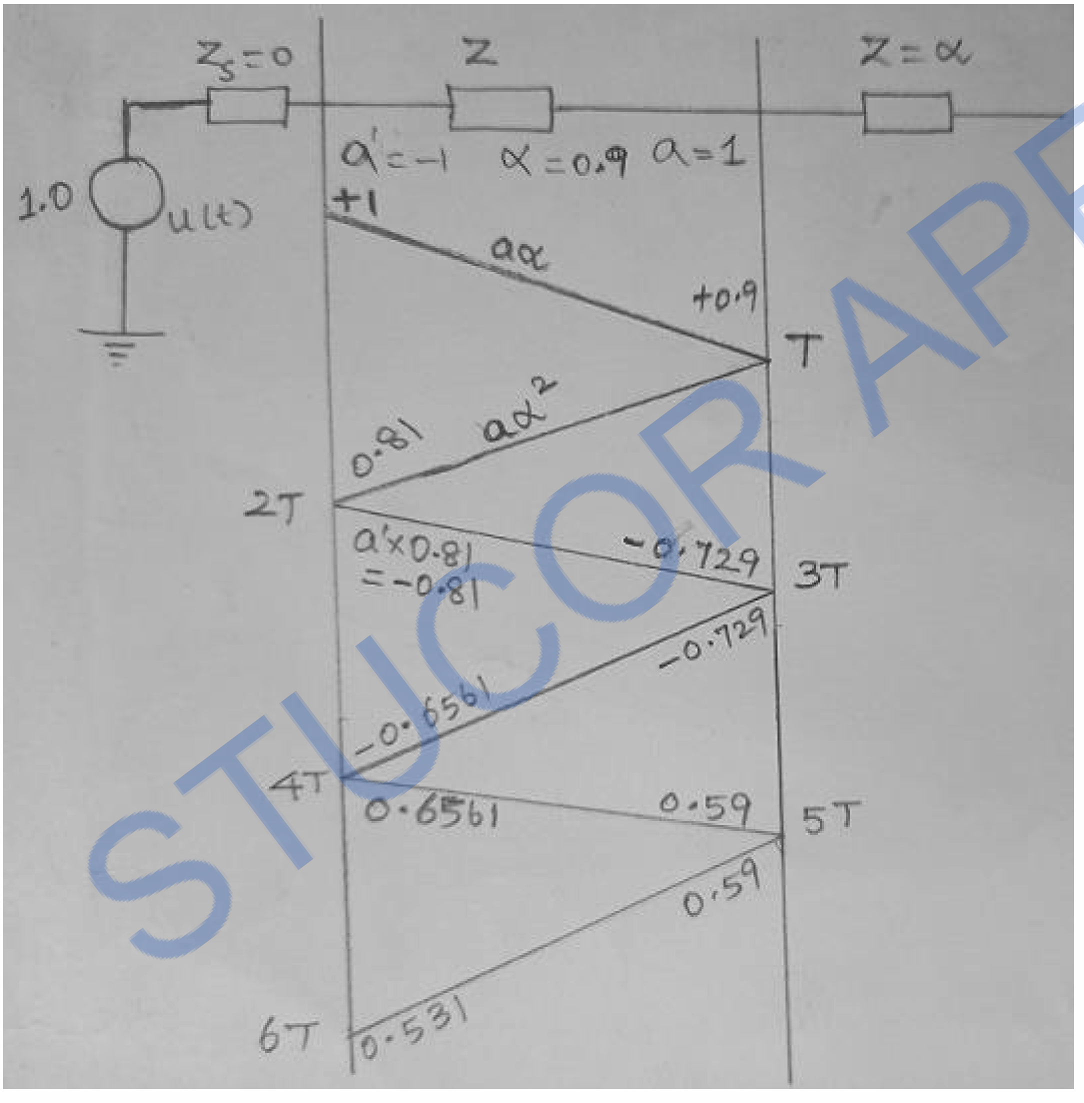
Refelection coefficient, $a = \frac{(\infty - Z)}{(\infty + Z)} = 1.0$

At the sending end,

Reflection coeeficient, $a' = \frac{(0 - Z)}{(0 + Z)} = -1.0$

Lattice diagram is





Zs=0
Z
Z=α
1.0
u(t)
a'=-1
α=0.9
a=1
+1
aα
+0.9
T
aα²
0.81
2T
a'×0.81
=-0.81
-0.729
3T
-0.729
-0.6561
4T
0.6561
0.59
5T
0.59
6T
0.531

- As a travelling wave moves along a line, it suffers both **attenuation** and **distortion**.
- The decrease in the magnitude of the wave as it propagates along the line is called ***attenuation***.
- The elongation or change of wave shape that occurs is called ***distortion***.
- Sometimes, the steepness of the wave is reduced by distortion. Also, the current and voltage wave shapes become dissimilar even though they may be the same initially.
- Attenuation is caused due to the energy loss in the line and distortion is caused due to the inductance and capacitance of the line.
- The energy loss may be in the conductor resistance as modified by the skin effect, changes in ground resistance, leakage resistance and non-uniform ground resistances etc.
- In short cable lengths, or lines tapped at intervals, the travelling waves encounter successive reflections at the transition point. It is extremely difficult to calculate the multiplicity of these reflections
- Bewley has given the

Protection against Lightning Over voltages and Switching Surges of short Duration

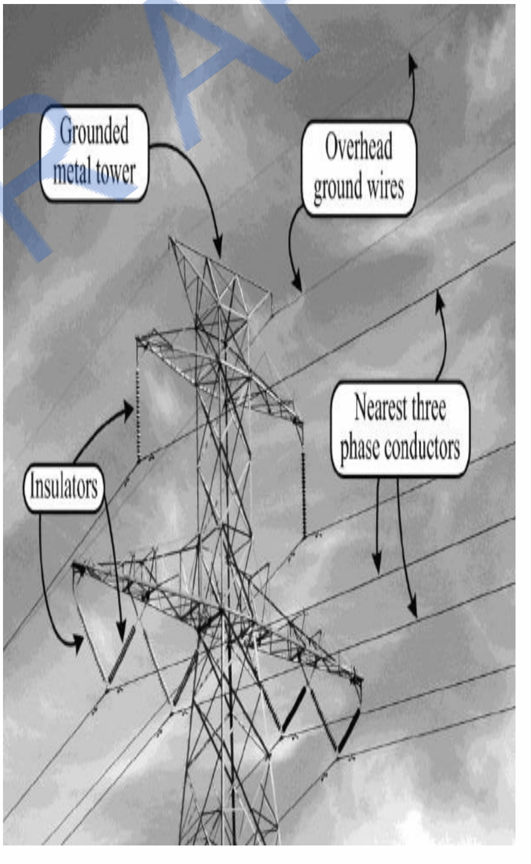
- Protection of transmission lines **against natural or lightning over voltages** and minimizing the lightning over voltages are done by suitable line designs, providing **guard and ground wires**, and using **surge diverters**

Switching surges and power frequency over voltages are accounted for by **providing greater insulation levels** and with proper insulation co-ordination

Over voltages due to lightning strokes can be avoided or minimized in practice by

(A) SHIELDING THE OVERHEAD LINES BY USING GROUND WIRES ABOVE THE PHASE 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



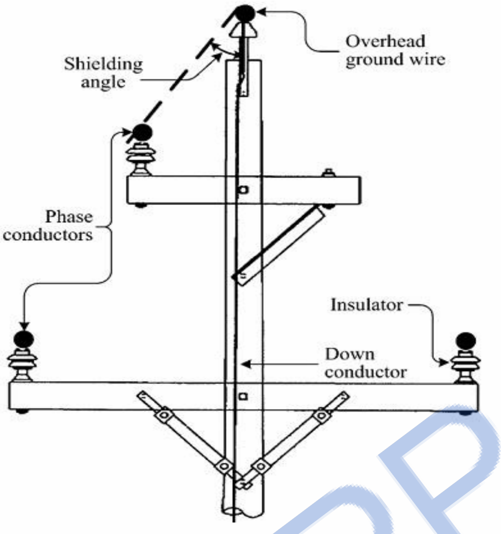
The conducting tower structure serves the purpose of down conductor to earth for Lightening Strikes

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

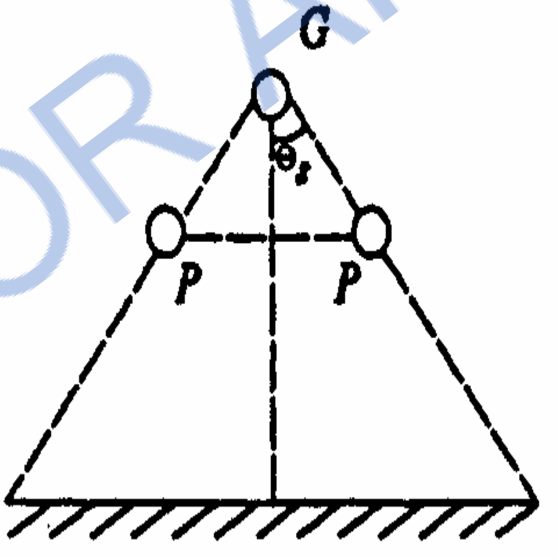
The effective protection or shielding given by the ground wire depends on the height of the ground wire above the ground (H) and the protection or shielding angle (usually 30°)

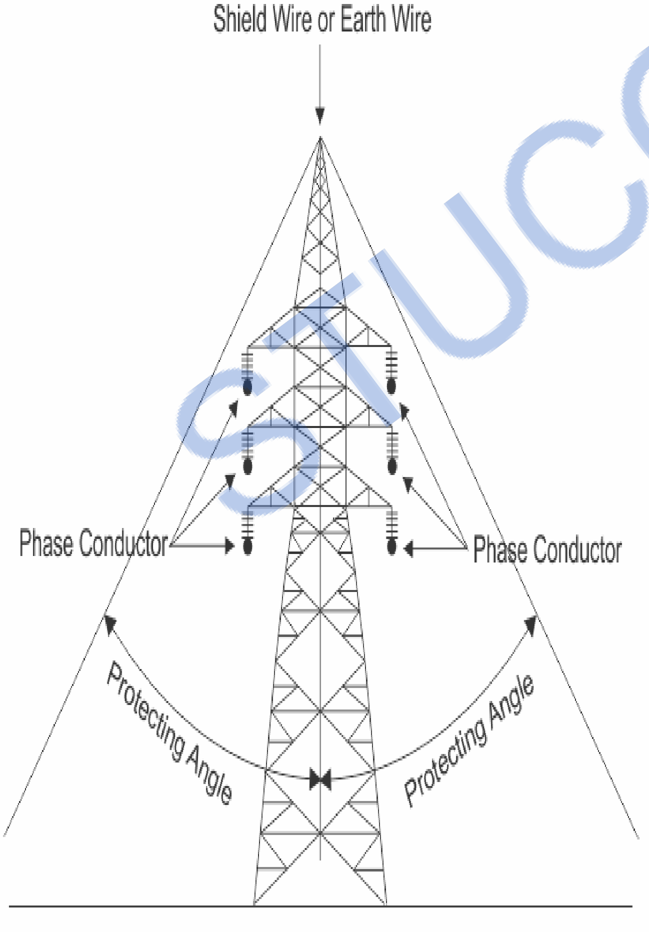
Shielding Angle

The **Shielding Angle** is defined as the angle between an imaginary vertical line extending downward from the overhead ground wire and an imaginary line connecting the ground wire and phase conductor, as shown in figure below.



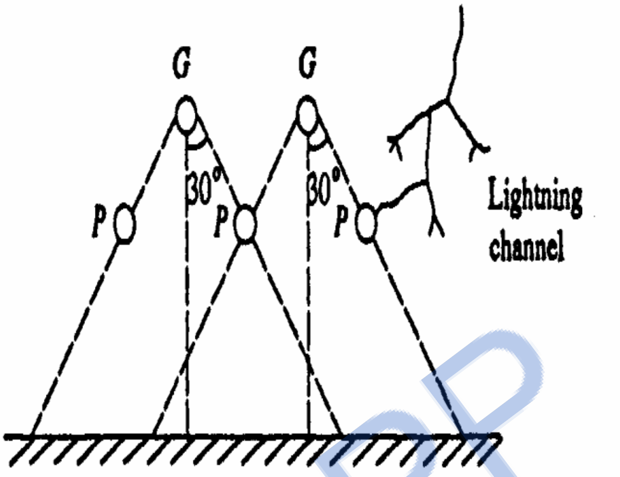
The shielding angle 30° was considered adequate for tower heights of 30 m or less





Failure modes

Lightning current injected into an overhead ground wire can result in "back-flashover" from the ground wire to a phase wire if the resultant voltage on the ground wire is high enough, as can occur if there is the combination of a large lightning current and inadequate grounding of the overhead ground wire.



Lightning may bypass an overhead ground wire and **strike a phase wire directly** if the overhead ground wire is not properly located, and sometimes even if it is.

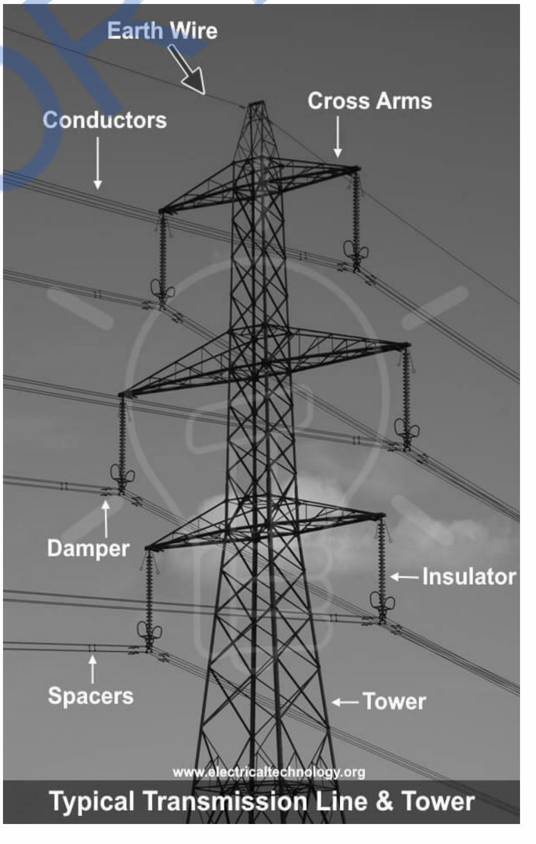
Thus the ground wire reduces the instantaneous potential to which the tower top rises considerably, as the current path is in three directions

The instantaneous potential to which tower top can rise is

- $V_T = I_0 \dfrac{Z_T}{1+\frac{Z_T}{Z_s}}$

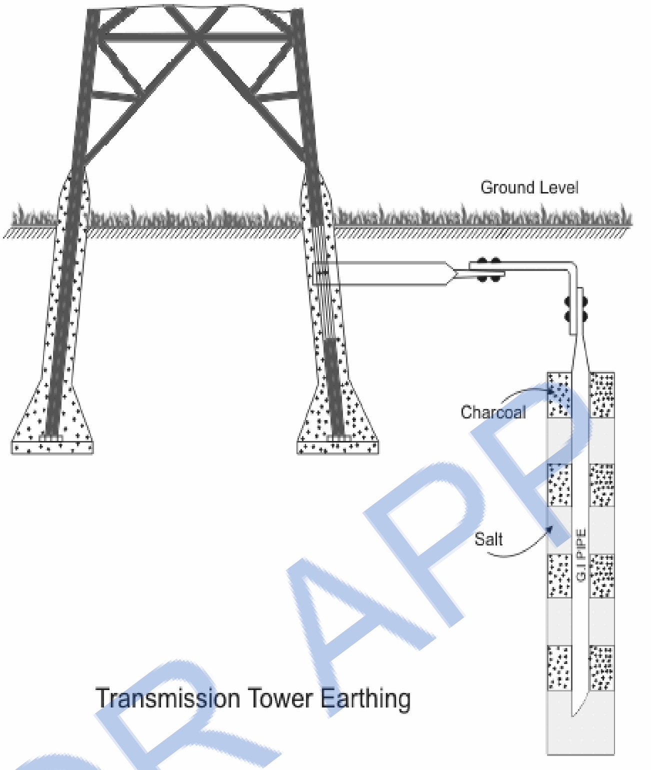
Where Z_T = Surge impedance of the tower

Z_s = Surge impedance of the ground wire



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 (**pipe Earthing system)**
- (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



Transmission Tower Earthing

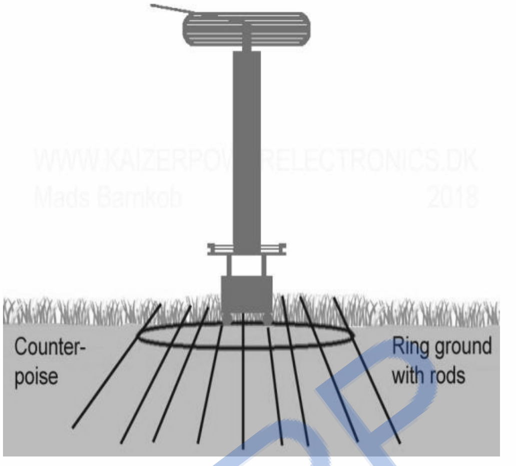
Pipe type Earthing

Ground rods are a number of rods about IS mm diameter and 2.5 to 3 m long driven into the ground
They are usually made of galvanized iron or copper bearing steel

Pipe Type Earthing

Counterpoise earth wires

Counterpoise 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 *ohm*

(C) INCLUDING PROTECTIVE DEVICES LIKE EXPULSION GAPS, PROTECTOR TUBES ON THE LINES, AND SURGE DIVERTERS AT THE LINE TERMINATIONS AND SUBSTATIONS.

Lightning arresters or surge diverters are used to protect the earth screen and ground wires in an electrical system against direct lightning strokes. They conduct the high voltage surges to the ground without getting affected to the system. The lightning arrestor provides a cone of protection which has a ground radius approximately equal to its height above the ground.

The **surge diverters** consist of a spark gap in series with a nonlinear resistor. The function of non linear resistor is very important. As the gap sparks over, due to the over voltage, the arc would get short circuited and may cause power flow current in the arrester. Since the characteristic of the resistor is to offer high resistance to high voltage, it prevents the effect of a **short circuit**. After the surge is over, the resistor offers high resistance to make the gap non-conducting.

Working of lightning arrester

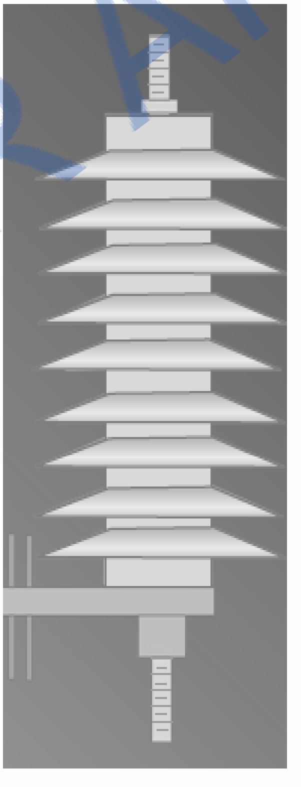
The lightning arrestor protects the structure from damage by intercepting flashes of lightning and transmitting their current to the ground. Since lightning strikes tends to strike the highest object in the vicinity, the rod is placed at the apex of a tall structure. It is connected to the ground by low-resistance cables. In the case of a building, the soil is used as the ground, and on a ship, water is used. A lightning rod provides a cone of protection, which has a ground radius approximately, equal to its height above the ground

What exactly does a surge arrester do

- Surge arresters does not absorb the lightning.

  Surge arresters does not stop the lightning.

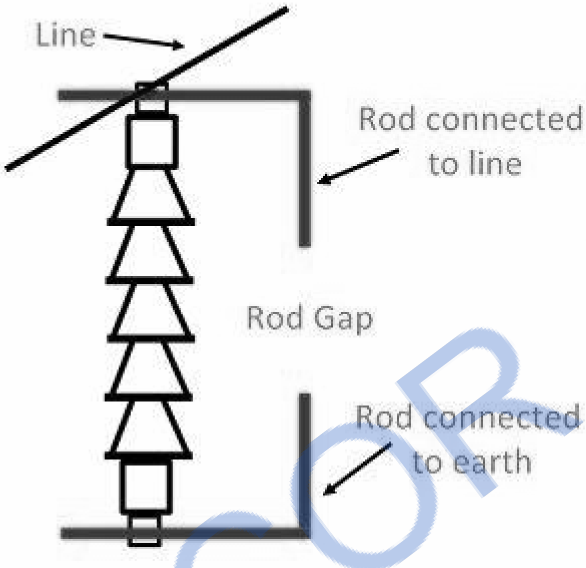
  Surge arresters divert the lightning to the ground.
- Surge arresters limit the voltage produced by lightning.



- Types of Lightning/Surge Arrestors
- Rod Gap **Arrester**.
- Sphere Gap **Arrester**.
- Horn Gap **Arrester**.
- Multiple-Gap **Arrester**.
- Impulse Protective Gap.
- Electrolytic **Arrester**.
- Expulsion **Type Lightning Arrester**.
- Valve **Type Lightning Arresters**.

Rod Gap Arrester

It is one of the simplest forms of the arrester. In such type of arrester, there is an air gap between the ends of two rods. The one end of the arrester is connected to the line and the second end of the rod is connected to the ground. The gap setting of the arrester should be such that it should break before the damage. When the high voltage occurs on the line, the gap sparks and the fault current passes to the earth. Hence the equipment is protected from damage.



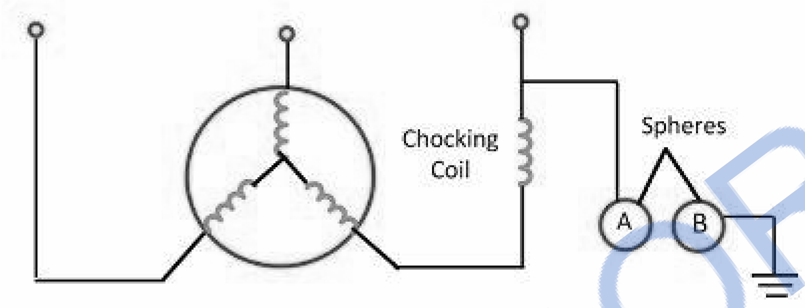
Rod gap on an insulator string

The difficulty with the rod arrester is that once the spark having taken place it may continue for some time even at low voltages. To avoid it a current limiting reactor in series with the rod is used. The resistance limits the current to such an extent that it is sufficient to maintain the arc. Another difficulty with the road gap is that the rod gap is liable to be damaged due to the high temperature of the arc which may cause the rod to melt.

Sphere Gap Arrester

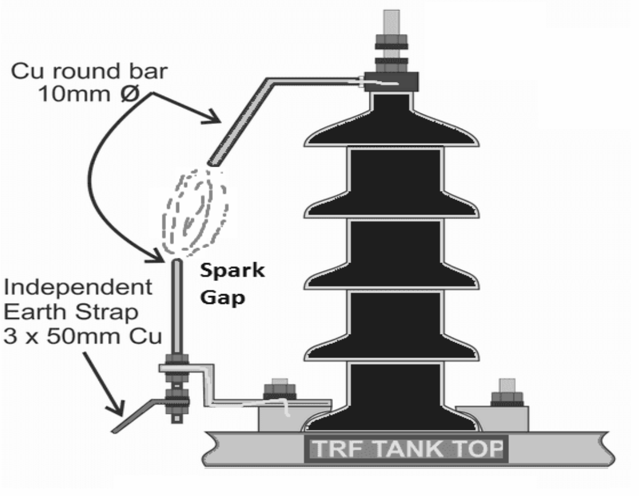
In such type of devices, the air gap is provided between two different spheres. One of the spheres is connected to the line, and the other sphere is connected to the ground. The spacing between the two spheres is very small. A choking coil is inserted between the phase winding of the transformer and spheres is connected to the line.

The air gap between the arrester is set in such a way so that the discharge must not take place at normal operating condition. The arc will travel up the sphere as the heated air near the arc tend to rise upward and lengthening till it is interrupted automatically.



Sphere Gap

Horn gap Arrester



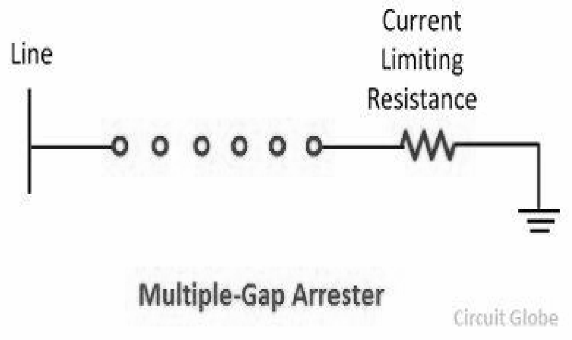
It consists of two horns shaded piece of metal separated by a small air gap and connected in shunt between each conductor and earth. The distance between the two electrodes is such that the normal voltage between the line and earth is insufficient to jump the gap.

But the abnormal high voltage will break the gap and so find a path to earth. There is no current limiting device provided so as to limit the current after spark over, 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 thunderstorm activity is less and the lines are protected by ground wires.

Multiple- Gap Arrester

The multiple gap arrester consists a series of small metal cylinder insulated from one another and separated by an air gap. The first and the last of the series is connected to ground. The number of gaps required depends on the line voltage.



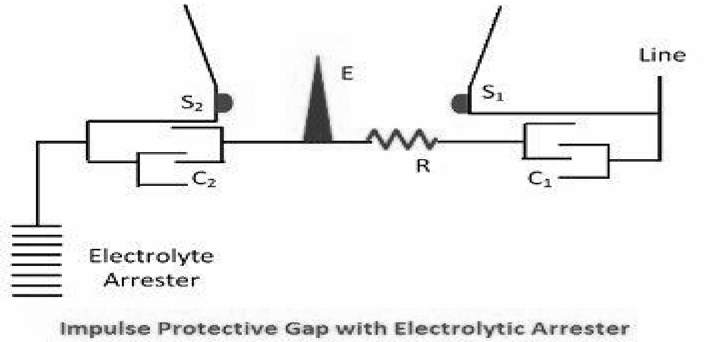
Multiple-Gap Arrester

Impulse Protective Gap

The protective impulse gap is designed to have a low voltage impulse ratio, even less than one and to extinguish the arc. Their working principle is very simple as shown in the figure below. It consists of two sphere electrode S_1 and S_2 which are connected respectively to the line and the arrester.

The auxiliary needle is placed between the mid of two sphere S_1 and S_2. At normal frequency, the impedance of the capacitance C_1 is quite large as compared to the impedance of resistor R. If C_1 and C_2 are equal the potential of the auxiliary electrode will be midway between those of the S_1 and S_2 and the electrode has no effect on the flash over between them.

When the transient occurs the impedance of capacitor C_1 and C_2 decrease and the impedance of the resistor now become effective. Due to this, the whole of the voltage is concentrated across the gap between E and S_1. The gap at once breakdown, the rest of the length between E and S_2 immediately follow.



Impulse Protective Gap with Electrolytic Arrester

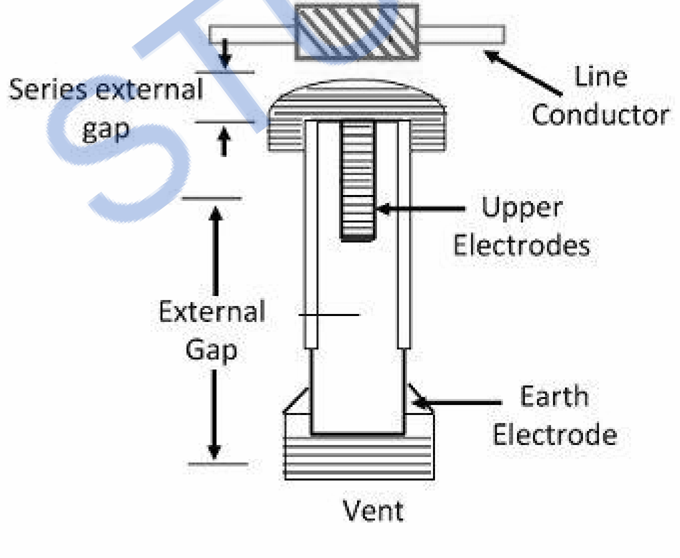
Electrolyte Arrester

In such type of arrester have high a large discharge capacity. It operates on the fact that the thin film of aluminium hydroxide deposits on the aluminium plates immersed in the electrolyte. The plate acts as a high resistance to a low value but a low resistance to a voltage above a critical value. Voltage more than 400 volts causes a puncture and a free flow of current to earth. When the voltage remains its normal value of 440 volts, the arrester again offers a high resistance in the path and leakage stops.

Expulsion Type Lightning Arrester

Expulsion type arrester is an improvement over the rod gap in that it seals the flow of power frequency follows the current. This arrester consists of a tube made up of fibre which is very effective, isolating spark gap and an interrupting spark gap inside the fibre tube.

During operation, the arc due to the impulse spark over inside the fibrous tube causes some fibrous material of the tube to volatile in the form of the gas, which is expelled through a vent from the bottom of the tube. Thus, extinguishing the arc just like in circuit breakers.



Expulsion-type Surge Diverter

Expulsion type lightning arrester is also known as a protector tube. It consists of – (i) a tube made of fibre which is very effective gas-evolving material (ii) an isolating spark gap (or external series gap) and (iii) an interrupting spark gap inside the fibre tube.

During operation arc due to the impulse spark-over inside the fibrous tube causes some fibrous material of the tube volatized in the form of gas, which is expelled through a vent from the bottom of the tube, thus extinguishing the arc just like in circuit breakers. Since the gases generated have to be expelled, one of the electrode is hollow and the diverter is open at its lower end.

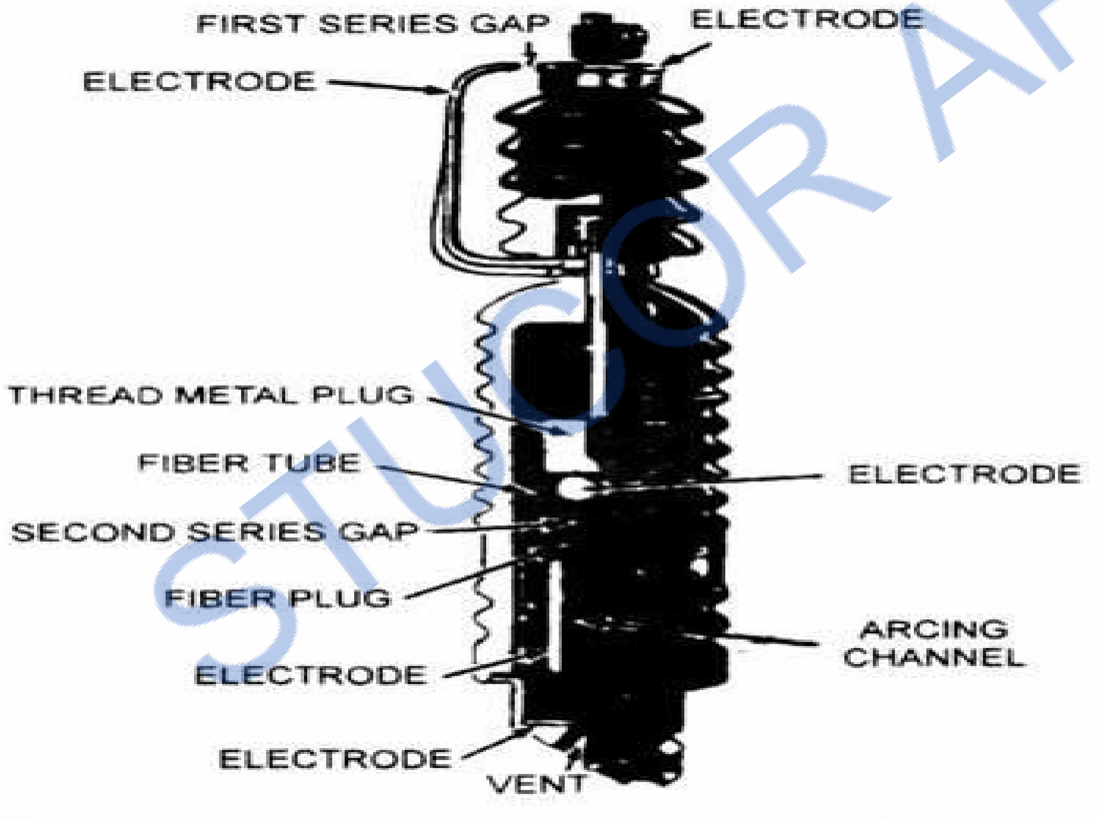


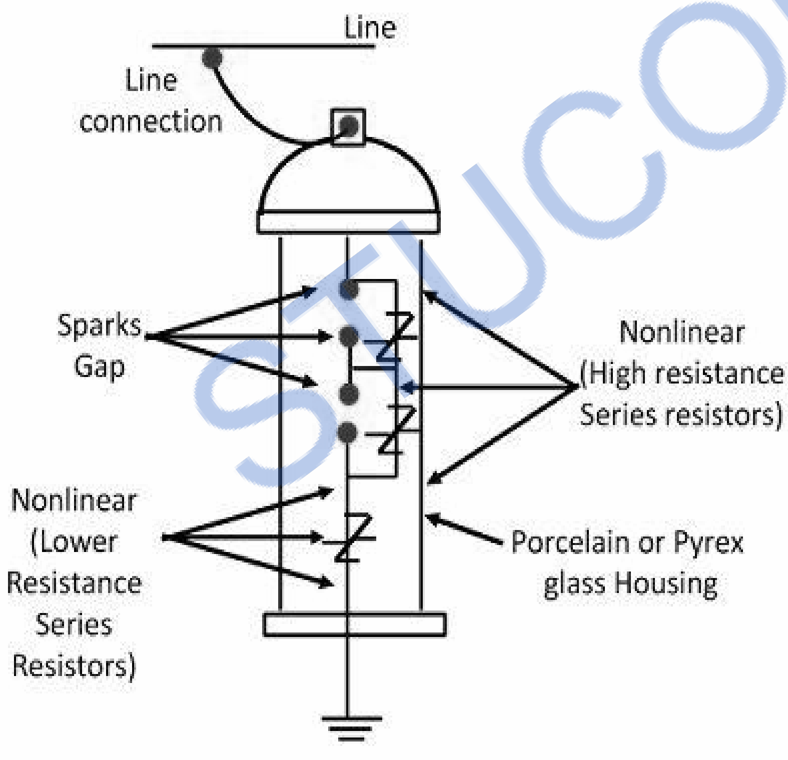
Fig. 9.26. ***Expulsion Type Lightning Arrester***

Valve Type Lightning Arrester

Such type of resistor is called nonlinear diverter. It essentially consists a divided spark gap in series with a resistance element having the nonlinear characteristic.

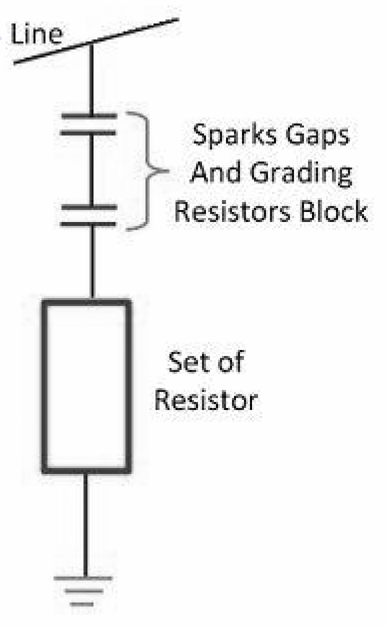
The divided spark gap consists of some identical elements coupled in series. Each of them consists two electrodes with the pre-ionization device. Between each element, a grading resistor of high ohmic value is connected in parallel.

During the slow voltage variations, there is no sparks-over across the gap. But when the rapid change in voltage occurs, the potential is no longer evenly graded across the series gap. The influence of unbalancing capacitance between the sparks gaps and the ground prevails over the grounded resistance. The impulse voltage is mainly concentrated on the upper spark gap which in spark over cause the complete arrester to spark over to.



Valve Type Lightning Arrester

Circuit Globe



Valve Type Lightning Arrester

Circuit Globe

Surge Diverters

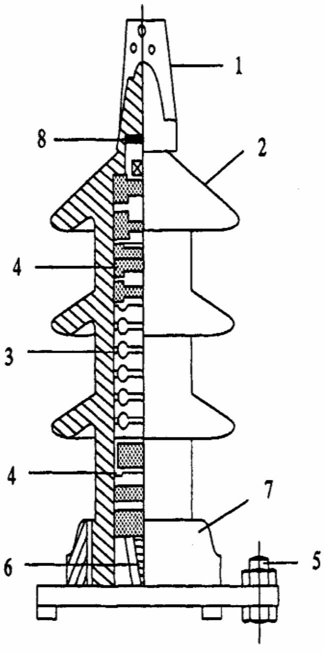


Fig. 8.23 Non-linear element surge diverter

These are non-linear resistors in series with spark gaps which act as fast switches. A typical surge diverter or lightning arrester is shown in Fig

A number of non-linear resistor elements made of silicon carbide are stacked one over the other into two or three sections. They are usually separated by spark gaps

the entire assembly is housed in a porcelain water-tight housing

The volt-ampere characteristic of a resistance element is of the form

$$I = kV^a \tag{8.43}$$

I = discharge current,

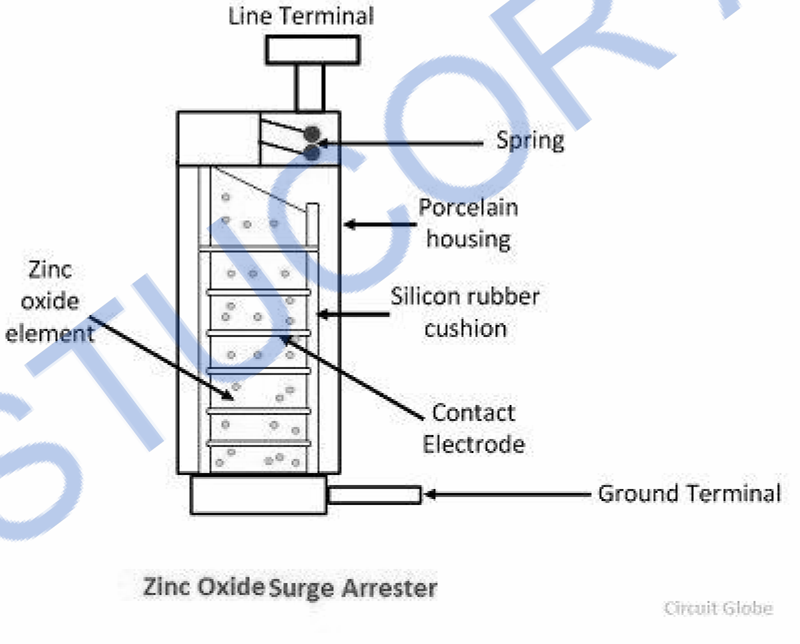
V = applied voltage across the element, and

k and a are constants depending on the material and dimensions of the element.

Metal Oxide Lightning Arrester

Such Types of diverter are also known as gapless surge diverters, or Zinc oxide diverter. The base material used for manufacturing metal oxide resistor is zinc oxide. It is a semiconducting N-type material. The material is doped by adding some fine power of insulating oxides. The powder is treated with some processes and then it is compressed into a disc-shaped. The disc is then enclosed in a porcelain housing filled with nitrogen gas or SF6.

This arrester consists a potential barrier at the boundaries of each disc of ZNO. This potential barrier controls the flow of current. At normal operating condition, the potential barrier does not allow the current to flow. When an overvoltage occurs, the barrier collapse and sharp transition from insulating to conducting take place. The current start flowing and the surge is diverted to ground.



Zinc Oxide Surge Arrester

Assignment-Unit 1

1.Explain the theory of lightning

2. Explain working Diiferent types of Surge arrestors.

Part-A 2 Marks Questions

1. What are the types of over voltages? (/ abnormalities) (CO1-K1)

Lightning over voltages, Switching over voltages, power frequency overvoltage's.

2. Explain the various regions of the cloud. (CO1-K1)

The upper regions of the cloud are positively charged, whereas the lower region and the base are predominantly negative except the local region near the base and the head which is possible.

3. Mention the different theories of charge formation. (CO1-K1)

Simpson's theory, Reynolds's theory and Mason's theory

4.What does a thunder cloud consist? (CO1-K1)

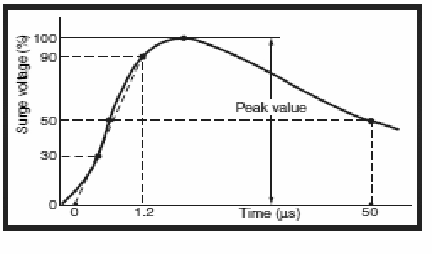
A thunder cloud consists of super cooled water droplets moving upwards and large hailstones moving downwards.

5. What is back flashover? (CO1-K1)

When a direct lightning stroke occurs on a tower, the tower has to carry huge impulse currents. If the tower footing resistance is considerable, the potential of the tower rises to a large value, steeply with respect to the line and consequently a flashover may take place along the insulator strings .This is known as back flashover.

6.State the parameters and the characteristics of the lightning strokes(lightning /voltage). (CO1-K1)

Amplitude of the current, the rate of rise, the probability distribution of them and the wave shapes of the lightning voltages and currents.



7.Define Isokeraunic level or thunderstorm days. (CO1-K1)

It is defined as the number of days in a year when the thunder is heard or recorded in a particular location. Often it does not distinguish between the ground strokes and the cloud-to-cloud strokes.

8.State the factors influence the lightning induced voltages on transmission lines. (CO1-K1)

The ground conductivity, the leader stroke current and the corona.

9.State the attenuation and distortion of travelling waves. (CO1-K1)

The decrease in the magnitude of the wave as it propagates along the line is called attenuation. The elongation or change of wave shapes that occur is called distortion.

10. When over voltages are generated in EHV system? (CO1-K1)

Over voltages are generated in EHV systems when there is a sudden release of internal energy stored either in the electrostatic form or in the electromagnetic form.

11. What are the causes for power frequency and its harmonic over voltages? (CO1-K1)

Sudden loss of loads, Disconnection of inductive loads or connection of capacitive loads, Ferranti effect, unsymmetrical faults and saturation in transformers etc.

12.What are the uses of shunt reactors? (CO1-K1)

used to limit the voltage rise due to Ferranti effect.

used to reduce surges caused due to sudden energizing.

13.What is ground wire? (CO1-K1)

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.

14. What is the use of ground wire? (CO1-K1)

It shields the transmission line conductor from induced charges, from clouds as well as from a lightning discharge.

15. What is an expulsion gap? (CO1-K1)

Expulsion gap is a device which consists of a spark gap together with an arc quenching device which extinguishes the current arc when the gap breaks over due to overvoltage.

16. Mention the parts of an expulsion gap. (CO1-K1)

It consists of a rod gap in air in air in series with a second gap enclosed within a fiber Tube.

17. What is a protector tube? (CO1-K1)

It is a device which 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.

18. How are the insulation level and the protective safety margin arrived? (CO1-K1)

Selecting the risk of failure, the statistical safety factor and by firing the withstand level of any equipment or apparatus corresponding to 90% or 95% of the withstand voltage.

19. How are the insulation level and the protective safety margin arrived? (CO1-K1)

Selecting the risk of failure, the statistical safety factor and by firing the withstand level of any equipment or apparatus corresponding to 90% or 95% of the withstand voltage.

20. Define Basic Impulse Level. (CO1-K1)

It is defined as the minimum insulation impulse withstands voltage of any power equipment or apparatus. The BIL of a power system is usually chosen as 25% to 30% more than the protective level offered by the protective devices.

21.Mention the various insulation levels in a substation? (CO1-K1)

The bus bar insulation is the highest to ensure the continuity of supply in a substation. The circuit breakers, isolators, instrument and relay transformers are given the next lower limiting level. The power transformers are the costliest and sensitive device and the insulation level for it is the lowest.

22.What are the various types of surge arresters used for EHV and UHV systems? (CO1-K1)

Silicon carbide arresters with spark gaps, Silicon carbide arresters with current limiting gaps and the gapless metal oxide arresters.

23.Write the equation of surge admittance and surge impedance of the transmission line. (CO1-K1)

$Y(S) = C/L\ ((S+\alpha - \beta)\ (S+\alpha + \beta\ ))^{1/2}$

$Z(S) = L/C\ ((S+\alpha-\beta)(S+\alpha-\beta))\ ^{1/2}$

Where α is the attenuation constant and β is the wavelength constant.

Part-B 13 marks Questions

1.Explain the various theories of charge formation in clouds? **(CO1-K1)**

2. Explain Cloud And The Associated theories and Phenomenon. **(CO1-K1)**

3. Derive the Mathematical model for lightning discharge**(CO1-K1)**

4. Describe the causes for switching and power frequency over voltages **(CO1-K1)**

5. Explain various causes of switching surges? **(CO1-K1)**

6. Explain Various Methods of Over Voltage **(CO1-K1)**

5.Explain Bewly's Lattice diagram? **(CO1-K1)**

6. Explain n the construction and working principle of Expulsion gaps and Protector tubes. **(CO1-K1)**

7. Explain in detail the protection of transmission lines against over voltage

(CO1-K1)

Part C- 15 marks questions

1. A long transmission line is energised by a unit-step voltage 1.0 V at the sending end and is open circuited at the receiving end. Construct the Bewley lattice diagram and obtain the value of the voltage at the receiving end after a long time. Take the attenuation factor α = 0.8. **(CO1-K2)**

2. An underground cable of inductance 0.189 mH/km and of capacitance 0.3 μF/km is connected to an overhead line having an inductance of 1.26 mH/km and capacitance of 0.009 μF/km. Calculate the transmitted and reflected voltage and current waves at the junction, if a surge of 200 kV travels to the junction, (i) along the cable, and (ii) along the overhead line **(CO1-K2)**

3. (i) Cloud discharge 14 coulombs within 2ms on to a transmission line during lightening. Estimate the voltage produced at the point of stroke on the transmission line. Assume the surge impedance of the line is 350 ohm.(8)

   (ii) An overhead line has inductance of 1.26 mH/km and capacitance of 0.009μF/km. Calculate the voltage developed when lightning strikes transmission line injecting a current of 15kA (7)

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- https://www.udemy.com/course/protection-and-control-of-high-voltage-power-circuits/

  Protection and control of high voltage power circuit

Real time Applications in day to day life and to Industry

Distribution

- Electrical transmission and distribution lines for electric power typically use voltages between tens and hundreds of kilovolts. The lines may be overhead or underground. High voltage is used in power distribution to reduce ohmic losses when transporting electricity long distance.
- High voltage is used in electrical power distribution, in cathode ray tubes, to generate X-rays and particle beams, to produce electrical arcs, for ignition, in photomultiplier tubes, and in high-power amplifier vacuum tubes, as well as other industrial, military and scientific applications.

Industrial

It is used in the production of semiconductors to sputter thin layers of metal films on the surface of the wafer. It is also used for electrostatic flocking to coat objects with small fibers that stand on edge.

Thank you

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HIGH VOLTAGE ENGINEERING

Department: Electrical and Electronics Engineering

Batch/Year: 2017-2021 Subject code : EE8701

Created by: K.GUNALAN M.E.,(Ph.D)
Associate Professor/EEE
RMK College of Engineering and Technology

Table of Contents

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Course Objectives

To impart knowledge on the following Topics

1. Various types of over voltages in power system and protection methods.
2. Generation of over voltages in laboratories.
3. Measurement of over voltages.
4. Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.
5. Testing of power apparatus and insulation coordination

Pre Requisites (Course Names with Code)

EE8402- Transmission and Distribution
EE8501 Power System Analysis
EE8602 Protection and Switchgear

SYLLABUS

EE8701 HIGH VOLTAGE ENGINEERING **L T P C**

3 0 0 3

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UNIT I OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS 9

Causes of over voltages and its effects on power system – Lightning, switching surges and temporary over voltages, Corona and its effects – Bewley lattice diagram- Protection against over voltages.

UNIT II DIELECTRIC BREAKDOWN 9

Properties of Dielectric materials - Gaseous breakdown in uniform and non-uniform fields – Corona discharges – Vacuum breakdown – Conduction and breakdown in pure and commercial liquids, Maintenance of oil Quality – Breakdown mechanisms in solid and composite dielectrics- Applications of insulating materials in electrical equipments.

UNIT III GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

Generation of High DC voltage: Rectifiers, voltage multipliers, vandigraff generator: generation of high impulse voltage: single and multistage Marx circuits – generation of high AC voltages: cascaded transformers, resonant transformer and tesla coil-generation of switching surges – generation of impulse currents - Triggering and control of impulse generators.

UNIT IV MEASUREMENT OF HIGH VOLTAGES AND HIGH CURRENTS

High Resistance with series ammeter – Dividers, Resistance, Capacitance and Mixed dividers - Peak Voltmeter, Generating Voltmeters - Capacitance Voltage Transformers, Electrostatic Voltmeters – Sphere Gaps - High current shunts- Digital techniques in high voltage measurement.

UNIT V HIGH VOLTAGE TESTING & INSULATION COORDINATION 9

High voltage testing of electrical power apparatus as per International and Indian standards – Power frequency, impulse voltage and DC testing of Insulators, circuit breakers, bushing, isolators and transformers- Insulation Coordination& testing of cabilitys.

TOTAL : 45 PERIODS

COURSE OUTCOME

Course Outcome		Level of Knowledge
CO1	Interpret the causes and Protection of power systems over voltages	K2
CO2	Explain the breakdown mechanism of different dielectrics	K1
CO.3	Illustrate the generation of High voltages and currents	K2
CO4	Summarize the methods of HV measurements	K2
CO5	Analyze the testing of power system apparatus	K2
CO6	Compute the importance of insulation coordination	K2

PROGRAM OUTCOMES (POs)

a. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
b. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
c. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
d. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
e. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
f. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
g. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
h. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
i. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
j. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
k. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary **environments.**
l. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES (PSOs)

PSO 1: Design and analyze electrical systems incorporating electrical machines, power controllers along with the design of electrical layout for the complete structure.

PSO 2 : Use the modern tools for implementing the solutions to engineering problems that can arise in the fields of Electrical, Electronics and Telecommunication Engineering along with Information Technology Services.

PSO 3 : Face the challenges in the society by adopting the non-conventional energy resources and utilizing the modern technologies for energy efficient transmission and power quality improvement delivering clean energy for the well being of the mankind.

COs - POs/PSOs MATRICES

COs	PO												PSO		
	a	b	c	d	e	f	g	h	i	j	k	l	**1**	**2**	**3**
CO1	**3**	**3**	**1**	**1**				-	-	-	-		1	-	-
CO2	**3**	3	1	1				-	-	-	-		1	-	-
CO3	**3**	3	2	1				-	-	-	-		2	2	-
CO4	**3**	3	2	1				-	-	-	-		1	2	-
CO5	**3**	3	2	1				-	-	-	-		1	2	-
CO6	**3**	3	2	1				-	-	-	-		2	1	-

Relevance: 1: Slight (Low) 2: Moderate (Medium) 3: Substantial (High)

UNIT-II
LECTURE PLAN

S. NO	TOPIC	No. of Periods	Proposed date	Actual Lecture Date	Pertaining CO	Taxonomy level	Mode of Delivery
1	Properties of Dielectric materials				CO2	K1	Power Point Presentation
2	Gaseous breakdown in uniform and non-uniform fields				CO2	K1	Power Point Presentation
3	Corona discharges				CO2	K1	Power Point Presentation
4	Vacuum breakdown				CO2	K1	Power Point Presentation
5	Conduction and breakdown in pure and commercial liquids				CO2	K1	Power Point Presentation
6	Maintenance of oil Quality				CO2	K1	Power Point Presentation
7.	Breakdown mechanisms in solid				CO2	K1	Power Point Presentation
8.	composite dielectrics				CO2	K1	Power Point Presentation
9.	Applications of insulating materials in electrical equipment's.				CO2	K1	Power Point Presentation

E Books

1. https://b-ok.asia/book/541362/93a5bb

   High voltage engineering , by C.L Wadhwa

2. https://b-ok.asia/book/593383/a732c8

   High voltage engineering by MS.Naidu &V.Kamaraju

3. https://b-ok.asia/book/462609/d72278

   High Voltage Engineering Fundamentals, by E. Kuffel and W.S. Zaengl, J.Kuffel

4. https://b-ok.asia/book/1132470/e51f4c

   High-voltage engineering: theory and practice, by Mazen Abdel – Salam, Hussein Anis, Ahdab A-Morshedy, Roshday Radwan

VIDEO LINKS

TITLE	LINK
The Science of Lightning	https://www.youtube.com/watch?v=h-0gNl5f4BU
Thunderstorms	https://www.youtube.com/watch?v=zUNEFefftt8
Lightning physics	https://www.youtube.com/watch?v=JJubgrI0T0g
Switching surges	https://www.youtube.com/watch?v=4-Lu1vnH_d8
500 kV Motor Operated Disconnect Switch	https://www.youtube.com/watch?v=MqICjzh-cgQ
500kv air switches being closed	https://www.youtube.com/watch?v=BlutEhZyN2I
Surge Arrestors	https://www.youtube.com/watch?v=vpcRY0SLt1o
Lightning Arrestor- how its made	https://www.youtube.com/watch?v=lFTns1TBQ5s

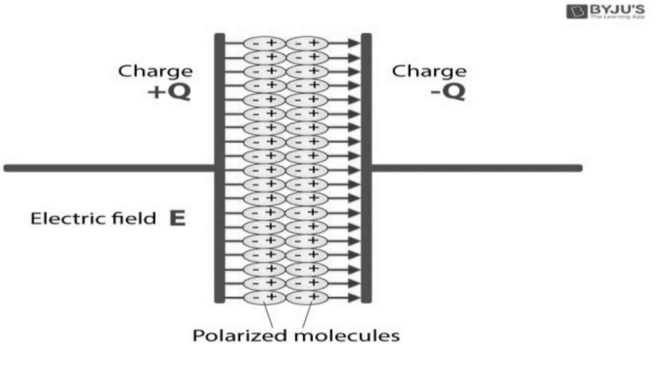
UNIT -II

DIELECTRIC BREAKDOWN

Introduction- Properties of Dielectric Materials

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

A system (transmission, switchgear, etc.) designed for 400 kV and above using conventional insulating materials is both bulky and expensive and, therefore, newer and newer insulating materials are being investigated to bring down both the cost and space requirements. The electrically live conductors are supported on insulating materials and sufficient air clearances are provided to avoid flashover or short circuits between the live parts of the system and the grounded structures. Sometimes, a live conductor is to be immersed in an insulating liquid to bring down the size of the container and at the same time provide sufficient insulation between the live conductor and the grounded container. In electrical engineering all the three media, viz. the gas, the liquid and the solid are being used and, therefore, we study here the mechanism of breakdown of these media.



Dielectric Material

A dielectric material is defined as the non-metallic material with specific resistance high, temperature coefficient of resistance negative and with large insulation resistance. The other way of defining dielectric material is that it is non-conducting material which stores electrical charges. When a dielectric is placed in an electric field, the electric charges do not flow through the material, instead, they cause dielectric polarization by shifting from the mean/equilibrium position. As a result, the positive charges are oriented in the same direction as that of the electric field and negative charges are shifted in the opposite direction. This phenomenon yields an internal electric field, which in turn reduces the overall electric field within the dielectric material. The dielectrics are mostly solids. Some of the dielectrics are composed of weakly bonded molecules. In such scenarios along with polarisation, we can also observe that molecules reorient themselves to align their symmetry axes with the field.

❁ Dielectric Properties

Dielectric properties of materials are defined as a molecular property which is fundamental in all the materials that are capable of impending electron movement resulting in polarization within the material on exposure to an external electric field.

Properties of Dielectric materials

Following are the exhibited by the dielectric materials:

- The energy gap in the dielectric materials is very large.
- The temperature coefficient of resistance is negative and the insulation resistance is high.
- The dielectric materials have high resistivity.
- The attraction between the electrons and the parent nucleus is very strong.
- The electrical conductivity of these materials is very low as there are no free electrons to carry current.

Dielectric Properties of Insulation

Following are the dielectric properties of insulation:

- Breakdown voltage
- Dielectric parameters such as:
- Conductivity
- Power factor
- Loss angle
- Permittivity

Dielectrics	Insulators
Material that can develop an electric field with minimal loss of energy is known as a dielectric.	A substance that has low conductivity and that which obstructs the flow of current is known as an insulator.
Weakly bonded as compared to the insulators	Covalently bonded
Stores charges	Obstructs charges
Their application lies in power cables, capacitors and more	They are used in the high voltage system and conducting wires

Application of Dielectric Properties

Dielectrics are used as a capacitor for storing energy.

The dielectric material in a transformer is used as an insulator and as a cooling agent.

Mechanism Of Breakdown Of Gases

Gaseous breakdown in uniform and non-uniform fields

The simplest and the most commonly found dielectrics are gases. Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as nitrogen (N_2), carbon dioxide (CO_2), freon (CCl_2F_2) and sulphur hexafluoride (SF_6) are also used.

In order to understand the breakdown phenomenon in gases, a study of the electrical properties of gases and the processes by which high currents are produced in gases is essential. The electrical discharges in gases are of two types, i.e.

(i) non-sustaining discharges, and

(ii) self-sustaining types.

The breakdown in a gas, called spark breakdown is the transition of a non-sustaining discharge into a self-sustaining discharge. The build-up of high currents in a breakdown is due to the process known as ionization in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents.

At present two types of theories, viz.

(i) ***Townsend theory***, and

(ii) ***Streamer theory*** are known which explain the mechanism for breakdown under different conditions.

The various physical conditions of gases, namely, pressure, temperature, electrode field configuration, nature of electrode surfaces, and the availability of initial conducting particles are known to govern the ionization processes.

Ionization by Collision

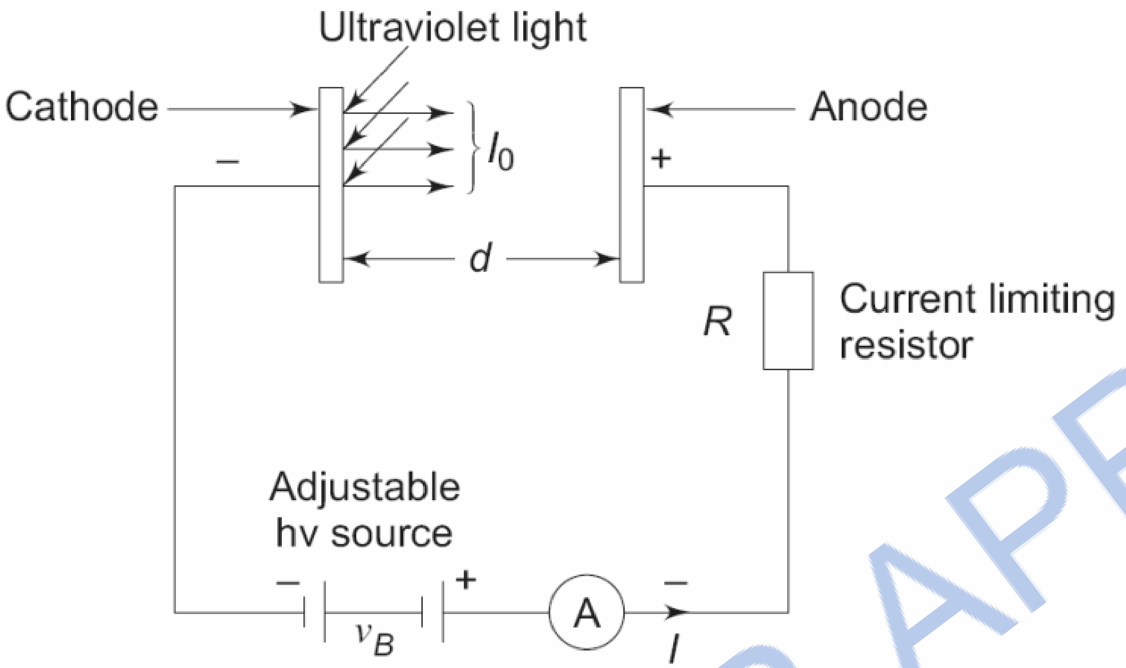
process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionization.

process of ionisation by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion.

If the energy (ϵ) gained during this travel between collisions exceeds the ionisation potential, V_i, which is the energy required to dislodge an electron from its atomic shell, then ionisation takes place.

$$e^- + A \xrightarrow{\varepsilon > V_i} e^- + A^+ + e^-$$

Where, A is the atom, A^+ is the positive ion and e^- is the electron.



A few of the electrons produced at the cathode by some ***external means, say by ultra-violet light falling on the cathode***, ionise neutral gas particles producing positive ions and additional electrons. The additional electrons, then, themselves make 'ionizing collisions' and thus the process repeats itself. This represents an increase in the electron current, since the ***number of electrons reaching the anode per unit time is greater than those liberated at the cathode***. In addition, the ***positive ions also reach the cathode and on bombardment on the cathode give rise to secondary electrons.***

Photo-ionisation

The photo ionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionisation potential. There are several processes by which radiation can be absorbed by atoms or molecules. They are

(a) excitation of the atom to a higher energy state

(b)continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionisation etc.

As an ***excited atom emits radiation*** when the electron returns to the *lower state or to the ground state, the reverse process takes place* when **an atom absorbs radiation**.

This reversible process can be expressed as

$$h\nu + A \rightleftharpoons A^*$$

Ionisation occurs when

$$\lambda \leq c \cdot \frac{h.}{V_i}$$

where, h is the Planck's constant, c is the velocity of light, λ is the wavelength of the incident radiation and V_i is the ionisation energy of the atom. Substituting for h and c, we get

$$\lambda \leq \left(\frac{1.27}{V_i}\right) \times 10^{-6}\text{cm}$$

where V_i is in electron volts *(eV).*

Thermal Ionisation

The term thermal ionisation in general applies to the ionizing actions of molecular collisions, radiation and electron collisions occurring in gases at high temperatures. High temperature, some of the gas molecules acquire high kinetic energy and these particles after collision with neutral particles ionize them and release electrons.

Thermodynamic equilibrium condition the rate of new ion formation must be equal to the rate of recombination. Saha derived an expression for the degree of ionization β in terms of the gas pressure and absolute temperature as follows:

$$\frac{\beta^2}{1-\beta^2} = \frac{1}{p}\frac{(2\pi m_e)^{3/2}}{h}(KT)^{5/2}\ e^{-W/KT}$$

or

$$\frac{\beta^2}{1-\beta^2} = \frac{2.4 \times 10^{-4}}{p} T^{5/2}\ e^{-W_i/KT}$$

where p is the pressure in Torr, W_i the ionization energy of the gas, K the Boltzmann's constant, β the ratio n_i/n and n_i the number of ionized particles of total n particles.

TOWNSEND'S FIRST IONIZATION COEFFICIENT

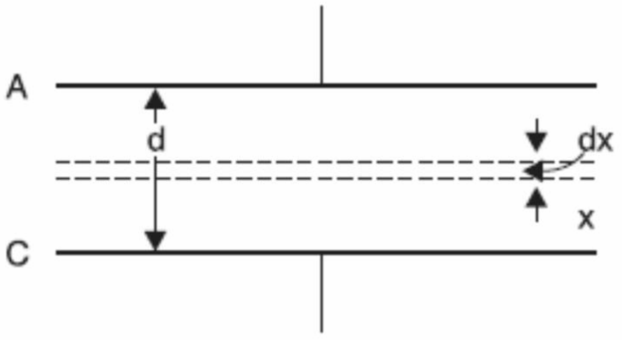


Fig. 1.1 Parallel plate capacitor

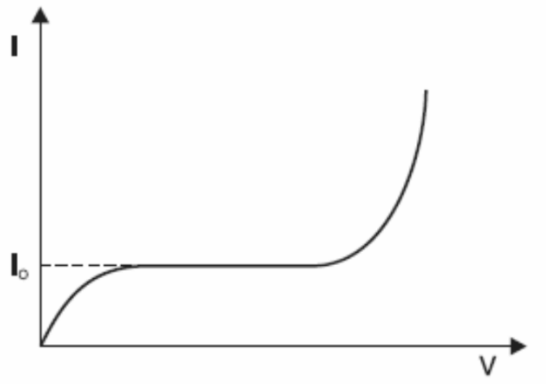


Fig. 1.2 Variation of current as a function of voltage

To explain the exponential rise in current, Townsend introduced a coefficient α known as *Townsend's first ionization coefficient* and is defined as the number of electrons produced by an electron per unit length of path in the direction of field.

Let n_0 be the number of electons leaving the cathode and when these have moved through a distance x from the cathode, these become n. Now when these n electrons move through a distance dx produce additional dn electrons due to collision. Therefore

$$dn = \alpha\, n\, dx$$

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

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

Now at $x = 0$, $n = n_0$. Therefore,

$$\ln n_0 = A$$

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

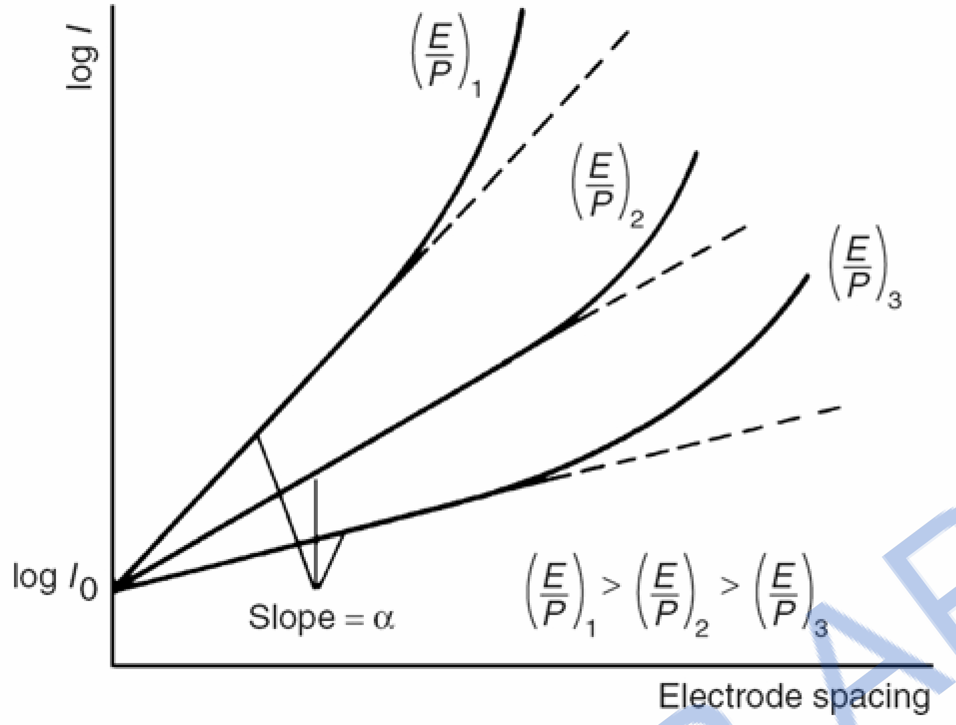
or $$\ln \frac{n}{n_0} = \alpha x$$

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

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

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

TOWNSEND SECOND IONISATION COEFFICIENT



Variation of gap current with electrode spacing in uniform E

Townsend in his earlier investigations had observed that the current in parallel plate gap increased more rapidly with increase in voltage as compared to the one given by the above equation. To explain this departure from linearity, Townsend suggested that a **second mechanism** must be affecting the current. He postulated that **the additional current must be due to the presence of positive ions and the photons**. The positive ions will liberate electrons by collision with gas molecules and by bombardment against the cathode. Similarly, the photons will also release electrons after collision with gas molecules and from the cathode after photon impact.

Let n_0 be the number of electrons released from the cathode by ultraviolet radiation, n_+ the number of electrons released from the cathode due to positive ion bombardment and n the number of electrons reaching the anode.

Let γ, known as *Townsend second ionization co-efficient* be defined as the number of electrons released from cathode per incident positive ion,

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

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

$$n_+ = \nu\,[n - (n_0 + n_+)]$$

or
$$n_+ = \nu n - \nu n_0 - \nu n_+$$

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

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

Substituting n_+ in the previous expression for n, we have

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

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

or
$$(n + \nu n) = n_0\, e^{\alpha d} + \nu n e^{\alpha d}$$

or
$$n + \nu n - \nu n e^{\alpha d} = n_0 e^{\alpha d}$$

or
$$n[1 + \nu - \nu e^{\alpha d}] = n_0 e^{\alpha d}$$

or
$$n = \frac{n_0 e^{\alpha d}}{1 + \nu n(1 - e^{\alpha d})} = \frac{n_0 e^{\alpha d}}{1 - \nu\,(e^{\alpha d} - 1)}$$

In terms of current

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

When voltage between the anode and cathode is increased, the current at the anode is given by

The current becomes infinite if

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

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

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

Since normally $$e^{\alpha d} >> 1$$

The current in the anode equals the current in the external circuit. Theoretically the current becomes infinitely large under the above mentioned condition but practically it is limited by the resistance of the external circuit and partially by the voltage drop in the arc.

The condition $v.e^{\alpha d} = 1$ defines the condition for beginning of spark and is known as the Townsend criterion for spark formation or Townsend breakdown criterion. Using the above equations, the following three conditions are possible.

$ve^{\alpha d} = 1$

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

$ve^{\alpha d} > 1$

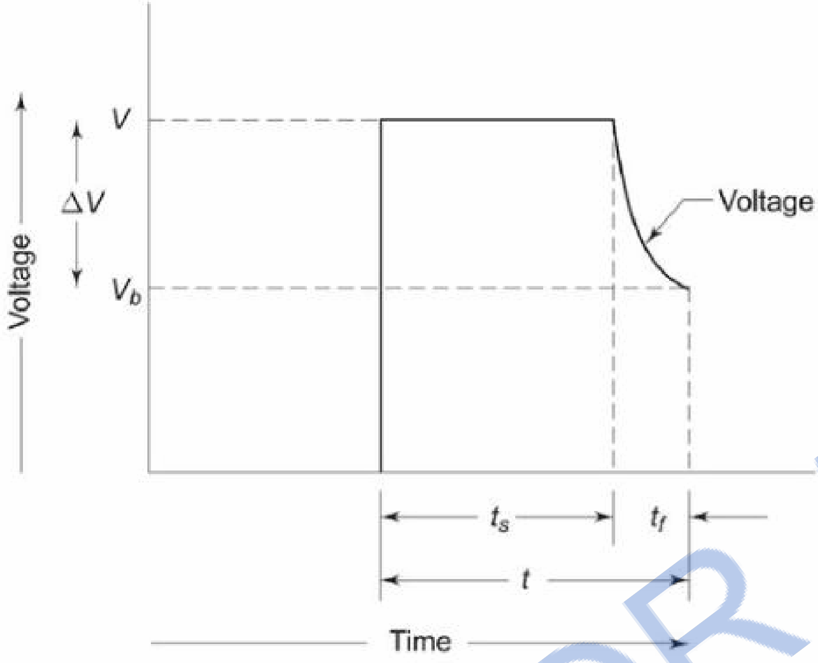
Here ionization produced by successive avalanche is cumulative. The spark discharge grows more rapidly the more $ve^{\alpha d}$ exceeds unity.

$ve^{\alpha d} < 1$

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

Time Lag (t)

The time t which lapses between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag (t_s) of the gap. The appearance of electrons is usually statistically distributed. After the appearance of the electron, a time t_t is required for the ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag (t_f). The total time $t_s + t_t = t$ is called the **total time lag**.



Breakdown with a step function voltage pulse. t_s = statistical time; t_f = formative time; t = total time

Drawbacks in Townsend's Mechanism

Current growth have taken from ionization only, but in practice the breakdown also depends on the pressure and geometry of gap.

The mechanism predicts time lags of the order of 10^{-5}S, while in actual practice breakdown was observed to occur at very short times of the order of 10^{-8}S (Time lag in breakdown).

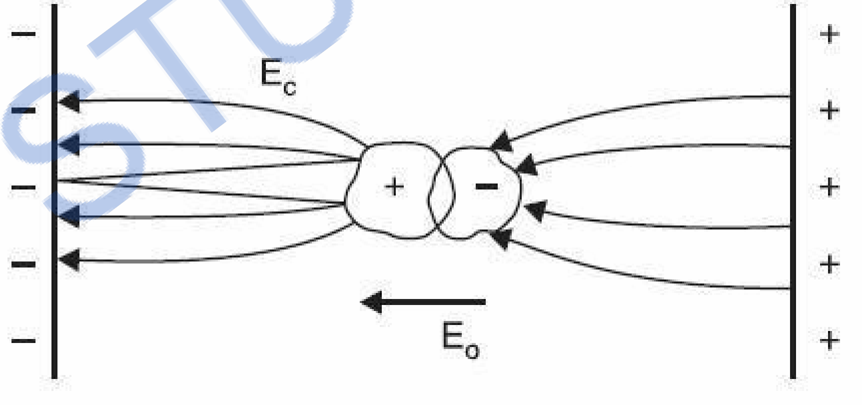
Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular.

Townsend mechanism failed to explain all these observed phenomena and as a result, around 1940, Raether and Meek and Loeb independently proposed the Streamer theory.

Streamer Theory Of Breakdown In Gases

We know that the charges in between the electrodes separated by a distance d increase by a factor $e^{\alpha d}$ when field between electrodes is uniform. This is valid only if we assume that the field E_0=V/d is not affected by the space charges of electrons and positive ions. Raether has observed that if the charge concentration is higher than 10^6 but lower than 10^8 the growth of an avalanche is weakened i.e., dn/dx $<e^{\alpha d}$.

Whenever the concentration exceeds 10^8, the avalanche current is followed by steep rise in current and breakdown of the gap takes place. The weakening of the avalanche at lower concentration and rapid growth of avalanche at higher concentration have been attributed to the modification of the electric field E_0 due to the space charge field. Fig. shows the electric field around an avalanche as it progresses along the gap and the resultant field i.e., the superposition of the space charge field and the original field E_0. Since the electrons have higher mobility, the space charge at the head of the avalanche is considered to be negative and is assumed to be concentrated within a spherical volume. It can be seen from Fig. that the filed at the head of the avalanche is strengthened.



Field redistribution due to space charge

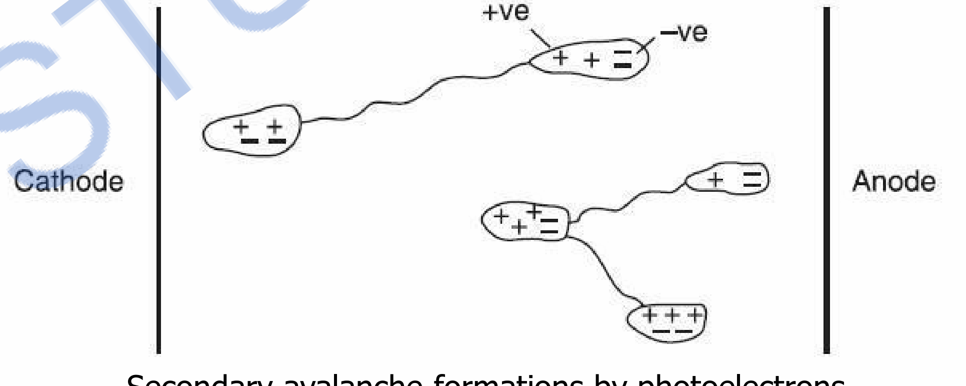
The field between the two assumed charge centres i.e., the electrons and positive ions is decreased as the field due to the charge centres opposes the main field E_0 and again the field between the positive space charge centre and the cathode is strengthened as the space charge field aids the main field E_0 in this region. It has been observed that if the charge carrier number exceeds 10^6, the field distortion becomes noticeable. If the distortion of field is of 1%, it would lead to a doubling of the avalanche but as the field distortion is only near the head of the avalanche, it does not have significance on the discharge phenomenon. However, if the charge carrier exceeds 10^8, the space charge field becomes almost of the same magnitude as the main field E_0 and hence it may lead to initiation of a streamer. The space charge field, therefore, plays a very important role in the mechanism of electric discharge in a non-uniform gap.

Townsend suggested that the electric spark discharge is due to the ionization of gas molecule by the electron impact and release of electrons from cathode due to positive ion bombardment at the cathode. According to this theory, the formative time lag of the spark should be at best equal to the electron transit time tr. At pressures around atmospheric and above $p.d > 10^3$ Torr-cm, the experimentally determined time lags have been found to be much shorter than tr. Study of the photographs of the avalanche development has also shown that under certain conditions, the space charge developed in an avalanche is capable of transforming the avalanche into channels of ionization known as streamers that lead to rapid development of breakdown. It has also been observed through measurement that the transformation from avalanche to streamer generally takes place when the charge within the avalanche head reaches a critical value of

$$n_0 e^{\alpha x} \approx 10^8 \text{ or } \alpha X_c \approx 18 \text{ to } 20$$

where Xc is the length of the avalanche path in field direction when it reaches the critical size. If the gap length d < Xc, the initiation of streamer is unlikely.

The short-time lags associated with the discharge development led Raether and independently Meek and Meek and Loeb to the advancement of the theory of streamer of Kanal mechanism for spark formation, in which the secondary mechanism results from photo ionization of gas molecules and is independent of the electrodes.



Secondary avalanche formations by photoelectrons

Raether and Meek have proposed that when the avalanche in the gap reaches a certain critical size the combined space charge field and externally applied field E_0 lead to intense ionization and excitation of the gas particles in front of the avalanche head. There is recombination of electrons and positive ion resulting in generation of photons and these photons in turn generate secondary electrons by the photo ionization process. These electrons under the influence of the electric field develop into secondary avalanches as shown in Fig. Since photons travel with velocity of light, the process leads to a rapid development of conduction channel across the gap.

Raether after thorough experimental investigation developed an empirical relation for the streamer spark criterion of the form

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

where Er is the radial field due to space charge and E_0 is the externally applied field.

Now for transformation of avalanche into a streamer Er ≈ E

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

For a uniform field gap, breakdown voltage through streamer mechanism is obtained on the assumption that the transition from avalanche to streamer occurs when the avalanche has just crossed the gap. The equation above, therefore, becomes

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

When the critical length Xc ≥ d minimum breakdown by streamer mechanism is brought about. The condition Xc = d gives the smallest value of α to produce streamer breakdown. Meek suggested that the transition from avalanche to streamer takes place when the radial field about the positive space charge in an electron avalanche attains a value of the order of the externally applied field. He showed that the value of the radial field can be obtained by using the expression.

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

where x is the distance in cm which the avalanche has progressed, p the gas pressure in Torr and α the Townsend coefficient of ionization by electrons corresponding to the applied field E. The minimum breakdown voltage is assumed to correspond to the condition when the avalanche has crossed the gap of length d and the space charge field Er approaches the externally applied field i.e., at x = d, Er = E. Substituting these values in the above equation, we have

$$E_r = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha d}}{(d/p)^{1/2}}$$

Taking ln on both the sides, we have

$$\ln E = -14.5 + \ln \alpha - \frac{1}{2} \ln \frac{d}{p} + \alpha d$$

$$\ln \frac{E}{P} = -14.5 + \ln \frac{\alpha}{p} - \frac{1}{2} \ln \frac{d}{p} + \alpha d$$

The experimentally determined values of α/p and the corresponding E/p are used to solve the above equation using trial and error method. Values of α/p corresponding to E/p at a given pressure are chosen until the equation is satisfied.

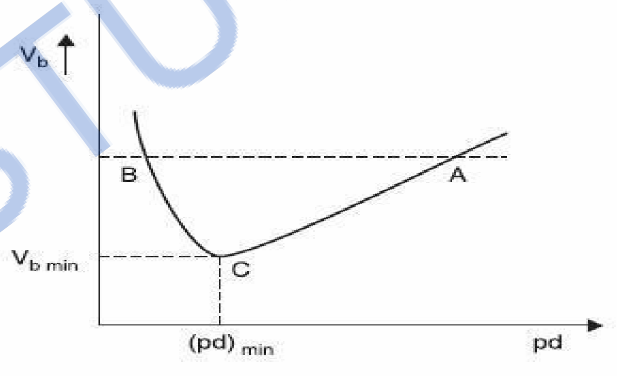
Paschen's Law

The Townsend's Criterion

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

enables the evaluation of breakdown voltage of the gap by the use of appropriate values of α/p and ν corresponding to the values E/p when the current is too low to damage the cathode and also the space charge distortions are minimum. A close agreement between the calculated and experimentally determined values is obtained when the gaps are short or long and the pressure is relatively low. An expression for the breakdown voltage for uniform field gaps as a function of gap length and gas pressure can be derived from the threshold equation by expressing the ionization coefficient α/p as a function of field strength E and gas pressure p i.e

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



Paschen's law curve

Substituting this, we have

$$e^{f\left(\frac{E}{P}\right)Pd} = \frac{1}{\nu} + 1$$

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

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

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

or $V_b = F(p.d)$

This shows that the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and the gap length for a particular gas and electrode material. This relation is known as Paschen's law. This relation does not mean that the breakdown voltage is directly proportional to product pd even though it is found that for some region of the product pd the relation is linear i.e., the breakdown voltage varies linearly with the product pd.

Penning Effect

Paschen's law does not hold good for many gaseous mixtures. A typical example is that of mixture of Argon in Neon.

A small percentage of Argon in Neon reduces substantially the dielectric strength of pure Neon.

In fact, the dielectric strength is smaller than the dielectric strengths of either pure Neon or Argon.

The lowering of dielectric strength is due to the fact that the lowest excited stage of neon is metastable and its excitation potential (16 ev) is about 0.9 ev greater than the ionization potential of Argon.

The metastable atoms have a long life in neon gas, and on hitting Argon atoms there is a very high probability of ionizing them.

This phenomenon is known as Penning Effect.

Corona Discharges

If the electric field is uniform and if the field is increased gradually, just when measurable ionization begins, the ionization leads to complete breakdown of the gap.

However, in non-uniform fields, before the spark or breakdown of the medium takes place, there are many manifestations in the form of visual and audible discharges. These discharges are known as *Corona discharges*.

In fact Corona is defined as a self-sustained electric discharge in which the field intensified ionization is localised only over a portion of the distance (non-uniform fields) between the electrodes.

The phenomenon is of particular importance in high voltage engineering where most of the fields encountered are non-uniform fields unless of course some design features are involved to make the filed almost uniform.

Corona is responsible for power loss and interference of power lines with the communication lines as corona frequency lies between 20 Hz and 20 kHz. This also leads to deterioration of insulation by the combined action of the discharge ion bombarding the surface and the action of chemical compounds that are formed by the corona discharge.

The voltage gradient required to produce visual a.c. corona in air at a conductor surface, called the corona inception field, can be approximately given for the case of parallel wires of radius r as

$$E_v = 30md\left[1 + \frac{0.301}{\sqrt{dr}}\right]$$

For the case of coaxial cylinders, whose inner cylinder has a radius *r* the equation becomes

$$E_c = 31md\left[1 + \frac{0.308}{\sqrt{dr}}\right]$$

where m is the surface irregularity factor which becomes equal to unity for highly polished smooth wires; *d* is the relative air density correction factor given by,

$$d = \frac{0.392b}{(273+t)}$$

where *b* is the atmospheric pressure in torr, and *t* is the temperature in ^{0}C, *d* = 1 at 760torr and 25^{0}C. The expressions were found to hold good from atmospheric pressure down to a pressure of several torr.

On the high voltage conductors at high pressures there is a distinct difference in the visual appearance of the corona under positive and negative polarities of the applied voltage.

When the voltage is **positive,** corona appears as a ***uniform bluish white sheath*** over the entire surface of the conductor.

On the other hand, when the voltage is **negative**, the corona will appear like ***reddish glowing spots*** distributed along the length of the wire.

Practical Considerations In Using Gases For Insulation Purposes

Generally, the preferred properties of a gaseous dielectric for high voltage applications are:

(a) high dielectric strength,

(b) thermal stability and chemical inactivity towards materials of construction,

(c) non-flammability and physiological intertness,

(d) low temperature of condensation,

(e) good heat transfer, and

(i) ready availability at moderate cost

Sulphur hexafluoride (SF6) which has received much study in recent years has been found to possess most of the above requirements.

VACUUM BREAKDOWN:

- According to the Townsend theory, the growth of current in a gap depends on the drift of the charged particles. In the absence of any such particles, as in the case of perfect vacuum, there should be no conduction and the vacuum should be a perfect insulating medium. However, in practice, the presence of metallic electrodes and insulating surfaces within the vacuum complicate the issue and, therefore, even in vacuum, a sufficiently high voltage will cause a breakdown. Recently there are research works conducted to determine the electrical properties of high vacuum. It finds different range of applications in devices such as vacuum contractors and interrupters, high frequency capacitors and relays, electrostatic generators, microwave tubes, etc. which are finding increasing applications in power systems.
- A vacuum is created in a system in which is pressure is maintained much below the atmospheric pressure. Vacuum may be classified as High vacuum, Very high vacuum, and Ultra high vacuum. High Vacuum is in the range of $1x10^{-3}$ to $1x\ 10^{-6}$ Torr, Very high vacuum in the range of $1x10^{-6}$ to $1x10^{-8}$ Torr, and very high Vacuum of $1x10^{-9}$ Torr and below. For electrical insulations high vacuum is used. You can view the electric arc formation in Vacuum in the following video

- There are different methods of Vacuum breakdown. They are classified as

- Particle Exchange mechanism
- Field Emission mechanism
- Clump Theory

Particle Exchange Mechanism

The particle-exchange mechanism involves electrons, positive ions, photons and the absorbed gases at the electrode surfaces. A charged particle would be emitted from one electrode under the action of the high electric field, and when it impinges on the other electrode, it liberates oppositely charged particles. These particles are accelerated by the applied voltage back to the first electrode where they release more of the original type of particles. When this process becomes cumulative, a chain reaction occurs which leads to the breakdown of the gap.

Qualitatively, an electron present in the vacuum gap is accelerated towards the anode, and on impact releases A positive ions and C photons. These positive ions are accelerated towards the cathode, and on impact each positive ion liberates B electrons and each photon liberates D electrons. The breakdown will occur if the coefficients of production of secondary electrons exceed unity. The equation is given as, [AB+ CD] > 1. But later this theory has been modified to include the negative ions and it is written as [AB+EF] > 1. Where and E and F represent the coefficients for negative and positive ion liberation by positive and negative ions. The values of the product EF were close enough to unity for copper, aluminum and stainless steel electrodes to make this mechanism applicable for voltages above 250 KV.

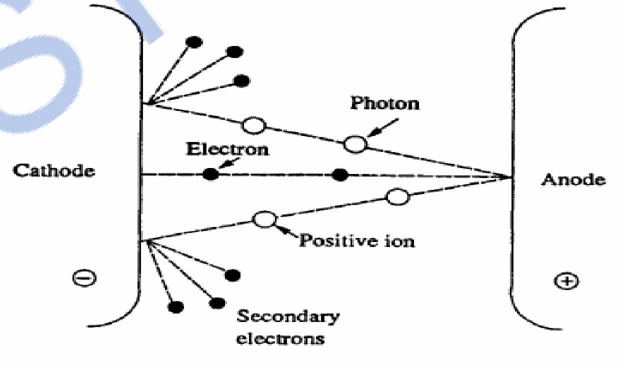


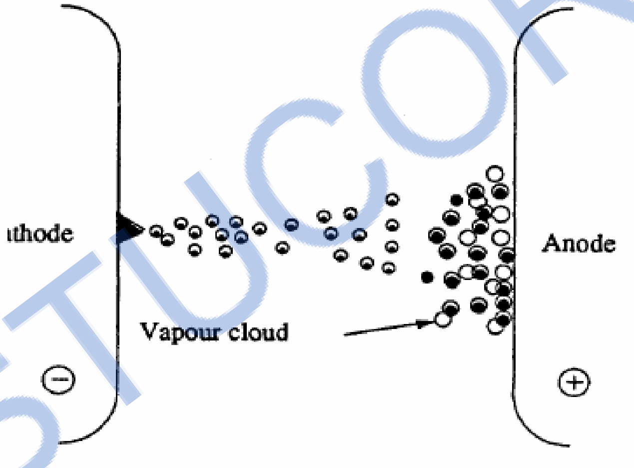
Image courtesy by Naidu and Kamaraju "High Voltage Engineering

Field Emission Theory

- There are two types of field emission theory
- Anode heating mechanism
- Cathode heating mechanism

Anode heating mechanism

This theory explains that electrons produced at micro-projections on the cathode due to field emission, bombard the anode causing a local rise in temperature and release gases and vapours into the vacuum gap. Now these ionize the atoms of the gas and produce positive ions. These positive ions arrive at the cathode, increase the primary electron emission due to space charge formation and produce secondary electrons by bombarding the surface. The process continues until a sufficient number of electrons are produced to give rise to breakdown.

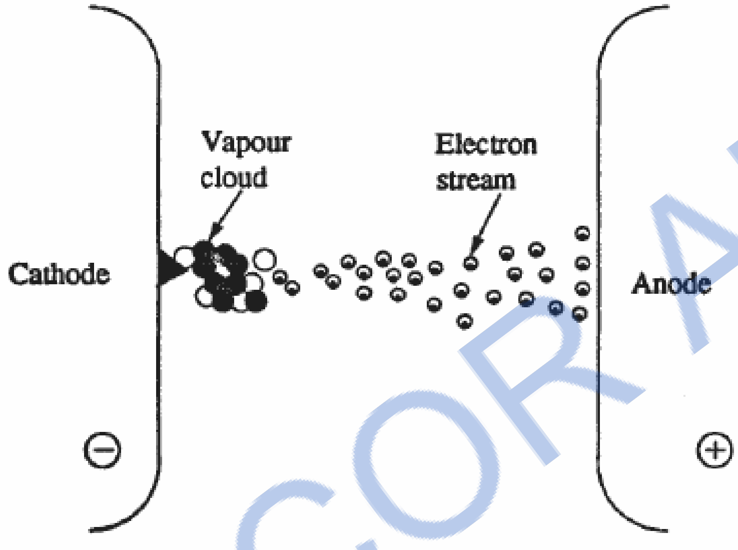


Anode heating Mechanism Image courtesy by Naidu and Kamaraju "High Voltage Engineering

Cathode Heating Mechanism

This mechanism explains that near the breakdown voltages of the gap, sharp points on the cathode surface are responsible for the existence of the pre-breakdown current, which is generated according to the field emission process described below.

This current causes resistive heating at the tip of a point and when a critical current density is reached, the tip melts and explodes, thus initiating vacuum discharge. Thus, the initiation of breakdown depends on the conditions and the properties of the cathode surface. The breakdown takes place by this process when the effective cathode electric field is of the order of 10^6 to 10^7 V/cm.



Cathode heating Mechanism Image courtesy by Naidu and Kamaraju "High Voltage Engineering "

3) Clump Mechanism

This mechanism is based on the following assumptions,

A loosely bound particle (clump) exists on one of the electrode surfaces

On the application of a high voltage, this particle gets charged, subsequently gets detached from the other electrode, and is accelerated across the gap.

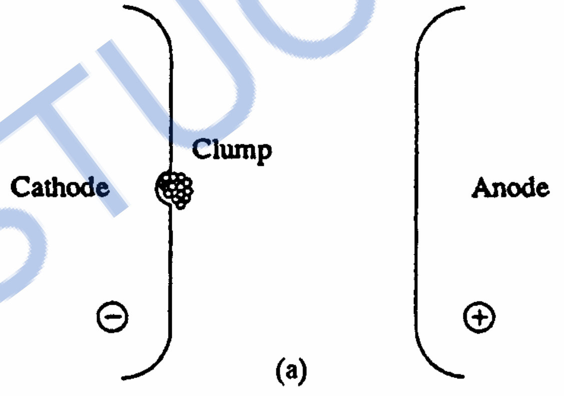
The breakdown occurs due to a discharge in the vapor or gas released by the impact of the particle at the target electrode.

The theory was proposed by cranberg. He initially assumed that breakdown will occur when the energy per unit area, W delivered to the target electrode by a clump exceeds a value C, a constant, characteristic of a given pair of electrodes. The quantity W *is* the product of gap voltage (V) and the charge density on the clump. The latter is proportional to the electric field E at the electrode of origin. The criterion for breakdown is $VE = C'$.

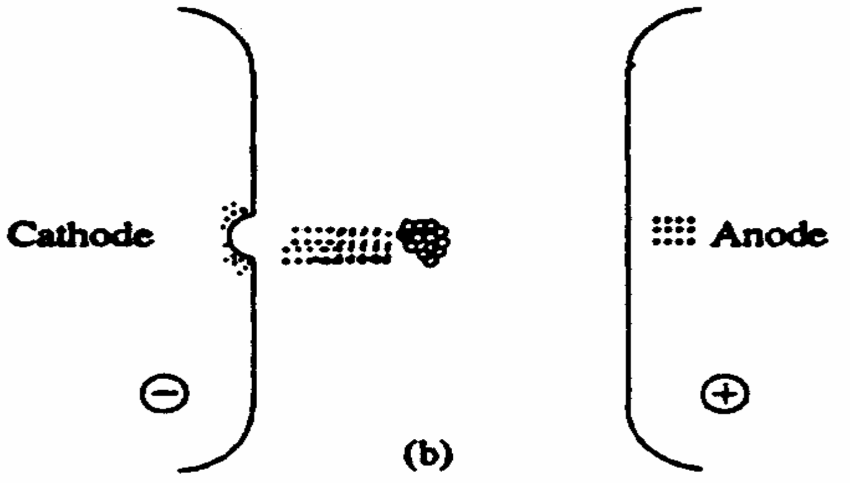
In Parallel plane electrodes the field E= V/d where *d* is the distance between the electrodes. So the generalized criterion for breakdown becomes,

$$V = (Cd)^{1/2}$$

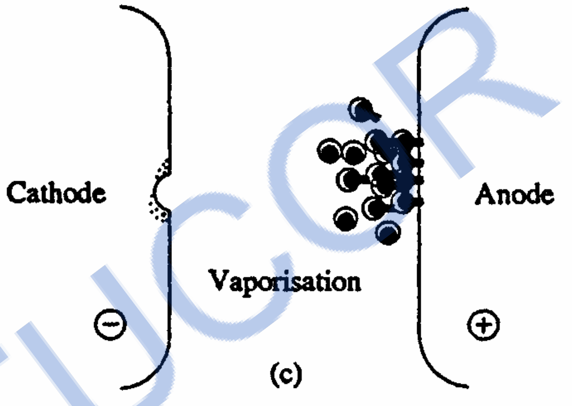
Where C is another constant . The value of C is obtained as 60x 10^{10} V^2/cm. But later the equation is modified as V = Cd power alpha . Where varies between 0.2 and 1.2 depending on the gap length and the electrode material, with a maximum at 0.6. The dependence of V on the electrode material, comes from the observations of markings on the electrode surfaces.



Clump is loosely attached to the surface



Clump is detached from the cathode surface and is accelerated across the gap



Impact of the clump on the anode gives out a cloud of metal vapour

Liquid dielectrics, because of their inherent properties, appear as though they would be more useful as insulating materials than either solids or gases. This is because both liquids and solids are usually 103 times denser than gases and hence, from Paschen's law it should follow that they possess much higher dielectric strength of the order of 10^{7}V/cm. Liquid dielectrics are used mainly as impregnants in high voltage cables and capacitors, and for filling up of transformers, circuit breakers etc.

Liquid dielectrics also act as heat transfer agents in transformers and as arc quenching media in circuit breakers. Petroleum oils (Transformer oil) are the most commonly used liquid dielectrics. Synthetic hydrocarbons and halogenated hydrocarbons are also used for certain applications. For very high temperature application, silicone oils and fluorinated hydrocarbons are also employed. In recent times, certain vegetable oils and esters are also being tried

Electrical Properties

The electrical properties that are essential in determining the dielectric performance of a liquid dielectric are

(a) its capacitance per unit volume or its relative permittivity

(b) its resistivity

(c) its loss tangent (tan 5) or its power factor which is an indication of the power loss under a.c. voltage application

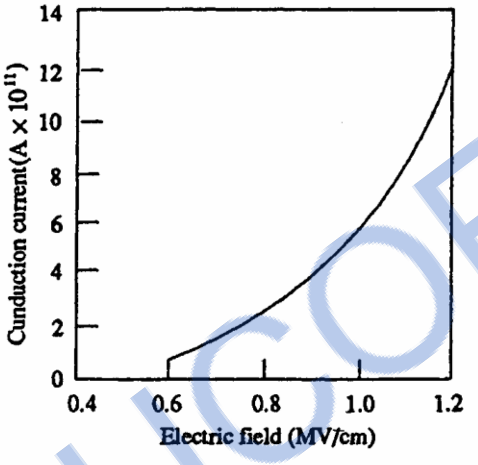
(d) its ability to withstand high electric stresses.

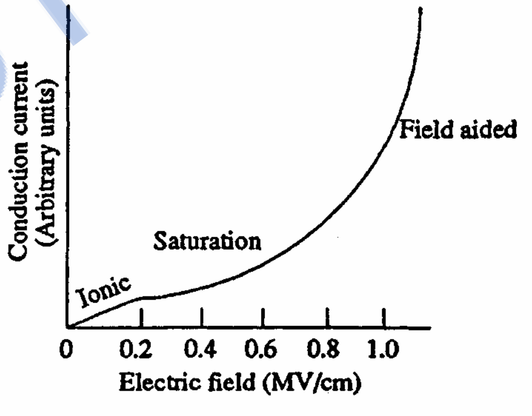
Conduction and breakdown in pure liquids

When low electric fields less than 1 kV/cm are applied, conductivities of 10^{-18} -10^{-20}mho/cm are obtained. These are probably due to the impurities remaining after purification. However, when the fields are high (> 100 kV/cm) the currents not only increase rapidly, but also undergo violent fluctuations which will die down after some time.

A typical mean value of the conduction current in hexane is shown above. This is the condition nearer to breakdown. However, if this figure is redrawn starting from very small currents, a current-electric field characteristics shown below, can be obtained. This curve will have three distinct regions as shown.

At very low fields the current is due to the dissociation of ions. With intermediate fields the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from the cathode gets multiplied in the liquid medium by a Townsend type of mechanism. The current multiplication also occurs from the electrons generated at the interfaces of liquid and impurities. The increase in process continues until breakdown occurs .





CONDUCTION AND BREAKDOWN IN COMMERCIAL LIQUIDS

The breakdown mechanism in commercial liquids is dependent, as seen above, on several factors, such as, the nature and condition of the electrodes, the physical properties of the liquid, and the impurities and gases present in the liquid.

Several theories have been proposed to explain the breakdown in liquids, and they are Classified as follows:

Suspended Particle Mechanism

Cavitation and Bubble Mechanism

Stressed Oil Volume Mechanism

(a)Suspended Particle Mechanism

In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres or as dispersed solid particles. The permittivity of these particles ϵ_1 will be different from the permittivity of the liquid ϵ_2 . If we consider these impunities to be spherical particles of radius r, and if the applied field is *E9* then the particles experience a force F, where

$$F = \frac{1}{2r^3}\frac{(\epsilon_2 - \epsilon_1)}{(2\,\epsilon_1 + \epsilon_2)} grad\, E^2$$

This force is directed towards areas of maximum stress, $\epsilon_2 > \epsilon_1$ if example, in the case of the presence of solid particles like paper in the liquid. On the other hand, if only gas bubbles are present in the liquid, i.e., $\epsilon_2 < \epsilon_1$ the force will be in the direction of areas of lower stress. If the voltage is continuously applied (d.c.) or the duration of the voltage is long (a.c.), then this force drives the particles towards the areas of maximum stress. If the number of particles present are large, they becomes aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

Thus the force will urge the particle to move to the strongest region of the field. In a uniform field gap or sphere gap of small spacing the strongest field is in the uniform region. In this region grad E is equal to zero so that the particle will remain in equilibrium there. Accordingly, particles will be dragged into the uniform field region. If the permittivity of the particle is higher than that of the medium, then its presence in the uniform field region will cause flux concentration at its surface. Other particles will be attracted into the region of higher flux concentration and in time will become aligned head to tail to form a bridge across the gap. The field in the liquid between the particles will be enhanced, and if it reaches critical value breakdown will follow. The movement of particles by electrical force is opposed by viscous drag, and since the particles are moving into the region of high stress, diffusion must also be taken into account.

- If there is only a single conducting particle between the electrodes, it will give rise to local field enhancement depending on its shape. If this field exceeds the breakdown strength of the liquid, local breakdown will occur near the particle, and this will result in the formation of gas bubbles which may lead to the breakdown of the liquid. The value of the breakdown strength of the liquids containing solid impurities was found to be much less than the values for pure liquids. The impurity particles reduce the breakdown strength, and it was also observed that the larger the size of the particles the lower were the breakdown strengths.

- **Cavitation and the Bubble Theory**

- It was experimentally observed that in many liquids, the breakdown strength depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of vapor bubble formed is responsible for breakdown. The following processes have been suggested to be responsible for the formation of the vapor bubbles:

- Gas pockets at the surface of the electrodes;

- b) electrostatic repulsive forces between space charges which may be sufficient to overcome the surface tension;

c) gaseous products due to the dissociation of liquid molecules by electron collisions; and

d) Vaporization of the liquid by corona type discharges from sharp points and irregularities on the electrode surfaces.

Once a bubble is formed it will elongated (long and thin) in the direction of the electric field under the influence of electrostatic forces. The volume of the bubble remains constant during elongation. Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the minimum value on the Paschen's curve for the gas in the bubble. The electric field in a spherical gas bubble which is immersed in a liquid of permittivity ϵ_2 is given by E_b=3E0/(ε2+2) ; where E0 is the field in the liquid in the absence of the bubble. When the field E_b becomes equal to the gaseous ionization field, discharge takes place which will lead to decomposition of the liquid and breakdown may follow.

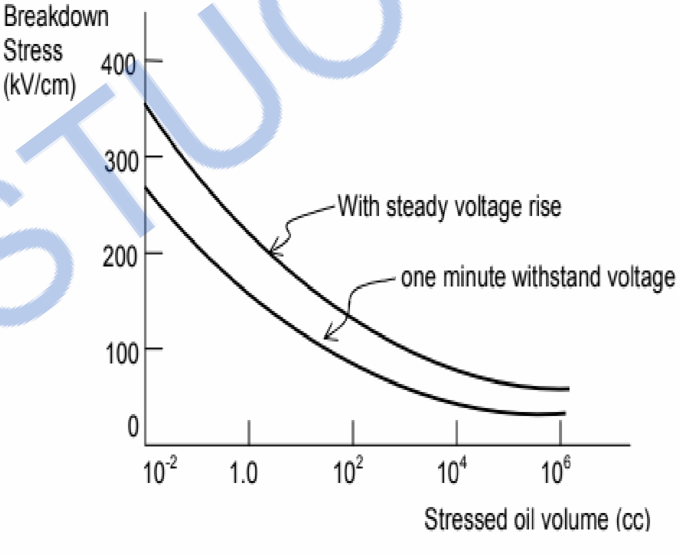
$$E_0 = \frac{1}{(\epsilon_1 \ -\epsilon_2)}\left[\frac{2\pi\sigma(2_{\epsilon 1+\epsilon 2})}{r}\left\{\sqrt{V_{b/2rE_0}} - 1\right\}1/2\right]$$

where σ is the surface tension of the liquid, ε_1 is the permittivity of the liquid, ε_2 is the permittivity of the gas bubble, r is the initial radius of the bubble assumed as a sphere and $V_b$is the voltage drop in the bubble (corresponding to minimum on the Paschen's curve). From this equation it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid. But this theory does not take into account the production of the initial bubble and hence the results given by this theory do not agree well with the experimental results.

Stressed Oil Volume Theory

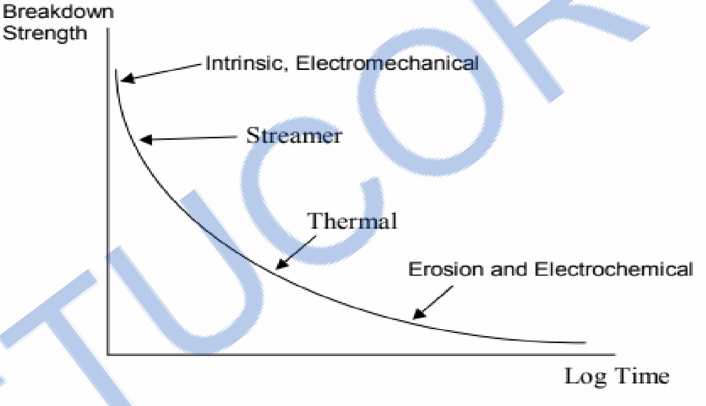
In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the "largest possible impurity" or "weak link". On a statistical basis it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region. In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress (Emax) contour.

According to this theory the breakdown strength is inversely proportional to the stressed oil volume. The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage. The variation of the breakdown voltage stress with the stressed oil volume is shown below



BREAKDOWN IN SOLID DIELECTRICS

Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusion, and moisture, and be resistant to thermal and chemical deterioration. Solid dielectrics have higher breakdown strength compared to liquids and gases. Studies of the breakdown of solid dielectrics are of extreme importance in insulation studies. When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field removed. The mechanism of breakdown is a complex phenomenon in the case of solids, and varies depending on the time of application of voltage as shown



The various breakdown mechanisms can be classified as follows:

(a)Intrinsic or ionic breakdown,

(b)electromechanical breakdown,

(c)failure due to treeing and tracking,

(d)thermal breakdown, (e)electrochemical breakdown, and

(f)breakdown due to internal discharges.

INTRINSIC BREAKDOWN

When voltages are applied only for short durations of the order of 10^8 s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. Experimentally, this highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature.

The maximum electrical strength recorder is 15 MV/cm for polyvinyl-alcohol at -1960C. The maximum strength usually obtainable ranges from 5 MV/cm. Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric. Usually, a small number of conduction electrons are present in solid dielectrics, along with some structural imperfections and small amounts of impurities.

The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have been proposed

i)Electronic Breakdown

Intrinsic breakdown occurs in time of the order of 10-8 s and therefore is assumed to be electronic in nature. The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisions occur. When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valence band to the conduction band. When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown.

ii) Avalanche or Streamer Breakdown

This is similar to breakdown in gases due to cumulative ionization. Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collision. Under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap.

An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions. When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron.

This process repeats itself resulting in the formation of an electron avalanche. Breakdown will occur, when the avalanche exceeds a certain critical size. In practice, breakdown does not occur by the formation of a single avalanche itself, but occurs as a result of many avalanches formed within the dielectric and extending step by step through the entire thickness of the material.

ELECTROMECHANICAL BREAKDOWN

When solid dielectrics are subjected to high electric fields, failure occurs due to electrostatic compressive forces which can exceed the mechanical compressive strength. If the thickness of the specimen is d0 and is compressed to thickness d under an applied voltage V, then the electrically developed compressive stress is in equilibrium if

$$\epsilon_0 \epsilon_{r=} \frac{v^2}{2d^2} = Y ln \frac{d_0}{d}$$

Where Y is the Young's Modulus

$$v^2 = d^2 \left[\frac{2y}{\epsilon_0 \, \epsilon_r}\right] ln \left[\frac{d_0}{d}\right]$$

Usually, mechanical instability occurs when d/d_0 =0.6 or d_0/d =1.67

Substituting the values the equation becomes

$$E_{max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\epsilon_0 \epsilon_r}\right]^{\frac{1}{2}}$$

The above equation is only approximate as Y depends on the mechanical stress. Also when the material is subjected to high stresses the theory of elasticity does not hold good, and plastic deformation has to be considered.

THERMAL BREAKDOWN

In general, the breakdown voltage of a solid dielectric should increase with its thickness. But this is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction. When an electric field is applied to a dielectric, conduction current however small it may be, flows through the material.

The current heats up the specimen and the temperature rise. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat radiated out, equals the heat generated.

$$W_{d.c} = E^2 \sigma \text{ W/cm}^3$$

where σ is the d. c. conductivity of the specimen.

Under a. c. fields, the heat generated

$$W_{a.c} = E^2 f_{\epsilon r} \tan \delta / 1.8*10^{12} \text{ W/ cm}^3$$

where, f= frequency in Hz,

δ - loss angle of the dielectric material and E= rms value

The heat dissipated W_r is given by

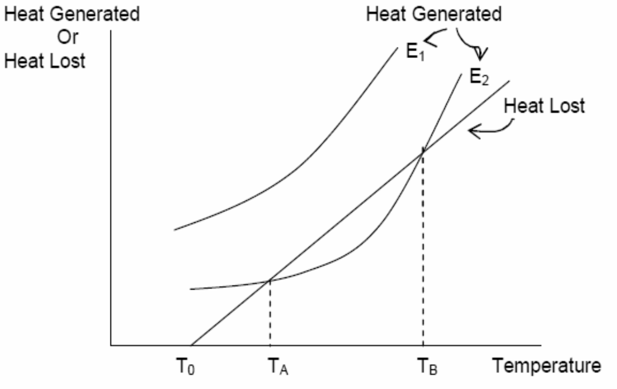
$$W_r = C_v \, dv/dt + \text{div}(K \text{ grad } T)$$

where, C_v = specific heat of the specimen

T = temperature of the specimen , K = thermal conductivity of the specimen

t = time over which the heat is dissipated.

Equilibrium is reached when the heat generated ($W_{d.c}$ or $W_{a.c}$) becomes equal to the heat dissipated (Wr). In actual practice there is always some heat that is radiated out. The thermal instability condition is shown in Fig.



Here, the heat lost is shown by a straight line, while the heat generated at fields E_1 and E_2 is shown by separate curves. At field E_2 breakdown occurs both at temperatures T_A and T_B heat generated is less than the heat lost for the field E_2, and hence the breakdown will not occur.

BREAKDOWN OF SOLID DIELECTRICS IN PRACTICE

There are certain types of breakdown which do not come under either intrinsic breakdown, but actually occur after prolonged operation. These are, for example, breakdown due to tracking in which dry conducting tracks act as conducting paths on the insulator surfaces leading to gradual breakdown along the surface of the insulator. Another type of breakdown in this category is the electrochemical breakdown caused by chemical transformations such as electrolysis, formation of ozone, etc. In addition, failure also occurs due to partial discharges which are brought about in the air pockets inside the insulation. This type of breakdown is very important impregnated paper insulation used in high voltage cables and capacitors.

Chemical and Electrochemical Deterioration and Breakdown

In the presence of air and other gases some dielectric materials undergo chemical changes when subjected to continuous stresses. Some of the important chemical reactions that occur are:

Oxidation

In the presence of air or oxygen, material such as rubber and polyethylene undergo oxidation giving rise to surface cracks

Hydrolysis

When moisture or water vapor is present on the surface of a solid dielectric, hydrolysis occurs and the material loses their electrical and mechanical properties. Electrical properties of materials such as paper, cotton tape, and other cellulose materials deteriorate very rapidly due to hydrolysis. Plastics like polyethylene undergo changes, and their service life considerably reduces.

Chemical Action

Even in the absence of electric fields, progressive chemical degradation of insulating materials can occur due to a variety of processes such as chemical instability at high temperatures, oxidation and cracking in the presence of air and ozone, and hydrolysis due to moisture and heat.

Since different insulating materials come into contact with each other in any practical reactions occur between these various materials leading to reduction in electrical and mechanical strengths resulting in a failure.

The effects of electrochemical and chemical deterioration could be minimized by carefully studying and examining the materials. High soda content glass insulation should be avoided in moist and damp conditions, because sodium, being very mobile, leaches to the surface giving rise to the formation of a strong alkali which will cause deterioration.

It was observed that this type of material will lose its mechanical strength within 24 hrs,when it is exposed to atmospheres having 100% relative humidity at 70° C. In paper insulation, even if partial discharges are prevented completely, breakdown can occur due to chemical degradation. The chemical and electrochemical deterioration increases very rapidly with temperature, and hence high temperatures should be avoided.

Breakdown Due to Treeing and Tracking

When a solid dielectric subjected to electrical stresses for a long time fails, normally two kinds of visible markings are observed on the dielectric material. They are:

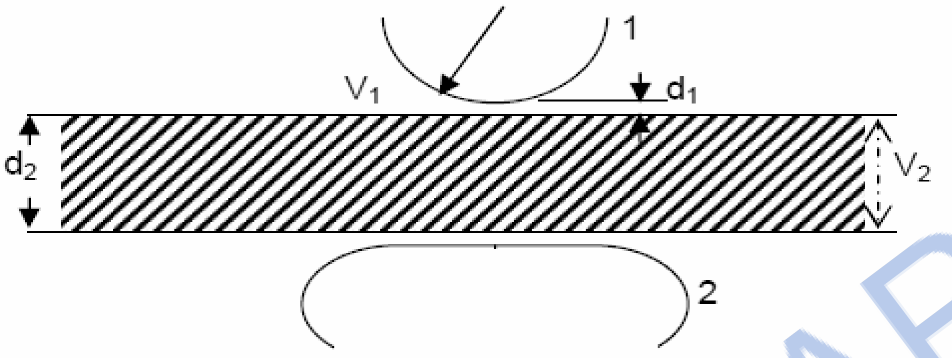
a) the presence of a conducting path across the surface of the insulation:

b) a mechanism whereby leakage current passes through the conducting path finally leading to the formation of a spark. Insulation deterioration occurs as a result of these sparks.

The spreading of spark channels during tracking, in the form of the branches of a tree is called treeing. Consider a system of a solid dielectric having a conducting film and two electrodes on its surface. In practice, the conducting film very often is formed due to moisture. On application of voltage, the film starts conducting, resulting in generation of heat, and the surface starts becoming dry. The conducting film becomes separate due to drying, and so sparks are drawn damaging the dielectric surface.

With organic insulating materials such as paper and bakelite, the dielectric carbonizes at the region of sparking, and the carbonized regions act as permanent conducting channels resulting in increased stress over the rest of the region. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes. This phenomenon, called tracking and is common between layers of bakelite, paper and similar dielectrics built of laminates.

On the other hand treeing occurs due to the erosion of material at the tips of the spark. Erosion results in the roughening of the surfaces, and hence becomes a source of dirt and contamination. This causes increased conductivity resulting either in the formation of conducting path bridging the electrodes or in a mechanical failure of the dielectric.



Arrangement for study of treeing phenomena.1 and 2 are electrodes.

When a dielectric material lies between two electrodes as shown in Fig., there is possibility for two different dielectric media, the air and the dielectric, to come series. The voltages across the two media are as shown (V1 across the air gap, and V2 across the dielectric). The voltage V1 across the air gap is given as,

$$V_1 = \frac{V\, d_1}{d_1 + \left(\frac{\epsilon_1}{\epsilon_2}\right) d_2}$$

Where V is the applied voltage .

Since $\epsilon_2 > \epsilon_1$ most of the voltage appears across 1 d , the air gap. Sparking will occur in the air gap and charge accumulation takes place on the surface of the insulation. Sometimes the spark erodes the surface of the insulation. As time passes, break-down channels spread through the insulation in an irregular "tree' like fashion leading to the formation of conducting channels. This kind of channeling is called treeing. Under a.c. voltage conditions treeing can occur in a few minute or several hours. Hence, care must be taken to see that no series air gaps or other weaker insulation gaps are formed.

Usually, tracking occurs even at very low voltage of the order of about 100 V, whereas treeing requires high voltages. For testing of tracking, low and medium voltage tracking tests are specified. These tests are done at low voltages but for times of about 100 hr or more. The insulation should not fail. Sometimes the tests are done using 5 to 10 kV with shorter durations of 4 to 6 hour. The numerical value that initiates or causes the formation of a track is called "tracking index" and this is used to qualify the surface properties of dielectric materials.

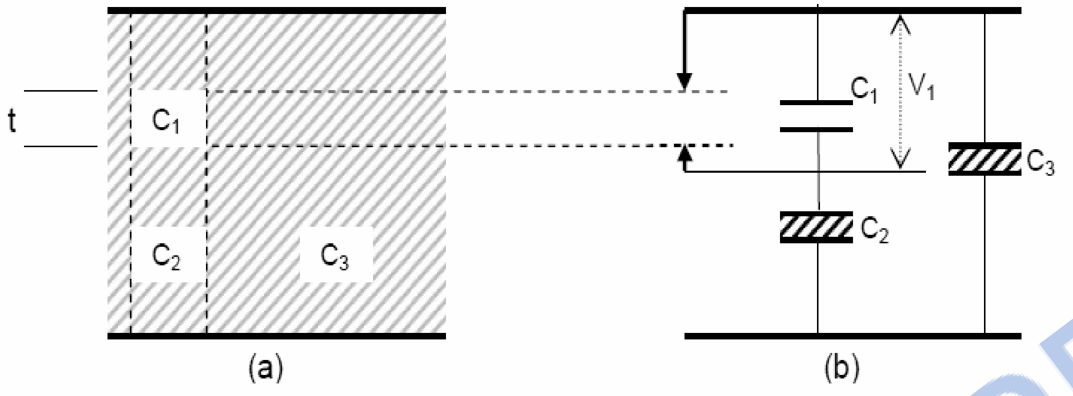
Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment. The materials chosen should be resistant to tracking. Sometimes moisture repellant greases are used. But this needs frequent cleaning and regressing. Increasing creeping distances should prevent tracking, but in practice the presence of moisture films defeat the purpose. Usually, treeing phenomena is observed in capacitors and cables, and extensive work is being done to investigate the real nature and causes of this phenomenon.

Breakdown Due to Internal Discharges

Solid insulating materials, and to a lesser extent liquid dielectrics contain voids or cavities within the medium or at the boundaries between the dielectric and the electrodes. These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation. Hence, the electric field strength in the voids is higher than that across the dielectric. Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur.

Let us consider a dielectric between two conductors as shown in . If we divide the insulation into three parts, an electrical network of C1 , C2 , C3 can be formed as shown in Fig.. In this, C1 represents the capacitance of the void or cavity, C2 is the capacitance of the dielectric which is in series with the void, and C3 is the capacitance of the dielectric

When the applied voltage is V, the voltage across the void, V1 is given by the same equation as



$$V_1 = \frac{V\,d_1}{d_1 + \left(\frac{\epsilon_1}{\epsilon_2}\right) d_2}$$

Usually $d_1 < d_2$, and if we assume that the cavity is filled with a gas, then

$$V_1 = V \epsilon_r \left(\frac{d_1}{d_2}\right)$$

When a voltage V is applied, V1 reaches the breakdown strength of the medium in the cavity (Vi) and breakdown occurs. Vi is called the "discharge inception voltage". When the applied voltage is a.c., breakdown occurs on both the half cycles and the number of discharges will depend on the applied voltage. When the first breakdown across the cavity occurs the breakdown voltage across it becomes zero. When once the voltage V1 becomes zero, the spark gets extinguished and again the voltage rises till breakdown occurs again. This process repeats again and again, and current pulses will be obtained both in the positive and negative half cycles. All these effect will result in a gradual erosion of the material and consequent reduction in the thickness of insulation leading to breakdown. The life of the insulation with internal discharges depends upon the applied voltage and the number of discharges. Breakdown by this process may occur in a few or days or may take a few years.

BREAKDOWN OF COMPOSITE INSULATION

In certain cases the behavior of the insulation system can be predicted by the behavior of the components. But in most cases, the system as a whole has to be considered. The following considerations determine the performance of

The stress distribution at different parts of the insulation system is distorted due to the component dielectric constant and conductivities,

The breakdown characteristics at the surface are affected by the insulation boundaries of various components,

The internal or partial discharge products of one component invariably affect the other components in the system, and

The chemical ageing products of one component also affect the performance of other components in the system.

Ageing is the process by which the electrical and mechanical properties of insulation normally becomes worse in condition (deteriorate) with time. Ageing occurs mainly due to oxidation, chemical degradation, irradiation, and electron and ion bombardment on the insulation. Tracking is another process by which ageing of the insulation occurs. Usually partial discharge tests are used in ageing studies to estimate the discharge magnitudes, discharge inception, and extinction voltages. Change of loss angle during electrical stressing provides information of the deterioration occurring in insulation systems. The knowledge of the mechanical stresses in the insulation, controlling of the ambient conditions such as temperature and humidity, and a study of the gaseous products evolved during ageing processes will also help to control the breakdown process in composite insulation. Finally, stress control in insulation systems to avoid high electric stress regions is an important factor in controlling the failure of insulation systems.

Assignment

1. Discuss about Various Mechanisms of Vaccum Breakdown
2. Explain various theories that explain the Breakdown in Liquid Dielectrics.

UNIT II-DIELECTRIC BREAKDOWN
PART A (2 marks)

1. Mention the gases used as the insulating medium in electrical apparatus? (CO2 K1)

- Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as nitrogen, carbon dioxide, Freon and sulphur hexafluoride

2 .What is breakdown voltage? (CO2 K1)

- The maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage

3.What is ionization? (CO2 K1)

- The process of liberating an electron from a gas molecule with a simultaneous production of a positive ion is called ionization.

4.W**hat is a Townsend's first ionization coefficient? (CO2 K1)**

- Townsend's first ionization coefficient is the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field.

5.What is a Townsend's secondary ionization coefficient? (CO2 K1)

- The Townsend's secondary ionization coefficient is defined as the net number of secondary electrons produced per incident, positive ion, photon, excited particle or meta-stable particle.

6. What are electro negative gases? (CO2 K1)

- The gases which are highest breakdown strength due to attachment of free electrons to neutral atoms or molecules to form negative ions, thus removing free electrons that would otherwise led to breakdown is called as electro negative gases.

7.Define an attachment coefficient. (CO2 K2)

- An attachment co-efficient is defined as the number of attaching collusions made by one electron drifting one centimeter in the direction of the field.

8.What is meant by time lag? (CO2 K1)

- The time difference between the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself is called as time lag.

9.Mention some of the applications of liquid dielectrics. (CO2 K1)

They are used as impregnants in high voltage cables and capacitors, and for filling up of transformers, circuit breakers. They are also used as heat transfer agents in transformers and as arc quenching media in circuit breakers.

10.Name some examples of liquid dielectrics. (CO2 K1)

Petroleum oils, Synthetic hydrocarbons, halogenated hydrocarbons, silicone oils and fluorinated hydrocarbons.

11. What are pure liquids? Give examples. (CO2 K1)

They are chemically pure and do not contain any other impurity even in traces of 1in 109 and are structurally simple. Examples are n-hexane, n-heptane and other paraffin hydrocarbons.

12.What are the different types of solid insulating materials? (CO2 K1)

Organic materials: paper, wood and rubber, Inorganic materials: Mica, glass and porcelain Synthetic polymers: Perplex, PVC, epoxy resins.

13.State the properties of good dielectrics (CO2 K2)

Low dielectric loss, high mechanical strength, should be free from gaseous inclusions and moisture and be resistant to thermal and chemical deterioration.

14. State and explain Paschen's law. (CO2 K2)

The Townsends breakdown criterion for gases is given by γ(eαd-1) = Where α, γ are the Townsends co-efficient and are functions of (E/p).

15. What do you mean by "Intrinsic strength" of a solid dielectric? (CO2 K1)

When voltage is applied for a short time of the order of 10-8 , the electric strength of the solid material increases rapidly to an upper limit. This is called Intrinsic strength.

16.Define treeing and tracking. (CO2 K2)

Treeing is the formation of a continuous conducting path across the surface of the insulation mainly due to surface erosion under voltage application. Insulation failure occurs when carbonized tracks bridge the distance between the electrodes . This phenomenon is called tracking.

17.What is meant by corona discharges? (CO2 K2)

In non-uniform fields, the increase in voltage cause breakdown in the gas at points with highest electric field intensity(sharp points), or where the electrodes are curved or on transmission lines. This form of discharge is called as corona discharge.

18.What are the properties required for a gaseous dielectric for HV application? (CO2 K2)

Generally , the preferred properties of a gaseous dielectric for high voltage applications are:

High dielectric strength

Thermal stability and chemical inactivity towards materials of construction

Non-flammable and physiological inertness, and environmentally non-hazardous

Low temperature of condensation

Arc extinguishing ability

Good heat transfer

Commercially available at moderate cost.

19. **What are commercial liquid dielectrics and how are they different from pure liquid dielectrics? (CO2 K1)**

Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 109, and are structurally simple. Examples of such simple, pure liquids are n-hexane , n-heptane and other paraffin hydrocarbons.

Commercial liquids which are insulating liquids like oils which are not chemically pure. Normally consist of mixtures of complex organic molecules which cannot be easily specified or reproduced in a series of experiments.

20.What is Penning Effect ? ? (CO2 K1)

It is a form of Chemi-ionization , an ionization process involving the reactions between neutral atoms or molecules .

21. What are the factors which affect the breakdown in gaseous dielectrics? (CO2 K1)

Low dielectric strength ,Flammability and hazardous, Thermal and chemical instability,Bad heat transfer

Part B- 13 marks Questions

1. Discuss about Various Mechanisms of Vaccum Breakdown [CO2 K1]
2. Explain various theories that explain the Breakdown in Liquid Dielectrics. [[CO2 K1]
3. Discuss Various Properties of Composite Dielectrics [CO2 K1]
4. Derive the Townsend current growth equation in uniform gaseous dielectric field [CO2/K1]
5. Discuss the Phenomenon of Thermal Breakdown in solid dielectrics [CO2 K1]
6. What are the different mechanisms of Breakdown in Vaccum, Explain any one mechanism in detail [CO2 K1]
7. Explain the Suspended particle mechanism of Breakdown in commercial liquid dielectrics [CO2 K1]
8. From the fundamental principles, derive Townsend's criteria for breakdown in gases. [CO2 K1]
9. Define town send's first and second ionization coefficients. How the condition is for breakdown obtained in town send's discharge? [CO2 K1]
10. Explain paschen's law and breakdown in electro negative gases? [CO2 K1]
11. Explain the phenomenon of corona discharge in detail. [CO2 K1]
12. Explain the following breakdown mechanism in solid dielectric

    (i)Intrinsic breakdown,(ii)Electromechanical breakdown,(iii) Thermal breakdown (iv) (ii) Treeing and Tracking [CO2 K1]
13. Explain in detail about the breakdown mechanism in composite

    dielectrics(13) [CO2 K1]

Part C-15 marks questions

1. (i).List out the problems caused by corona discharge.(7)

   (ii)describe the mechanism of short term breakdown composite insulation.(8) [CO2 K2]

2. (i) Name the primary ionization processes in gaseous dielectrics and explain in detail.(8)

   (ii) how vacuum breakdown occurs according to particle exchange mechanism.(7) [CO2 K2]

3. State why the very high intrinsic strength of solid dielectric is not fully realized in practice. Explain in detail any one mechanism of breakdown in solid dielectrics.(15) [CO2 K2]

4. (i).A steady state current of 5.5x10-8 A was noted during experiments in certain gas at 8Kv at a distance of 0.4cm between plane electrodes. Keeping the field constant and reducing the distance to 0.1cm resulted in a current of 5.5x10-9 A. Calculate Townsend's primary ionization coefficient alpha α.(8)

(ii).Derive and expression for the growth of current due to Townsend's primary ionization. Assume necessary data.(7) [CO2 K3]

Supportive online Certification courses

- https://nptel.ac.in/courses/108/104/108104048/

  High voltage Engineering –NPTEL Web based course

- https://www.udemy.com/course/protection-and-control-of-high-voltage-power-circuits/

  Protection and control of high voltage power circuit

Real time Applications in day to day life and to Industry

- Spark gaps were used historically as an early form of radio transmission. Similarly, lightning discharges in the atmosphere of Jupiter are thought to be the source of the planet's powerful radio frequency emissions.
- High voltages have been used in landmark chemistry and particle physics experiments and discoveries. Electric arcs were used in the isolation and discovery of the element argon from atmospheric air. Induction coils powered early X-ray tubes. Moseley used an X-ray tube to determine the atomic number of a selection of metallic elements by the spectrum emitted when used as anodes. High voltage is used for generating electron beams for microscopy. Cockcroft and Walton invented the voltage multiplier to transmutate lithium atoms in lithium oxide into helium by accelerating hydrogen atoms.

Prescribed Text Books

TEXT BOOKS:

- 1. S.Naidu and V. Kamaraju, ‘High Voltage Engineering’, Tata McGraw Hill, Fifth Edition, 2013.
- 2. E. Kuffel and W.S. Zaengl, J.Kuffel, ‘High voltage Engineering fundamentals’, Newnes Second Edition Elsevier , New Delhi, 2005.
- 3. C.L. Wadhwa, ‘High voltage Engineering’, New Age International Publishers, Third Edition, 2010.
- REFERENCES
- 1. L.L. Alston, ‘High Voltage Technology’, Oxford University Press, First Indian Edition , 2011.
- 2. Mazen Abdel – Salam, Hussein Anis, Ahdab A-Morshedy, Roshday Radwan,
- High Voltage Engineering – Theory &Practice, Second Edition Marcel Dekker, Inc., 2010.
- 3. Subir Ray,’ An Introduction to High Voltage Engineering’ PHI Learning Private Limited, New Delhi, Second Edition, 2013.

Assesment Schedule- Proposed

Internal Assessment 1 – 01/08/2020 (Proposed)

Internal Assesment2 --

Model Exam --

Mini Project Suggestions :

- https://www.ecs.soton.ac.uk/research/projects/High%20Voltage%20Engineering
- Advanced NAno-Structured TApeS for electrotechnical high power Insulating Applications (ANASTASIA)
- An Investigation into Electrical Degradation Mechanisms within Air-Filled Cavities in Solid Dielectric Materials
- An investigation into partial discharge sources and locations along the high voltage transformers
- An Investigation into the Next Generation of Ultra High Voltage, High Power Density, DC Power Supplies
- Application of Machine learning for condition assessment of large high voltage autotransformers
- Charge Transport in Nanodielectrics
- Condition and Climatic Environment for Power Transformer (ConCEPT)
- Condition monitoring and prognostic indicators for network reliability
- Continuous Online PD Monitoring for HV Cables
- Continuous Online PD Monitoring for HV Cables
- Continuous Online PD Monitoring for HV Cables
- Corrosive Sulphur Condition Monitoring of Large Transformers
- Cryogenic Dielectrics
- Degradation Behaviour of Voids in Silicone Rubber under Applied AC Electric Fields
- Effect of LN2 Bubble Dynamics on Insulation Performance of High Temperature Superconducting Power Apparatus
- Effect of nucleating agent on a polyethylene blend
- Three Phase Partial Discharge monitoring of MV PILC cables
- Three Phase Partial Discharge monitoring of MV PILC cables
- Towards Enhanced HVDC Cable Systems
- Towards Intelligent Insulation

Mini Project Suggestions :

- Effect of oil passivation on the electrical properties of high voltage transformers
- Electric Field Determination in DC Polymeric Power Cable in the Presence of Space Charge and Temperature Gradient
- FEAR - Finite Element Analysis for cable Ratings
- Flexible Rating Options for DC Operation
- Impact of Seabed Properties on Ampacity and Reliability of Cables
- Impact of thermal mechanical stresses on electric field of Cables and Joints
- Impulse ageing of polymeric materials
- Influence of oil contamination on the electrical performance of power transformers
- Insulation for high voltage dc power transformer
- Inter-phase pressboard surface discharge characteristics under influence of general electric fields
- Management of Evaluation of Cable Equipment State
- Mechanical Deformation of Dielectrics
- Modelling and Parameter Estimation of High Voltage Transformers for Partial Discharge Detection and Identification
- Modelling of Thermal Damage in Carbon Fibre Composites
- Modelling PD in Cavities under DC and AC Electric Fields
- Modelling the Aging Processes of Polymeric Insulation using Electroluminescence and Space Charge Measurement Data
- On Line Detection of Partial Discharge Activity in HV Cables and Accessories Using Directional Coupling Techniques
- On Line Detection of Partial Discharge Activity in HV Cables and Accessories Using Directional Coupling Techniques
- On-line Condition Monitoring of HV Cables
- On-line Condition Monitoring of HV Cables
- On-line Condition Monitoring of HV Cables

Mini Project Suggestion

- Optimization of a PPT for nano and pico satellite applications
- Partial discharge (PD) analysis of defective paper insulated lead covered (PILC) cable samples under three-phase rated condition
- Partial discharge detection in cable systems
- Partial Discharge Discrimination
- Penetrant Diffusion in Dielectrics
- Polar/non-polar Polymer Blends: On structural evolution and the electrical properties of PE and EVA blends
- Polymeric Insulation for high voltage DC application
- Potential decay of corona charged LDPE film
- Probabilistic Dynamic Cable Rating Algorithms
- Renewable materials for high voltage applications
- Silicone oil degradation analysis (SODA)
- Space charge measurement and analysis in polyethylene film
- SPARCARB
- Study of Surface Discharge Behaviour at the Oil-pressboard Interface of Large Transformers
- Substation Earthing
- Supergen V: Amperes: Infrastructure for reducing environmental impact
- Surface Discharge in the Inter-phase barrier region of large Transformers
- Surface discharge measurement using the pockels effect
- The effect of cross-linking byproduct on electrical properties of soaked LDPE.
- The Use of Raman Microscopy in the Analysis of Electerical Aging in Polymeric Insulators
- Thermal ageing and its impact on charge trap density and Insulating properties in LDPE
- Thermal bubble behaviours in high voltage thermosyphon coolants under electric field

Thank you

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HIGH VOLTAGE ENGINEERING

Department: Electrical and Electronics Engineering
Batch/Year: 2017-2021 **Subject code : EE8701**

Created by: 1) K.GUNALAN M.E.,(Ph.D)
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RMK College of Engineering and Technology

2) K.Praveen Kumar Reddy M.E (Ph.D)
Assistant Professor/EEE
RMD Engineering College

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Assistant Professor/EEE
RMK Engineering College

Table of Contents

R.M.K GROUP OF INSTITUTIONS

Table of Contents

Course Objectives

To impart knowledge on the following Topics

1. Various types of over voltages in power system and protection methods.
2. Generation of over voltages in laboratories.
3. Measurement of over voltages.
4. Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.
5. Testing of power apparatus and insulation coordination

Pre Requisites (Course Names with Code)

EE8402- Transmission and Distribution
EE8501 Power System Analysis
EE8602 Protection and Switchgear

SYLLABUS

EE8701 HIGH VOLTAGE ENGINEERING **L T P C**

3 0 0 3

OBJECTIVES:

To impart knowledge on the following Topics

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UNIT I OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS 9

Causes of over voltages and its effects on power system – Lightning, switching surges and temporary over voltages, Corona and its effects – Bewley lattice diagram- Protection against over voltages.

UNIT II DIELECTRIC BREAKDOWN 9

Properties of Dielectric materials - Gaseous breakdown in uniform and non-uniform fields – Corona discharges – Vacuum breakdown – Conduction and breakdown in pure and commercial liquids, Maintenance of oil Quality – Breakdown mechanisms in solid and composite dielectrics- Applications of insulating materials in electrical equipments.

UNIT III GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

Generation of High DC voltage: Rectifiers, voltage multipliers, vandigraff generator: generation of high impulse voltage: single and multistage Marx circuits – generation of high AC voltages: cascaded transformers, resonant transformer and tesla coil- generation of switching surges – generation of impulse currents - Triggering and control of impulse generators.

UNIT IV MEASUREMENT OF HIGH VOLTAGES AND HIGH CURRENTS

High Resistance with series ammeter – Dividers, Resistance, Capacitance and Mixed dividers - Peak Voltmeter, Generating Voltmeters - Capacitance Voltage Transformers, Electrostatic Voltmeters – Sphere Gaps - High current shunts- Digital techniques in high voltage measurement.

UNIT V HIGH VOLTAGE TESTING & INSULATION COORDINATION 9

High voltage testing of electrical power apparatus as per International and Indian standards – Power frequency, impulse voltage and DC testing of Insulators, circuit breakers, bushing, isolators and transformers- Insulation Coordination& testing of cabilitys.

TOTAL : 45 PERIODS

COURSE OUTCOME

Course Outcome		Level of Knowledge
CO1	Understand various types of over voltages experienced by the power system	K2
CO2	Understand and explain the breakdown mechanism of different types of dielectrics	K1
CO3	Explain the generation of High voltages and currents and apply the same for calculating the voltage to be generated for testing an apparatus of a particular rated voltage	K3
CO4	Understand various methods of HV measurements and identify the appropriate measuring system for various types of over voltages and currents	K2
CO5	Understand process of testing of various power system apparatus	K2
CO6	Understand the significance of insulation coordination and apply the same for fixing the BIL of an apparatus	K3

PROGRAM OUTCOMES (POs)

a. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
b. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
c. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
d. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
e. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
f. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
g. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
h. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
i. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
j. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
k. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary **environments.**
l. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES (PSOs)

PSO 1: Design and analyze electrical systems incorporating electrical machines, power controllers along with the design of electrical layout for the complete structure.

PSO 2 : Use the modern tools for implementing the solutions to engineering problems that can arise in the fields of Electrical, Electronics and Telecommunication Engineering along with Information Technology Services.

PSO 3 : Face the challenges in the society by adopting the non-conventional energy resources and utilizing the modern technologies for energy efficient transmission and power quality improvement delivering clean energy for the wellbeing of the mankind.

COs - POs/PSOs MATRICES

COs	PO												PSO		
	a	b	c	d	e	f	g	h	i	j	k	l	1	2	3
CO1	3	3	2	3	2	2	2	-	-	-	-	2	2	-	-
CO2	3	2	1	2	1	2	2	-	-	-	-	2	2	-	-
CO3	3	2	2	3	3	2	2	-	-	-	-	2	3	1	-
CO4	3	2	2	3	3	2	2	-	-	-	-	2	3	2	1
CO5	3	2	2	3	3	2	2	-	-	-	-	2	2	3	1
CO6	3	2	2	3	3	2	2	-	-	-	-	2	2	-	-

Relevance: 1: Slight (Low) 2: Moderate (Medium) 3: Substantial (High)

UNIT-III
LECTURE PLAN

S. NO	TOPIC	No. of Periods	Proposed date	Actual Lecture Date	Pertaining CO	Taxonomy level	Mode of Delivery
1	Generation of High DC voltage: Rectifiers, voltage multipliers				CO3	K3	Power Point Presentation
2	vandigraff generator				CO3	K1	Power Point Presentation
3	generation of high AC voltages: cascaded transformers				CO3	K2	Power Point Presentation
4	Resonant transformer and tesla coil				CO3	K2	Power Point Presentation
5	Generation of high impulse voltage: singlestage Marx circuits				CO3	K3	Power Point Presentation
6	Multistage Marx circuits				CO3	K3	Power Point Presentation
7	Generation of switching surges				CO3	K2	Power Point Presentation
8	Generation of impulse currents				CO3	K2	Power Point Presentation
9	Triggering and control of impulse generators.				CO3	K2	Power Point Presentation

E Books

1. https://b-ok.asia/book/541362/93a5bb

   High voltage engineering , by C.L Wadhwa

2. https://b-ok.asia/book/593383/a732c8

   High voltage engineering by MS.Naidu &V.Kamaraju

3. https://b-ok.asia/book/462609/d72278

   High Voltage Engineering Fundamentals, by E. Kuffel and W.S. Zaengl, J.Kuffel

4. https://b-ok.asia/book/1132470/e51f4c

   High-voltage engineering: theory and practice, by Mazen Abdel – Salam, Hussein Anis, Ahdab A-Morshedy, Roshday Radwan

VIDEO LINKS

TITLE	LINK
Cockroft-walton Voltage Multiplier Circuit	https://www.youtube.com/watch?v=yfykYXdAUNY https://www.youtube.com/watch?v=yfykYXdAUNY&list=RDCMUCEWpbFLzoYGPfuWUMFPSaoA&index=1 https://www.youtube.com/watch?v=ep3D_LC2UzU https://www.youtube.com/watch?v=litsAzP4oqw https://www.youtube.com/watch?v=IqzA3-bgIIE
Vande Graff Generators	https://www.youtube.com/watch?v=Xqt2gAalV4Y https://www.youtube.com/watch?v=jZEFuCxD7BE https://www.youtube.com/watch?v=VebB-D61XDM https://www.youtube.com/watch?v=3Ptu07enIsY https://www.youtube.com/watch?v=ubZuSZYVBng https://www.youtube.com/watch?v=X-vW7r5K76I
Generation of Impulse voltages	https://www.youtube.com/watch?v=yBedWO5cRF0 https://www.youtube.com/watch?v=2O6aPrO5Iw4 https://www.youtube.com/watch?v=ZEIikw36P80 https://www.youtube.com/watch?v=ZEIikw36P80 https://www.youtube.com/watch?v=goOS2FDqAyU

UNIT -3

GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

Definition of Voltage Levels (IEC60038)

- A high voltage is voltage being greater than 1000 V for ac and greater than 1200 V for dc.
- Voltage class

Voltage class	Europe	USA
Low Voltage, LV (volt)	220/240 380/415 650 1000	120 208 600
Medium Voltage, MV (kV)	5 11 22 33 66	2.4 6.9 12.47 23 34.5 69
High Voltage, HV (kV)	110 132 156 220	115 138 161 230
Extra High Voltage, EHV (kV)	275 380 400 800	287 345 500 765
Ultra High Voltage, UHV (kV)	1000	

- In the fields of electrical engineering and applied physics, high voltages (d.c, a.c & impulse) are required for several applications.
- For electron microscopes and x-ray units require high d.c voltage.
- High a.c voltages are required for testing power apparatus (trasformers, cables, capacitors, circuit breakers, etc).
- High impulse voltages are required for testing purposes to simulate overvoltages that occur in power system due to lightning or switching action.
- For electrical engineers, the main concern of high voltages is for the insulation testing of various components in power systems.

Generation of High DC Voltages

- For the generation of D.C voltages of up to 100kV, electronic valve rectifiers are used and the output currents are about 100 mA.
- The rectifier valves require special construction since a high electrostatic field of several kV/cm exists.
- There are two methods of generating high D.C voltages:-
  - through the process of rectification employing voltage multiplier circuits (Half-wave Rectifier Circuit, Full-wave Rectifier Circuit, Voltage Doubler Circuit & Cockroft-Walton Voltage Multiplier).
  - Electrostatic generators.

Half-wave Rectifier Circuit

- The simplest circuit for generation of high direct voltage is the half wave rectifier shown in Fig. 1(a)

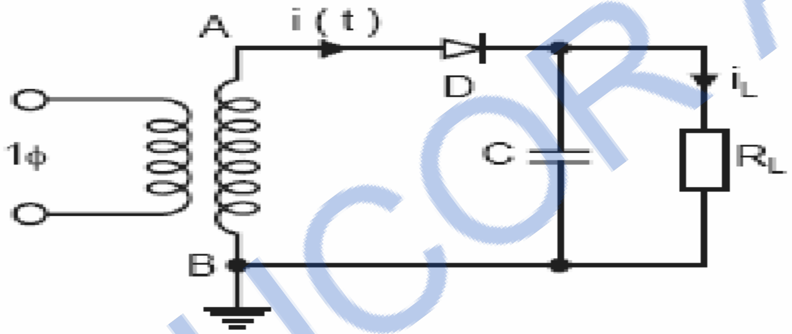


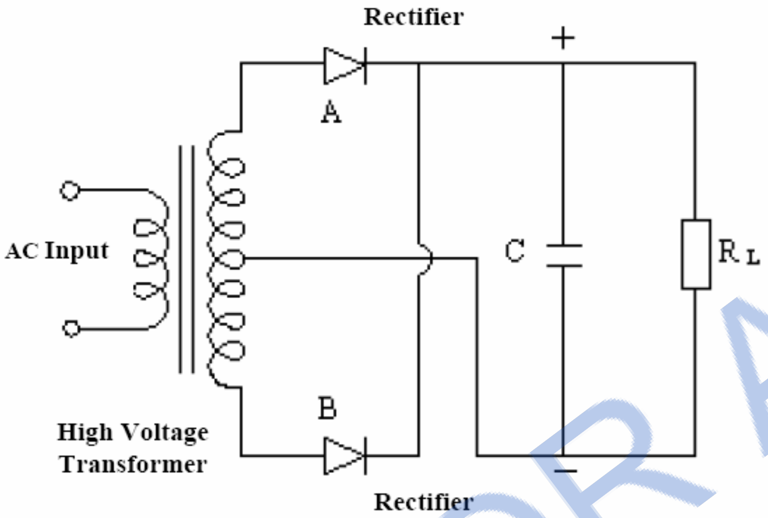
Fig. 1 (a) Single Phase rectifier

Here RL is the load resistance and C the capacitance to smoothen the d.c. output voltage.

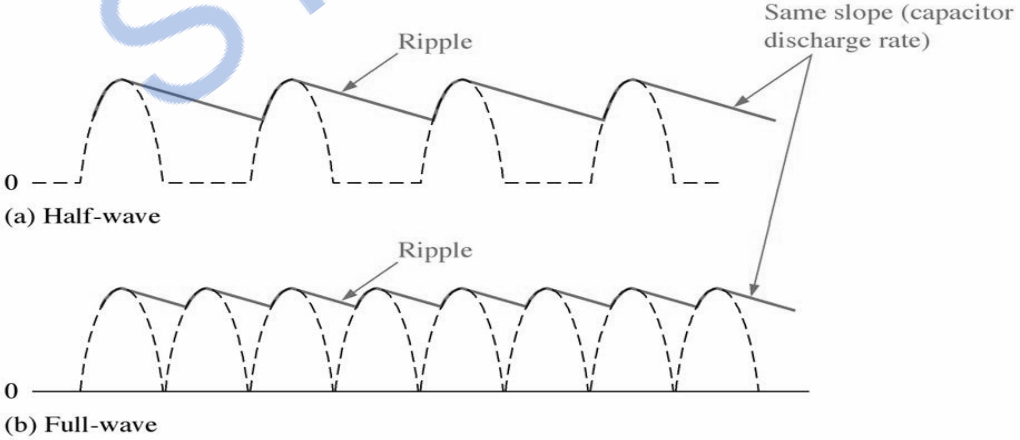
- Assuming the ideal transformer and small internal resistance of the diode during conduction the capacitor C is charged to the maximum voltage Vmax during conduction of the diode D.
- Assuming that there is no load connected, the d.c voltage across capacitance remains constant at Vmax whereas the supply voltage oscillates between ±Vmax
- During negative half cycle the potential of point A becomes – Vmax
- The single phase half-wave rectifier circuits have the following disadvantages:
- (i) The size of the circuits is very large if high and pure d.c. output voltages are desired.
- (ii) The h.t. transformer may get saturated if the amplitude of direct current is comparable with the nominal alternating current of the transformer.

Full-wave Rectifier Circuit

- A full wave rectifier circuit is shown in Fig. 2
- In the positive half cycle, the rectifier A conducts and charges the capacitor C.
- In the negative half cycle the rectifier B conducts and charges the capacitor.
- The sources transformer requires a centre tapped secondary with a rating of 2 V



- **Ripple Voltage**: the variation in capacitor voltage due to the charging and discharging.
- The advantage of a full-wave rectifier over a half-wave is quite clear. The capacitor can more effectively reduce the *ripple* when the time between peaks is *shorter*



Voltage Doubler Circuit

- High d.c. voltages can be generated by using :-
- Voltage doubler
- cascaded voltage multiplier circuits.
- One of the most popular doubler circuit due to Greinacher is shown in Fig. 3
- Suppose B is more positive with respect to A and the diode D1 conducts thus charging the capacitor C1 to Vmax with polarity.
- 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 2 Vmax through D2.
- Normally the voltage across the load will be less than 2 Vmax depending upon the time constant of the circuit C_2R_L.

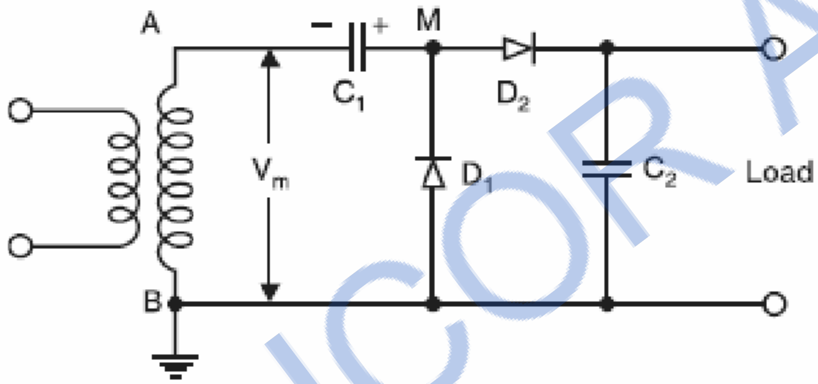


Fig. 3 Greinacher Voltage Doubler Circuit

Cockroft-Walton Voltage Multiplier

Fig. 4 shows a multistage single phase cascade circuit of the Cockroft-Walton type

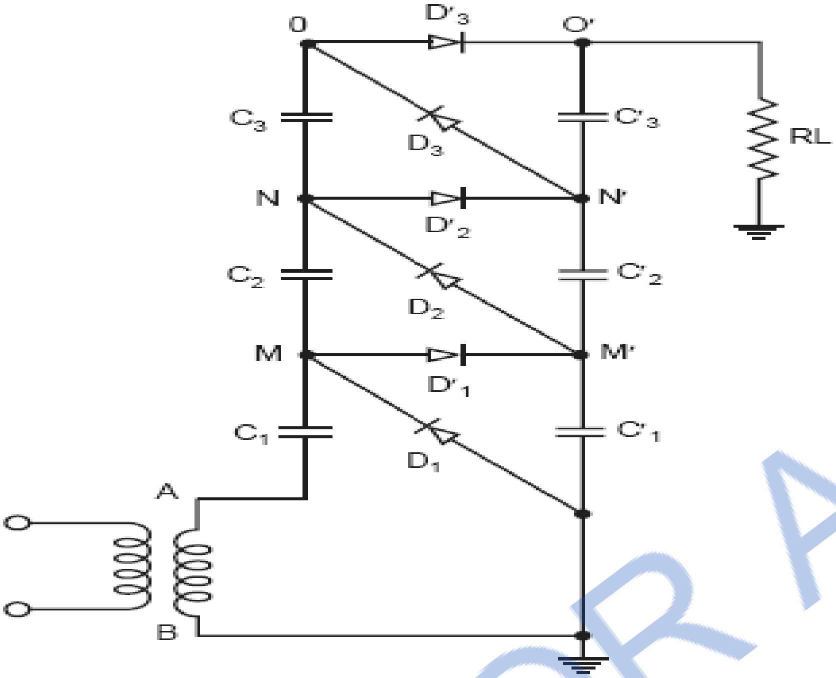


Fig. 4 **Cockroft-Walton Voltage Multiplier Circuit**

NO LOAD OPERATION

- 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.
- Finally all the capacitors C′1, C′2, C′3, C1, C2, and C3 are charged.
- The voltage across the column of capacitors consisting of C1, C2, C3, keeps on oscillating as the supply voltage alternates.
- 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.
- The total output voltage is 2n Vmax where n is the number of stages.
- The equal stress of the elements (both capacitors and diodes) used is very helpful and promotes a modular design of such generators.

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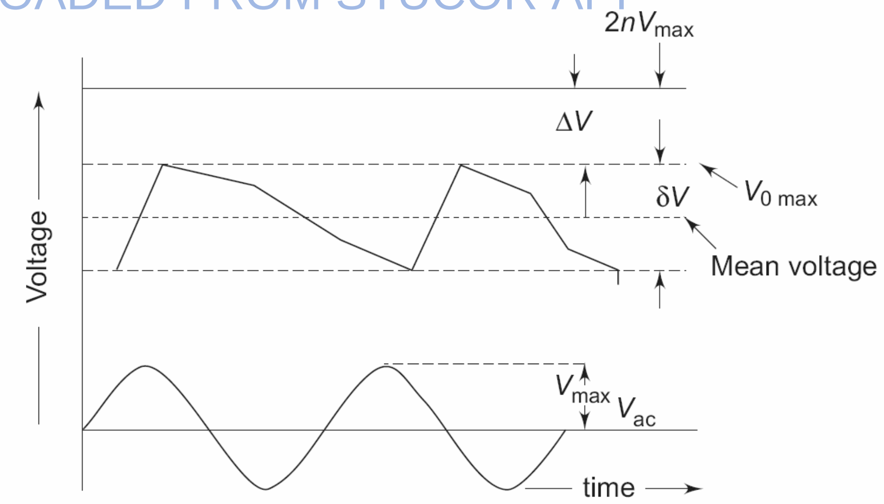


Fig. 6.4e *Ripple voltage δV and the voltage drop ΔV in a cascaded voltage multiplier circuit shown in Fig. 6.4b*

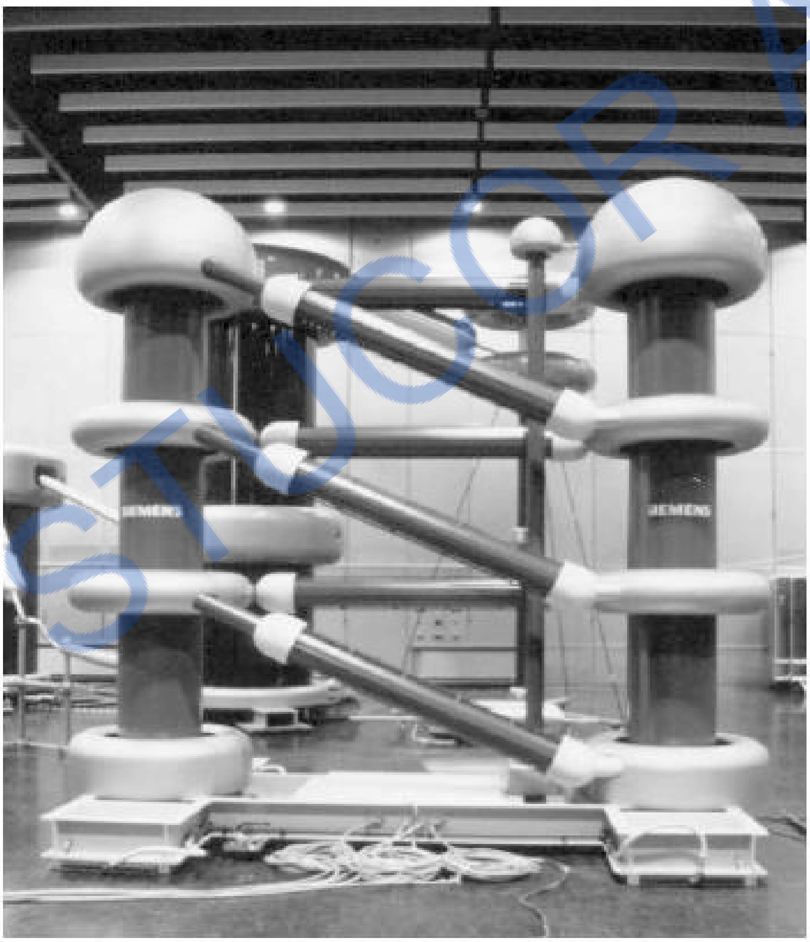


Figure 2.5 *A Cockroft–Walton d.c. generator for voltages up to 900 kV/ 10 mA with fast polarity reversal at ETH Zurich (courtesy HIGH VOLT, Dresden, Germany)*

GENERATOR LOADED

- When the generator is loaded, the output voltage will never reach the value 2n Vmax.
- 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.
- For n-stage circuit, the total ripple will be,

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

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

$$\text{where}, C'_n = C'_{n-1} = \cdots C'_1 = C$$

Ripple voltage,

$$\delta V = \frac{I}{fC} \times \frac{(n)(n+1)}{2} = \frac{I}{2fC} \times (n)(n+1)$$

Total Ripple,

$$\delta V_T = 2 \text{ x } \delta V$$

% Ripple,

$$\% \, \delta_{VT} = \frac{\delta V_T}{2n \, V_{max}} x \, 100\%$$

Voltage drop, ΔV is the difference between the theoretical no load voltage 2nVmax and the on load voltage,

Voltage Drop, $\Delta V = \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6}\right)$

For large values of n (≥5)will be small and may be neglected, thus

Voltage Drop, $$\Delta V = \frac{I}{fC}\left(\frac{2}{3}n^3\right)$$

% Voltage Regulation, $$\%\,\Delta V = \frac{\Delta V}{2n\,V_{max}}\,x\,100\%$$

Voltage regulation is the ratio between voltage drop and no load voltage, 2nVmax

The optimum number of stages assuming a constant *Vmax, I, f and C can be obtained*

$$n_{optimum} = \sqrt{\frac{V_{max}\ x\ fc}{I}}$$

In general, it is more economical to use high frequency and smaller value of capacitance to reduce the ripples or the voltage drop rather than low frequency and high capacitance.

PROBLEM1:

A ten stages Cockraft-Walton circuit has all capacitors of 0.06 µF. The secondary voltage of the supply transformer is 100 kV at a frequency of 150 Hz. If the load current is 1 mA, determine

(i) the voltage ripple

(ii) the voltage drop and regulation

(iii) the max output voltage

(iv) the optimum number of stages

Solution:

(i) the voltage ripple

$$\delta V = \frac{I}{fC} \times \frac{(n)(n+1)}{2} = \frac{I}{2fC} \times \frac{(n)(n+1)}{}$$

= 6.111 kV

ii) the voltage drop and regulation

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

$$= \frac{1m}{150 \times 0.06\mu}\left(\frac{2}{3} \times 10^3\right)$$

$$= 74.07\ kV$$

$$\text{Voltage regulation} = \frac{\Delta V}{2nV_{max}} \times 100\%$$

$$= \frac{74.07\ kV}{2 \times 10 \times 100\ \text{kV}} \times 100\%$$

$$= 3.7\%$$

(iii) the max output voltage

$$V_{o\,max} = 2nV_{max} - \Delta V$$

$$= (2 \times 10 \times 100\ kV) - 74.07\ kV$$

$$= 1925.93\ kV$$

(iv) the optimum number of stages

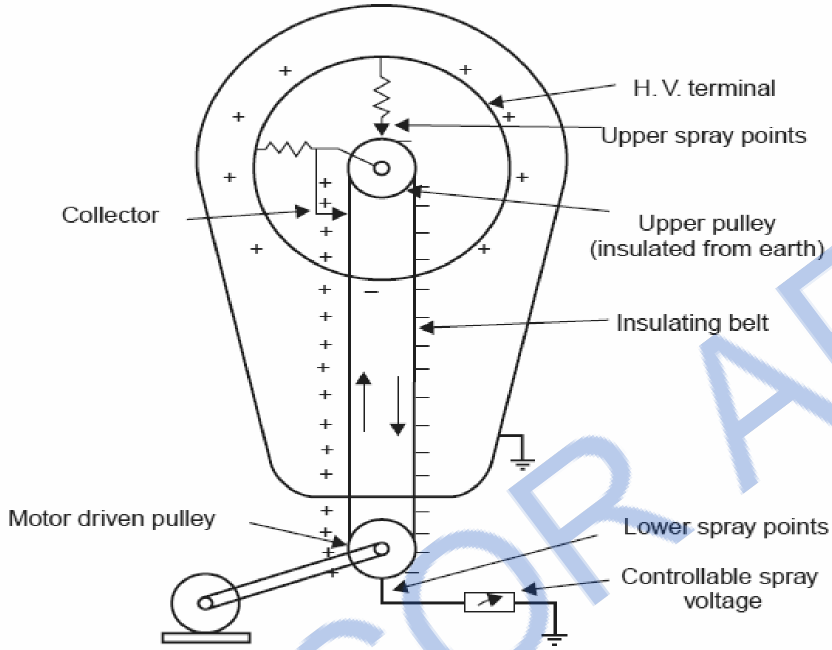
$$n_{optimum} = \sqrt{\frac{V_{max} f C}{I}}$$

$$= \sqrt{\frac{100\ kV \times 150 \times 0.06\mu}{1m}}$$

$$= 30$$

Van de Graaff Generators (Electro static Generator)

Fig. below shows belt driven electrostatic generator developed by Van deGraaf in 1931.



- An insulating belt is run over pulleys. The belt, the width of which may vary from a few cms to metres is driven at a speed of about 15 to 30 m/sec, by means of a motor connected to the lower pulley. The belt near the lower pully 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 is 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 raised to relatively higher voltage without corona discharges or for a certain voltage a smaller size of the equipment will result. Also, the shape of the h.t., electrode should be such that the surface gradient of electric field is made uniform to reduce again corona discharges, even though it is desirable to avoid corona entirely. An isolated sphere is the most favourable electrode shape and will maintain a uniform field *E with a voltage of Er where r is the radius of the sphere.*

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. It appears as though if the charge were collected for a long time any amount of voltage could be generated. However, as the potential of electrode rises, the field set up by the electrode increases and that may ionise the surrounding medium and, therefore, this would be the limiting value of the voltage. In practice, equilibrium is established at a terminal voltage which is such that the charging current

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

equals the discharge current which will include the load current and the leakage and corona loss currents. The moving belt system also distorts the electric field and, therefore, it is placed within properly shaped field grading rings. The grading is provided by resistors and additional corona discharge elements.

The collector needle system is placed near the point where the belt enters the h.t. terminal. A second point system excited by a self-inducing arrangement enables the down going belt to be charged to the polarity opposite to that of the terminal and thus the rate of charging of the latter, for a given speed, is doubled. The self inducing arrangement requires insulating the upper pulley and maintaining it at a potential higher than that of the h.t. terminal by connecting the pulley to the collector needle system. The arrangement also consists of a row of points (shown as upper spray points in Fig. connected to the inside of the h.t. terminal and directed towards the pulley above its points of entry into the 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 neutralises any remaining positive charge on the belt and leaves an excess of negative charges on the down going belt to be neutralised 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.*

We know that $D = \varepsilon_0 E$ where D is the flux density and since the medium surrounding the h.t. terminal is say air $\varepsilon_r = 1$ and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/metre.

According to Gauss law, $D = \sigma$ the surface charge density.

Therefore, $D = \sigma = \varepsilon_0 E$

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

$$\sigma = 8.854 \times 10^{-12} \times 3000 \times 10^3$$

$$= 26.562 \times 10^{-6}\ \text{C/m}^2$$

Assuming for a typical system $b = 1$ metre and velocity of the belt $v = 10$ m/sec, and using equation (2.16), the current supplied by the generator is given as

$$I = \sigma bv$$
$$= 26.562 \times 10^{-6} \times 1 \times 10$$
$$= 26.562 \times 10^{-5} \text{ Amp}$$
$$= 265\ \mu\text{A}$$

From equation it is clear that current *I depends upon σ, b and v. The belt width (b) and velocity* v 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 ionisation 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.

The advantages of the generator are:

(i) Very high voltages can be easily generated

(ii) Ripple free output

(iii) Precision and flexibility of control

The disadvantages are:

(i) Low current output

(ii) Limitations on belt velocity due to its tendency for vibration. The vibrations may

make it difficult to have an accurate grading of electric fields

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

Generation of High AC Voltages

- Generation of high voltages and high currents are required for the purpose of testing various types of power system equipment.
- Test transformers normally used for the purpose have low power rating but high voltage ratings.
- These transformers are mainly used for short time tests on high voltage equipments.
- For higher voltage requirement, a single unit construction becomes difficult and costly.
- These drawbacks are overcome by series connection or cascading of the several identical units of transformers.
- High AC voltages can be generated by either Test transformers or Resonant Circuits
- For generating AC test voltages of less than a few hundred kV, a single transformer can be used.
- For voltages higher than 400 KV, it is desired to cascade two or more transformers.
- Fig. 6 shows a basic scheme for cascading three transformers.

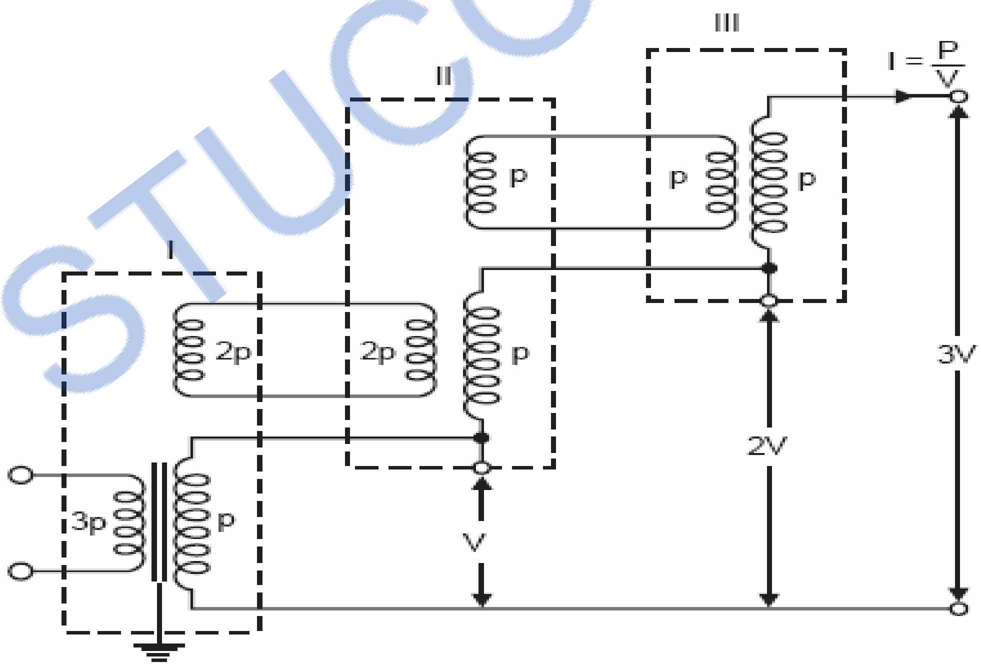


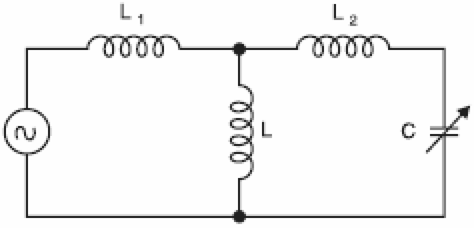
Fig. 6 Basic 3 stage cascaded transformer

- 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. 6.
- 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.
- The advantage of cascading the transformers is that the natural cooling is sufficient and the transformers are light and compact.
- The main disadvantage of this scheme :-
- 1) the lower stages of the primaries of the transformers are loaded more as compared with the upper stages
- 2) Bulky and heavy

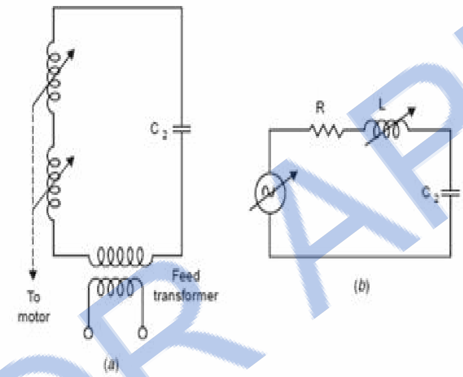
Three-stage cascade transformer 3 x 600 kV, 2 A cont. outdoor type with AC voltage divider 1500 kV

Series Resonant Circuit

- The equivalent circuit of a single-stage-test transformer alongwith 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. 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.



Equivalent circuit of a single stage loaded transformer



(a) Series resonance circuit with variable h.t. reactors (b) Equivalent circuit of (a)

Under resonance, the output voltage will be

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

Where *V is the supply voltage.*

Since at resonance

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

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

where *Q is the quality factor of the inductor which usually varies between 40 and 80. This means that* with *Q = 40, the output voltage is 40 times the supply voltage. It also means that the reactive power* requirements of the load capacitance in kVA is 40 times the power to be provided by the feed transformer in KW. This results in a relatively small power rating for the feed transformer.

Example 2.2. *A 100 kVA 250 V/200 kV feed transformer has resistance and reactance of 1% and 5% respectively. This transformer is used to test a cable at 400 kV at 50 Hz. The cable takes a charging current of 0.5 A at 400 kV. Determine the series inductance required. Assume 1% resistance of the inductor. Also determine input voltage to the transformer. Neglect dielectric loss of the cable.*

Solution: The circuit is drawn in Fig. Ex. 2.2

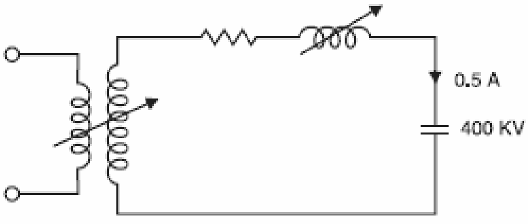


Fig. Ex. 2.2

The resistance and reactance of the transformer are

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

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

The resistance of the inductor is also 4 KΩ.

The capacitive reactance of capacitor (Test Specimen)

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

For resonance $X_L = X_C$

Inductive reactance of transformer is 20 KΩ . Therefore, additional inductive reactance required will be

$$800 - 20 = 780\ \text{K}\Omega$$

The inductance required $= \dfrac{780 \times 1000}{314} = 2484$ H

Total resistance of the circuit = 8 KΩ

under resonance condition the supply voltage

(Secondary voltage) $= IR = 0.5 \times 8 = 4$ kV

Therefore, primary voltage $= 4 \times \dfrac{250}{200} = 5$ volts **Ans.**

Tesla Coil (Generation of High Frequency a.c. High Voltages)

- A Tesla coil is a radio frequency oscillator that drives an air-core double-tuned resonant transformer to produce high voltages at low currents
- Tesla coils can produce output voltages from 50 kilovolts to several million volts for large coils. The alternating current output is in the low radio frequency range, usually between 50 kHz and 1 MHz
- Although some oscillator-driven coils generate a continuous alternating current, most Tesla coils have a pulsed output

  the high voltage consists of a rapid string of pulses of radio frequency alternating current.
- The common spark-excited Tesla coil circuit, shown below, consists of these components

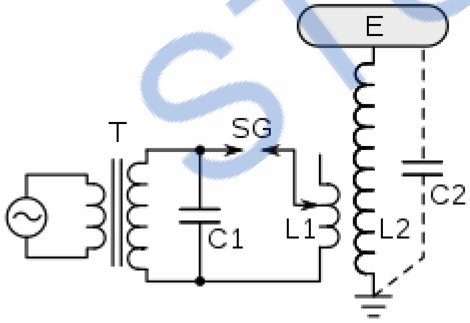
  1. A high voltage supply transformer *(T)*, to step the AC mains voltage up to a high enough voltage to jump the spark gap. Typical voltages are between 5 and 30 kilovolts (kV).[20]

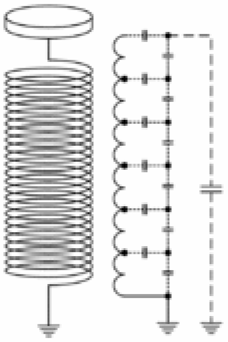
  2. A capacitor *(C1)* that forms a tuned circuit with the primary winding *L1* of the Tesla transformer

  3. A spark gap *(SG)* that acts as a switch in the primary circuit

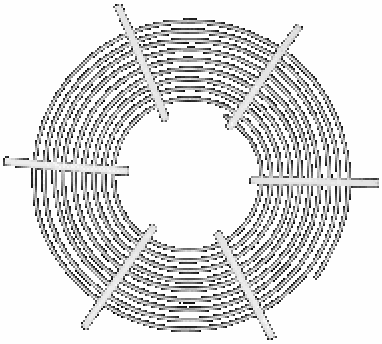
  4. The Tesla coil *(L1, L2)*, an air-core double-tuned resonant transformer, which generates the high output voltage.

  5. Optionally, a capacitive electrode (top load) *(E)* in the form of a smooth metal sphere or torus attached to the secondary terminal of the coil. Its large surface area suppresses premature air breakdown and arc discharges, increasing the Q factor and output voltage.



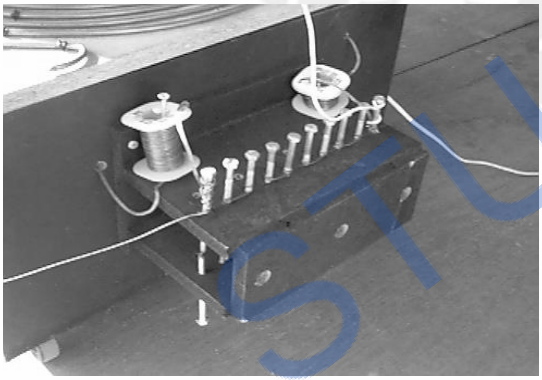


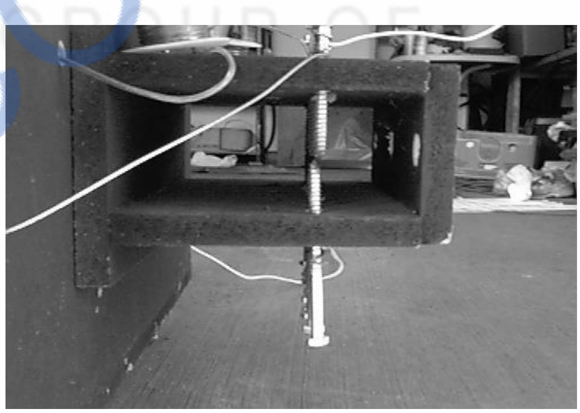
Primary coil:

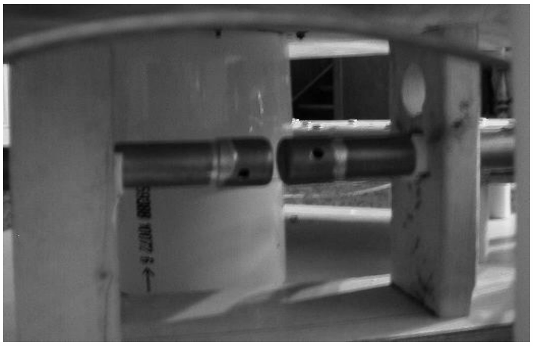


- High circulating current. 100 Amps or more.
- flat coil, not cylinder
- 1/4 inch refrigerator tubing
- 10 Ga wire.
- various tap positions.

Spark gap:

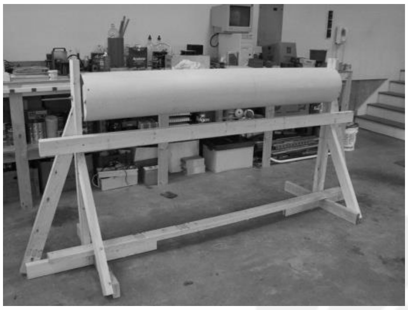


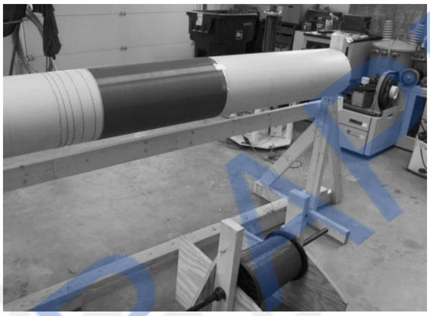


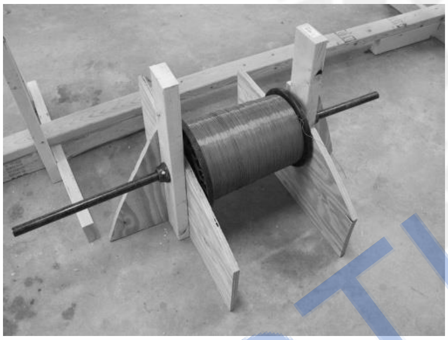


- high current
- not too wide: .25 inch.
- needs quenching
- static:
- 2 carriage bolts
- multiple copper tube gaps with blower
- Rotary: sync or async
- triggered gap

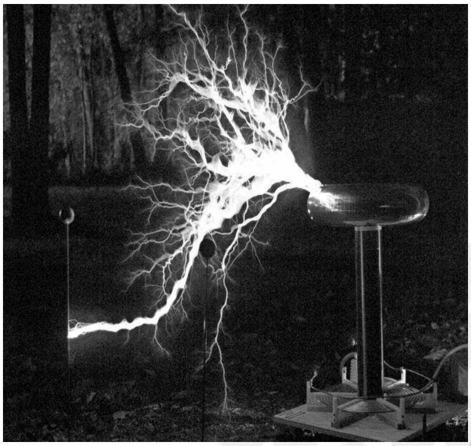
- Secondary Coil
  - 1000 to 1300 turns of magnet wire (24g to 32g)
  - PVC coil form . 3 to 8 inch diameter.
  - 6:1 width to height
  - Polyurethane first.
  - Use a winding jig. very tedious.
  - 3 finishing coats of poly. inside and out.





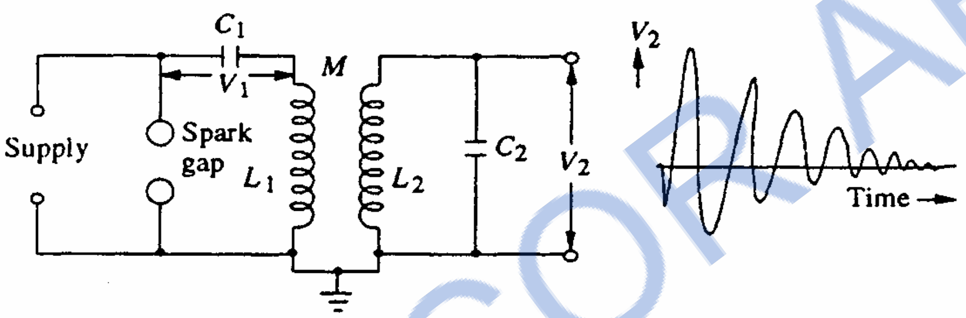


- Capacitance Hat.
  - A necessity
  - Toroid best
  - Sphere second best
  - stores energy on successive cycles.
  - can be too large or too small
  - made from dryer duct and aluminum tape
  - can buy spun aluminum toroids.



- The commonly used high frequency resonant transformer is the Tesla coil, which is a doubly tuned resonant circuit shown schematically in Fig. 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 Ci. A spark gap G connected across the primary is triggered at the desired voltage V1 which induces a high self-excitation in the secondary. The primary and the secondary windings (L1 and L2) 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 C1 and C2

- The output voltage V2 is a function of the parameters L1, L2, C1, C2 and the mutual inductance M. Usually, the winding resistances will be small and contribute only for damping of the oscillations.



(a) Equivalent circuit (b) Output waveform

- The analysis of the output waveform can be done in a simple manner neglecting the winding resistances. Let the condenser C1 be charged to a voltage V1 when the spark gap is triggered. Let a current i1 flow through the primary winding L1 and produce a current i2 through L2 and C2

Then,

$$V_1 = \frac{1}{C_1}\int_0^t i_1\,dt + L_1\frac{di_1}{dt} + M\frac{di_2}{dt}$$

and,

$$0 = \frac{1}{C_2}\int_0^t i_2\,dt + L_2\frac{di_2}{dt} + M\frac{di_1}{dt}$$

The Laplace transformed equations for the above are,

$$\frac{V_1}{s} = \left[L_1 s + \frac{1}{C_1 s}\right] I_1 + M s I_2$$

and,

$$0 = [Ms]I_1 + \left[L_2 s + \frac{1}{[C_2 s]}\right] I_2$$

where I_1 and I_2 are the Laplace transformed values, of i_1 and i_2.

The output voltage V_2 across the condenser C_2 is

$$V_2 = \frac{1}{C_2}\int_0^t i_2 dt;$$ or its transformed equation is

$$V_2(s) = \frac{I_2}{C_2 s}$$

where $V_2(s)$ is the Laplace transform of V_2.

The solution for V_2 from the above equations will be

$$V_2 = \frac{MV_1}{\sigma L_1 L_2 C_1} \frac{1}{\gamma_2^2 - \gamma_1^2} [\cos \gamma_1 t - \cos \gamma_2 t]$$

where,

$$\sigma^2 = 1 - \frac{M^2}{L_1 L_2} = 1 - K^2$$

K = coefficient of coupling between the windings L_1 and L_2

$$\gamma_{1,2} = \frac{\omega_1^2 + \omega_2^2}{2} \pm \sqrt{\left(\frac{\omega_1^2 + \omega_2^2}{2}\right)^2 - \omega_1^2 \omega_2^2 (1 - K^2)}$$

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \text{ and } \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

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,

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

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

A more simplified analysis for the Tesla coil may be presented by considering that the energy stored in the primary circuit in the capacitance C1 is transferred to C2 via the magnetic coupling. If W1 is the energy stored in C1 and W2 is the energy transferred to C2 and if the efficiency of the transformer is η, then

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

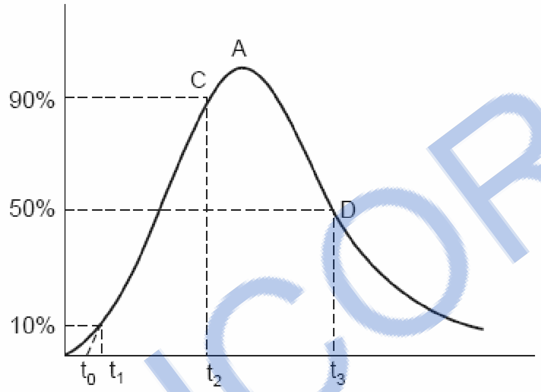
$$V_2 = V_1 \sqrt{\eta \frac{C_1}{C_2}}$$

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. This is shown in the next sections while dealing with the generation of switching surges.

Generation of Impulse Voltages

DEFINITIONS

- An impulse voltage is a unidirectional voltage which, rises rapidly to a maximum value and falls more or less rapidly to zero.
- The maximum value is called the peak value of the impulse.
- A full impulse voltage is characterized by its peak value and its two time intervals, the wave front and wave tail time intervals.
- 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.
- Wave tail time is measured between the nominal starting point t0 and the point on the wave tail where the voltage is 50% of the peak value i.e. wave tail time is expressed as (t3 – t0).



Impulse Wave

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

- The tolerances allowed in the front and tail durations are ±30% and ±20% respectively
- The tolerance allowed in the peak value is ±3%
- The standard lightning impulse wave has a front duration of 1.2 μs and a wave tail duration of 50 μs, and is described as a 1.2/50 μs wave.
- The definition of the front and tail is as described in the IEC 60060 standard

Two simplified but more practical forms of impulse generator circuits are shown in Fig. 6.10 *(a) and (b).*

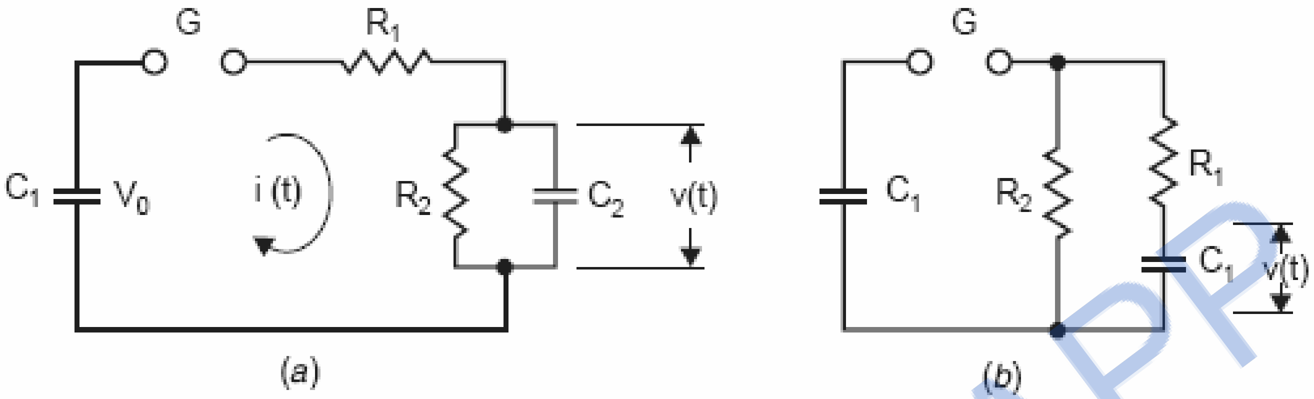


Fig. Simplified equivalent circuit of an impulse generator

- 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 to a d.c. voltage Vo
- 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.

ANALYSIS OF CIRCUIT 'a'

The output voltage

$$v_0(t) = \frac{V_{in}}{R_1C_2}\left(\frac{1}{\beta - \alpha}\right)\left[e^{-\alpha t} - e^{-\beta t}\right]$$

where

$$\alpha = \frac{1}{R_1C_2}$$

$$\beta = \frac{1}{R_2C_1}$$

- The front wave time and the tail wave time can be determined approximately
  - The time for wave front

$$t_1 = t_f = 3.0 R_1 \frac{C_1C_2}{C_1 + C_2}$$

  - The time for wave tail

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

Multistage Impulse Generators

- In the above discussion, the generator capacitance *C1 is to be first charged and then* discharged into the wave shaping circuits. A single capacitor C1 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.

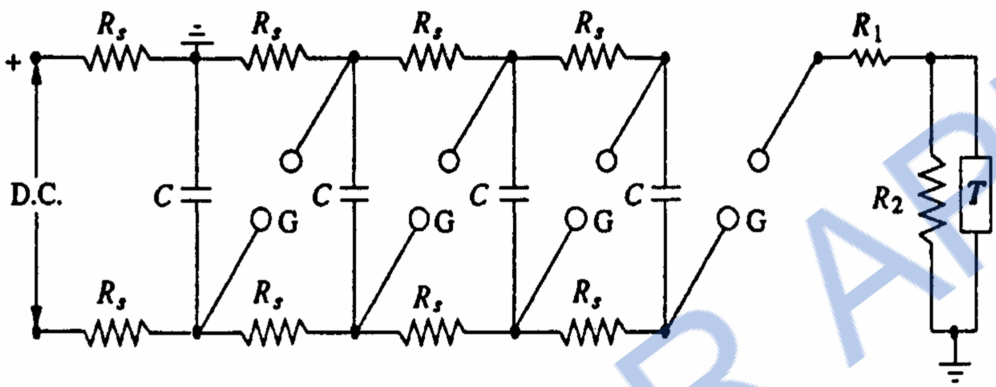
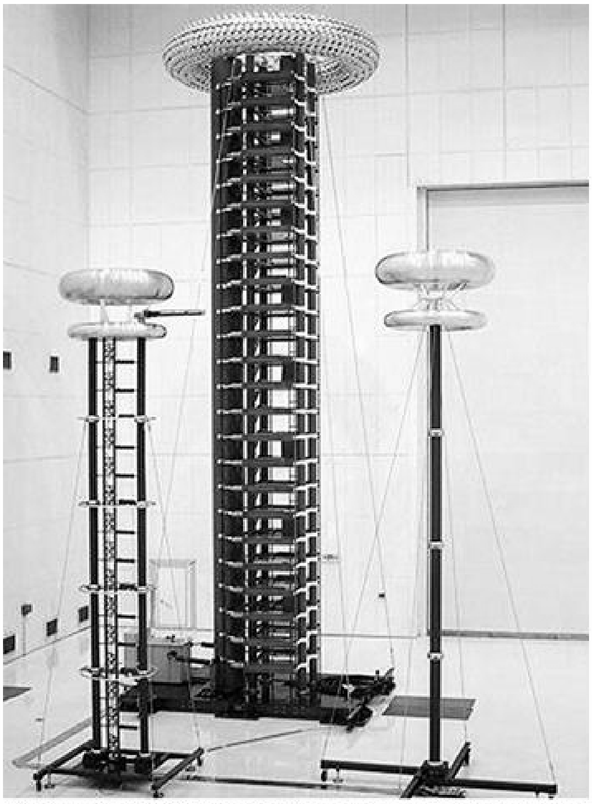


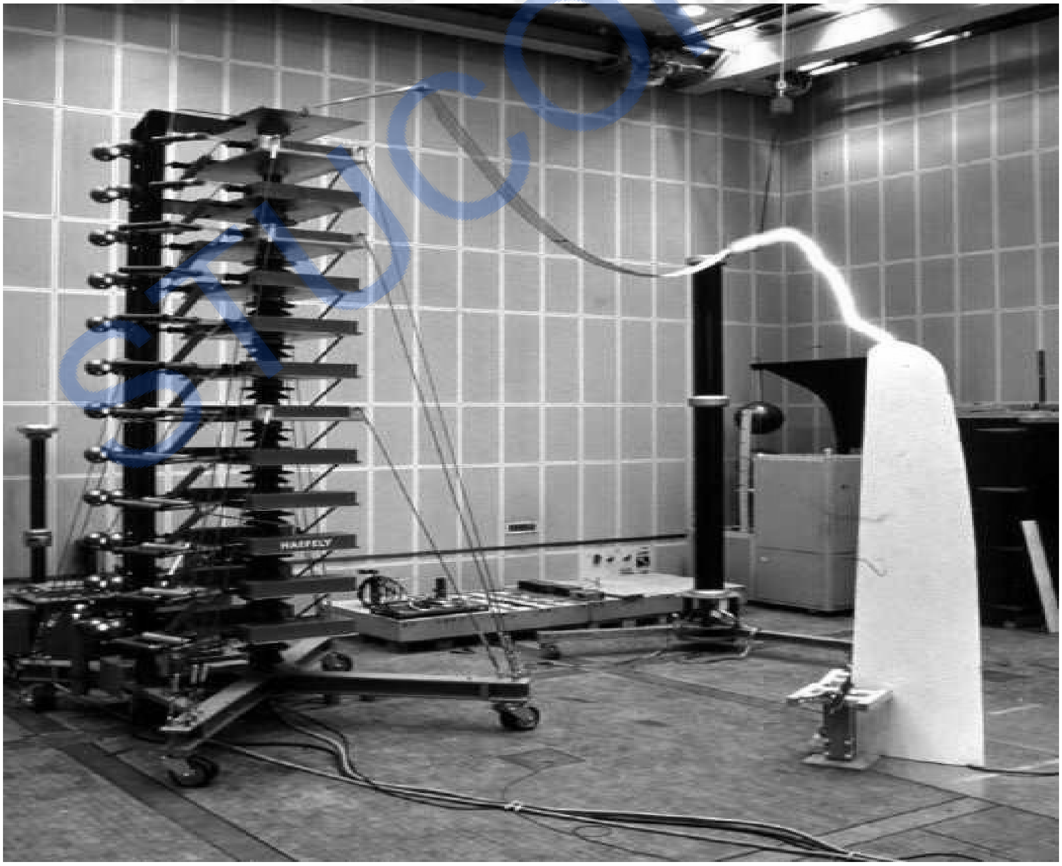
Fig . Schematic diagram of Marx circuit arrangement for multistage impulse generator

- The schematic diagram of Marx circuit and its modification are shown in Fig. Usually the charging resistance Rs 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 CR1/n (for n stages) will be very very small (microseconds), compared to the charging time constant CRs which will be few seconds. Hence, no discharge takes place through the charging resistors Rs. In the Marx circuit is of Fig . the impulse wave shaping circuit is connected externally to the capacitor uni.



TEEA Shenyang CDYH4800kV/720kJ complete set of impulse voltage generator test system (air cushion)

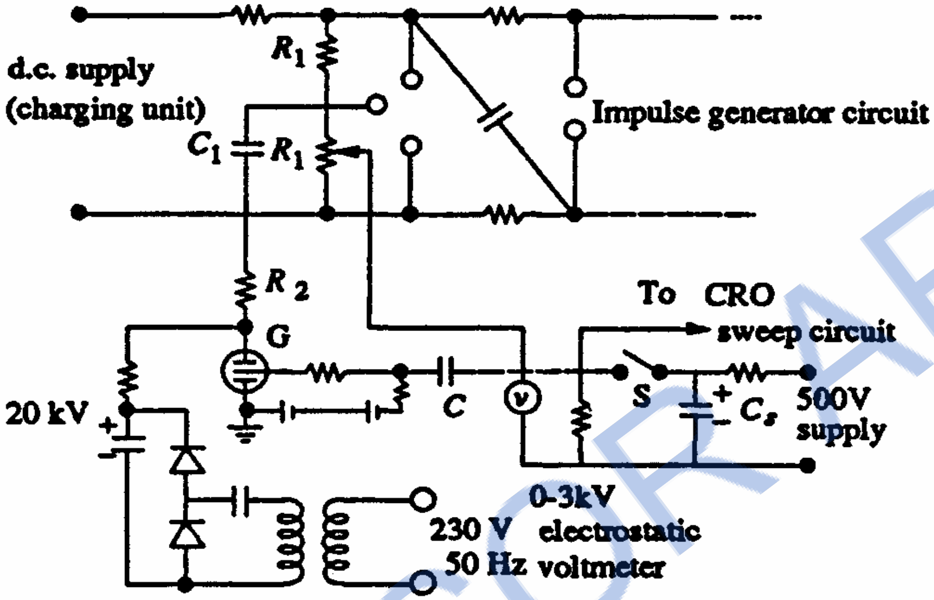
Argentina CDYL800kV/20kJ complete set of impulse voltage generator test system



TRIPPING AND CONTROL OF IMPULSE GENERATORS

In large impulse generators, the spark gaps are generally sphere gaps or gaps formed by hemispherical electrodes. The gaps are arranged such that sparking of one gap results in automatic sparking of other gaps as overvoltage is impressed on the other. In order to have consistency in sparking, irradiation from an ultra-violet lamp is provided from the bottom to all the gaps.

To trip the generator at a predetermined time, the spark gaps may be mounted on a movable frame, and the gap distance is reduced by moving the movable electrodes closer. This method is difficult and does not assure consistent and controlled tripping.



A simple method of controlled tripping consists of making the first gap a three electrode gap and firing it from a controlled source. Figure gives the schematic arrangement of a three electrode gap. The first stage of the impulse generator is fitted with a three electrode gap, and the central electrode is maintained at a potential in between that of the top and the bottom electrodes with the resistors R\ and RL. The tripping is initiated by applying a pulse to the thyratron G by closing the switch S. The capacitor C produces an exponentially decaying pulse of positive polarity. The pulse goes and initiates the oscillograph time base. The thyratron conducts on receiving the pulse from the switch S and produces a negative pulse through the capacitance Ci at the central electrode of the three electrode gap. Hence, the voltage between the central electrode and the top electrode of the three electrode gap goes above its sparking potential and thus the gap conducts. The time lag required for the thyratron firing and breakdown of the three electrode gap ensures that the sweep circuit of the oscillograph begins before the start of the impulse generator voltage. The resistance *R2 ensures* decoupling of voltage oscillations produced at the spark gap entering the oscilloscope through the common trip circuit.

Assignment-Unit 3

1. Explain the working of cockroft-walton voltage multiplier circuit under unloaded and loaded conditions
2. Describe the construction and working principle of vande graff generator with neat sketch

Part-A 2 Marks Questions

1. What are the different forms of high voltages? (CO3-K1)
   - High DC voltages
   - High ac voltages of power frequency
   - High ac voltages of high frequency
   - High transient or impulse voltage of very short duration
   - Transient voltages of longer duration such as switching surges.

2. What are the applications of high voltages? (CO3-K1)
   - Electron microscopes and x-ray units in the order of 100KV or more.
   - Electrostatic precipitators
   - Testing purposes to simulate over voltages due to lighning and switching.

3. Name the methods used to generate High voltage DC. (CO3-K1)
   - Half and full wave rectifier
   - Voltage doubler circuit
   - Voltage multiplier circuit
   - Van de Graff generator

4. Write the basic principle of Electrostatic machines. (CO3-K1)

   In electrostatic machines, current carrying conductors are moved in a magnetic field, so that the mechanical energy is converted into electrical energy.

5. What are the advantages of Van de graff generator? (CO3-K1)
   - Very high DC voltage
   - Ripple free output
   - Precision and flexible of control

6. What are the limitations of Van de graff generator? (CO3-K1)
   - Low current output.
   - Limitations on belt velocity due to vibration.
   - It is difficult to have an accurate grading of electric fields

7. What are the methods to generate High alternating voltages?
(CO3-K1)

- Cascaded Transformers
- Resonant Transformers

8. What are the advantages of using cascade transformer with isolating transformer?
(CO3-K1)

- Natural cooling is sufficient.
- Transformer are compact in size
- Constructional is identical
- Three phase connection in star or delta is possible

9. What are the advantages of resonant transformers?
(CO3-K1)

- It gives an output of pure sine wave
- . Power requirement is less.
- No high power arcing and heavy current surges occur.
- Cascading is also possible for very high voltages.
- Simple and compact test arrangement.

10. What are the advantages of High frequency ac transformers? (CO3-K1)

- The absence of iron core in transformers and hence saving in cost and size
- . Pure sine wave output.
- Slow build up of voltage over a few cycles and hence no damage due to switching surge

11. Define front time.

It is the time required for the response to raise from 10% to 90% or o to 100% of the final value at the very first instant.

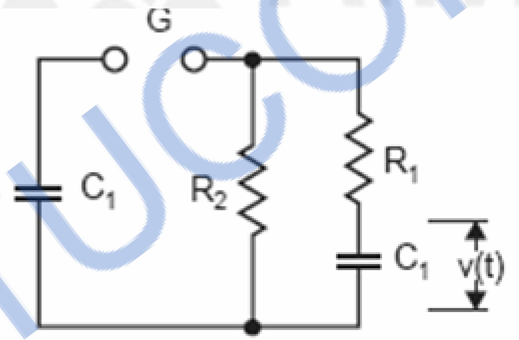
12. What are the components of multi-stage impulse generator?

- DC charging set
- Charging resistor
- Generator capacitor or spark gap
- Wave shaping resistors and capacitors
- Trigerring system
- Voltage dividers
- Gas insulated impulse generators

Part-B 13 marks Questions

1. a)Mention the necessity of generating high DC Voltages (CO3-K1)

   b) Describe the construction and working principle of vande graff generator with neat sketch (CO3-K1)
2. Explain the working of cockroft-walton voltage multiplier circuit under unloaded and loaded conditions (CO3-K2)
3. Derive the expression for total voltage drop and total voltage ripple of n-stage multiplier circuit and hence deduce the condition for optimum number of stages (CO3-K2)
4. Explain the working principle of parallel resonant transformer (CO3-K1)
5. Explain the cascaded transformer method of HVAC Generation (CO3-K1)
6. Explain the operation of basic impulse generator (CO3-K1)
7. Give the complete analysis of the given impulse circuit and derive the condition for physical realization of wave front and wave tail resistances (CO3-K1)



(b)

8. What is Tesla coil? How the Damped high frequency oscillations are obtained from Tesla coil? (CO3-K1)

Part C- 15 marks questions

PART-C (15 Marks)

1. A Cockroft Walton type voltage multiplier has eight stages with capacitances all equal to 0.05 micro farads. The supply transformer secondary voltage is 125 KV at a frequency of 125 Hz. If the load current to be supplied is 4.5 mA. Find

    a) the % ripple (CO3-K3)

    b) the regulation

    c) the optimum number of stages for minimum regulation of voltage drop

2. A 100 kVA 250 V/200 kV feed transformer has resistance and reactance of 1% and 5% respectively. This transformer is used to test a cable at 400 kV at 50 Hz. The cable takes a charging current of 0.5 A at 400 kV. Determine the series inductance required. Assume 1% resistance of the inductor. Also determine input voltage to the transformer. Neglect dielectric loss of the cable. (CO3-K3)

3. A six-stage impulse generator designed to generate the standard waveform (1.2/50 mocrS) has a per stage capacitance of 0.06microF to be used to test transformers with an equivalent winding to earth capacitance of 1nF. A peak output voltage of 550 kV is required for testing the transformer. Thewavefront time is to be defined based on 30% and 90% values. With the aid of appropriate calculations select the values of the resistive elements in the circuit to produce the required waveform. State any assumptions made (CO3-K3)

Supportive online Certification courses

- https://nptel.ac.in/courses/108/104/108104048/

  High voltage Engineering –NPTEL Web based course

- https://www.udemy.com/course/protection-and-control-of-high-voltage-power-circuits/

  Protection and control of high voltage power circuit

Real time Applications in day to day life and to Industry

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

Test transformers normally used for the purpose have low power rating but high voltage ratings. These transformers are mainly used for short time tests on high voltage equipments

Thank you

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HIGH VOLTAGE ENGINEERING

Department: Electrical and Electronics Engineering
Batch/Year: 2017-2021 Subject code : EE8701

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RMD Engineering College

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RMK Engineering College

Table of Contents

Table of Contents

Course Objectives

To impart knowledge on the following Topics

1. Various types of over voltages in power system and protection methods.

2. Generation of over voltages in laboratories.

3. Measurement of over voltages.

4. Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.

5. Testing of power apparatus and insulation coordination

Pre Requisites (Course Names with Code)

EE8402- Transmission and Distribution
EE8501 Power System Analysis
EE8602 Protection and Switchgear

SYLLABUS

EE8701 HIGH VOLTAGE ENGINEERING **L T P C**

3 0 0 3

OBJECTIVES:

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•Generation of over voltages in laboratories.

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•Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.

•Testing of power apparatus and insulation coordination

UNIT I OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS 9

Causes of over voltages and its effects on power system – Lightning, switching surges and temporary over voltages, Corona and its effects – Bewley lattice diagram- Protection against over voltages.

UNIT II DIELECTRIC BREAKDOWN 9

Properties of Dielectric materials - Gaseous breakdown in uniform and non-uniform fields – Corona discharges – Vacuum breakdown – Conduction and breakdown in pure and commercial liquids, Maintenance of oil Quality – Breakdown mechanisms in solid and composite dielectrics- Applications of insulating materials in electrical equipments.

UNIT III GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

Generation of High DC voltage: Rectifiers, voltage multipliers, vandigraff generator: generation of high impulse voltage: single and multistage Marx circuits – generation of high AC voltages: cascaded transformers, resonant transformer and tesla coil- generation of switching surges – generation of impulse currents - Triggering and control of impulse generators.

UNIT IV MEASUREMENT OF HIGH VOLTAGES AND HIGH CURRENTS

High Resistance with series ammeter – Dividers, Resistance, Capacitance and Mixed dividers - Peak Voltmeter, Generating Voltmeters - Capacitance Voltage Transformers, Electrostatic Voltmeters – Sphere Gaps - High current shunts- Digital techniques in high voltage measurement.

UNIT V HIGH VOLTAGE TESTING & INSULATION COORDINATION 9

High voltage testing of electrical power apparatus as per International and Indian standards – Power frequency, impulse voltage and DC testing of Insulators, circuit breakers, bushing, isolators and transformers- Insulation Coordination& testing of cabilitys.

TOTAL : 45 PERIODS

COURSE OUTCOME

Course Outcome		Level of Knowledge
CO1	Understand various types of over voltages experienced by the power system	K2
CO2	Understand and explain the breakdown mechanism of different types of dielectrics	K1
CO3	Explain the generation of High voltages and currents and apply the same for calculating the voltage to be generated for testing an apparatus of a particular rated voltage	K3
CO4	Understand various methods of HV measurements and identify the appropriate measuring system for various types of over voltages and currents	K2
CO5	Understand process of testing of various power system apparatus	K2
CO6	Understand the significance of insulation coordination and apply the same for fixing the BIL of an apparatus	K3

PROGRAM OUTCOMES (POs)

a.Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

b.Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

c.Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

d.Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

e.Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

f.The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

g.Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

h.Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

i.Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

j.Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

k.Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary **environments.**

l.Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES (PSOs)

PSO 1: Design and analyze electrical systems incorporating electrical machines, power controllers along with the design of electrical layout for the complete structure.

PSO 2 : Use the modern tools for implementing the solutions to engineering problems that can arise in the fields of Electrical, Electronics and Telecommunication Engineering along with Information Technology Services.

PSO 3 : Face the challenges in the society by adopting the non-conventional energy resources and utilizing the modern technologies for energy efficient transmission and power quality improvement delivering clean energy for the wellbeing of the mankind.

COs - POs/PSOs MATRICES

COs	PO												PSO		
	a	b	c	d	e	f	g	h	i	j	k	l	**1**	**2**	**3**
CO1	3	3	2	3	2	2	2	-	-	-	-	2	2	-	-
CO2	3	2	1	2	1	2	2	-	-	-	-	2	2	-	-
CO3	3	2	2	3	3	2	2	-	-	-	-	2	3	1	-
CO4	3	2	2	3	3	2	2	-	-	-	-	2	3	2	1
CO5	3	2	2	3	3	2	2	-	-	-	-	2	2	3	1
CO6	3	2	2	3	3	2	2	-	-	-	-	2	2	-	-

Relevance: 1: Slight (Low) 2: Moderate (Medium) 3: Substantial (High)

UNIT-I
LECTURE PLAN

S. NO	TOPIC	No. of Periods	Proposed date	Actual Lecture Date	Pertaining CO	Taxonomy level	Mode of Delivery
1	High Resistance with series ammeter				CO4	K1	Power Point Presentation
2	Dividers, Resistance Divider				CO4	K2	Power Point Presentation
3	Capacitance and Mixed potential Divider				CO4	K2	Power Point Presentation
4	Peak Voltmeter Generating voltmeter				CO4	K1	Power Point Presentation
5	Capacitance voltage transformer				CO4	K2	Power Point Presentation
6	Electrostatic voltmeter				CO4	K2	Power Point Presentation
7.	Sphere gap				CO4	K2	Power Point Presentation
8.	High current shunt				CO4	K2	Power Point Presentation
9.	Digital techniques in high voltage measurement				CO4	K2	Power Point Presentation

E Books

1. https://b-ok.asia/book/541362/93a5bb

   High voltage engineering , by C.L Wadhwa

2. https://b-ok.asia/book/593383/a732c8

High voltage engineering by MS.Naidu &V.Kamaraju

3. https://b-ok.asia/book/462609/d72278

High Voltage Engineering Fundamentals, by E. Kuffel and

W.S. Zaengl, J.Kuffel

4. https://b-ok.asia/book/1132470/e51f4c

High-voltage engineering: theory and practice, by Mazen Abdel – Salam, Hussein Anis, Ahdab A-Morshedy, Roshday Radwan

VIDEO LINKS

TITLE	LINK
Introduction to high voltage measurement	https://youtu.be/D-OZJkk51Jw
Series resistance Micro ammeter	https://youtu.be/w-D5gqfB0kE
HV measurement using potential dividers	https://youtu.be/7Tnyj34zyMY
Generating voltmeter	https://youtu.be/lG7DtyqDkC4
Electrostatic Voltmeter	https://youtu.be/DozBX3mn9v0
Chubb Fortescue peak Voltmeter	https://youtu.be/CN-wdyDpczI
Sphere gap	https://youtu.be/dOxgaH_YDL0

UNIT -4

MEASUREMENT OF HIGH VOLTAGES AND CURRENT

Measurement of High voltages

- Measurement of high d.c. voltages as in low voltage measurements, is generally accomplished by extension of meter range with a large series resistance. The net current in the meter is usually limited to one to ten microamperes for full-scale deflection. For very high voltages (1000 kV or more) problems arise due to large power dissipation, leakage currents and 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 sometimes better when high precision is needed. But potential dividers also suffer from the disadvantages stated above. Both series resistance meters and potential dividers cause current drain from the source.

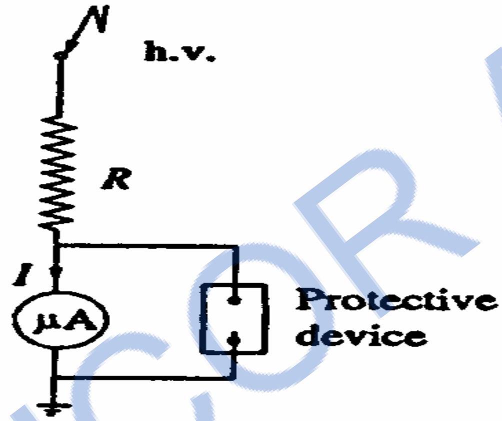
- Generating voltmeters are high impedance devices and do not load the source. They provide complete isolation from the source voltage (high voltage) as they are not directly connected to the high voltage terminal and hence are safer. Spark gaps such as sphere gaps are gas discharge devices and give an accurate measure of the peak voltage. These are quite simple and do not require any specialized construction.

High Ohmic Series Resistance with Micro ammeter

- High d.c. voltages are usually measured by connecting a very high resistance (few hundreds of mega ohms) in series with a micro ammeter as shown in Fig . Only the current I flowing through the large calibrated resistance R is measured by the moving coil micro ammeter. The voltage of the source is given by

$$V = IR$$

- The voltage drop in the meter is negligible, as the impedance of the meter is only few ohms compared to few hundred mega-ohms of the series resistance *R.* A protective device like a paper gap, a neon glow tube, or a zener diode with a suitable series resistance is connected across the meter as a protection against high voltages in case the series resistance *R* fails or flashes over. The ohmic value of the series resistance *R* is chosen such that a current of one to ten microamperes is allowed for full-scale deflection. The resistance is constructed from a large number of wire wound resistors in series. The voltage drop in each resistor element is chosen to avoid surface flashovers and discharges.

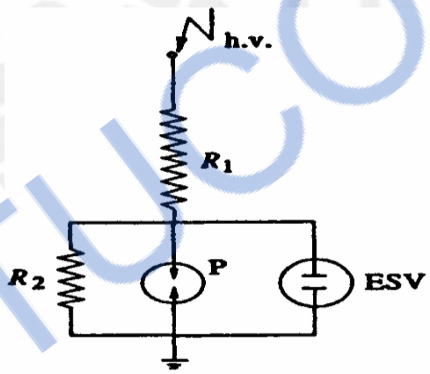


SERIES RESIISTANCE MICROMETER

The limitations in the design are Power dissipation and source loading , Temperature effects and long time stability , Voltage dependence of resistive elements, Sensitivity to mechanical stresses .

Resistance Potential Dividers for D.C. Voltages

- A resistance potential divider with an electrostatic or high impedance voltmeter is shown in fig . The influence of temperature and voltage on the elements is eliminated in the voltage divider arrangement. The high voltage magnitude is given by $[(R1+R2)/R2]V2$, where $V2$ is the d.c. voltage across the low voltage arm $R2$. With sudden changes in voltage, such as switching operations, flashover of the test objects, or source short circuits, flashover or damage may occur to the divider elements due to the stray capacitance across the elements and due to ground capacitances. To avoid these transient voltages, voltage controlling capacitors are connected across the elements. A corona free termination is also necessary to avoid unnecessary discharges at high voltage ends. A series resistor with a parallel capacitor connection for linearization of transient potential distribution is shown in Potential dividers are made with 0.05% accuracy up to 100 kV, with 0.1% accuracy up to 300 kV, and with better than 0.5% accuracy for 500 kV.



Generating Voltmeters

- A generating voltmeter is a variable capacitor voltage generator which generates current proportional to the voltage to be measured. It provides loss free measurement of D.C and A.C voltages. It is driven by a synchronous motor and does not absorb power or energy from the voltage measuring source.

- The charge stored in a capacitor of capacitance C is given by $q = CV$. If the capacitance of the capacitor varies with time when connected to the source of voltage *and* the current through the capacitor

I=dq/dt =V(dc/dt)+ c (dv/dt)

For d.c. voltages $dV/dt = 0$. Hence, I =dq/dt =V (dc/dt)

If the capacitance C varies between the limits Co and (Co + Cm) sinusoid ally

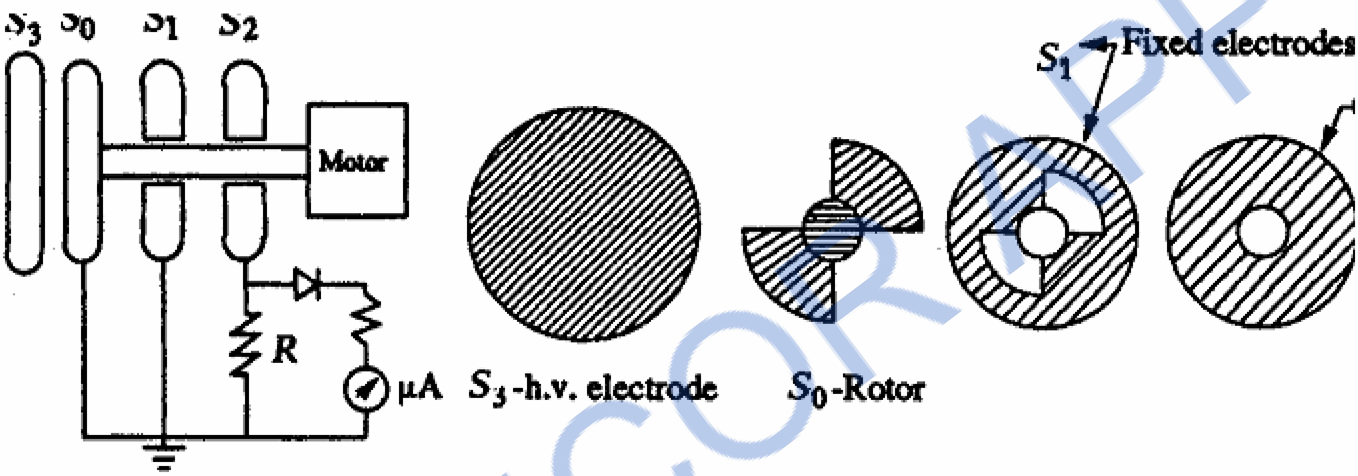
$C=C_0 + C_m \sin\omega t$

Current $I = i_m \sin\omega t$ where , $i_m = V C_m \omega$

For a constant angular frequency to, the current is proportional to the applied voltage V. More often, the generated current is rectified and measured by a moving coil meter. Generating voltmeter can be used for a.c. voltage measurements also provided the angular frequency ω is the same or equal to half that of the supply frequency. A generating voltmeter with a rotating cylinder consists of two excitation field electrodes and a rotating two pole armature driven by a synchronous motor at a constant speed n. The a.c. current flowing between the two halves of the armature is rectified by a commutator whose arithmetic mean may be calculated from i= n /30 (ΔCV)

This device can be used for measuring a.c. voltages provided the speed of the drive-motor is half the frequency of the voltage to be measured. Thus a four-pole synchronous motor with 1500 rpm is suitable for 50 Hz. For peak value measurements, the phase angle of the motor must also be so adjusted that Cmax and the crest value occur at the same instant. Generating voltmeters employ rotating sectors or vanes for variation of capacitance. Figure . gives a schematic diagram of a generating voltmeter. The high voltage source is connected to a disc electrode S_3 which is kept at a fixed distance on the axis of the other low voltage electrodes S_0 ,S_1, S_2 .The rotor S_0 driven at a constant speed by a synchronous motor at a suitable speed (1500,1800,3000, or 3600 rpm).

The rotor vanes of S_0 cause periodic change in capacitance between the insulated disc S_2 and the h.v. electrode S_3. The shape and number of the vanes of S_0 and S_1 are so designed that they produce sinusoidal variation in the capacitance. The generated a.c. current through the resistance *R* is rectified and read by a moving coil instrument An amplifier is needed, if the shunt capacitance is large or longer leads are used for connection to rectifier and meter. The instrument is calibrated using a potential divider or sphere gap. The meter scale is linear and its range can be extended by extrapolation



Advantages of Generating Voltmeters

- No source loading by the meter,
- No direct connection to high voltage electrode,
- scale is linear and extension of range is easy, and
- A very convenient instrument for electrostatic devices such as Van de Graaff Generator and particle accelerators

Limitations

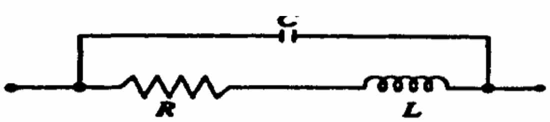
Requires calibration , careful construction and disturbance in position will effect calibration

Measurement of high a.c. voltages employ conventional methods like series impedance voltmeters, potential dividers, potential transformers, or electrostatic voltmeters. But their designs are different from those of low voltage meters, as the insulation design and source loading are the important criteria. When only peak value measurement is needed, peak voltmeters and sphere gaps can be used. Often, sphere gaps are used for calibration purposes. Impulse and high frequency a.c. measurements invariably use potential dividers with a cathode ray oscillograph for recording voltage waveforms. Sphere gaps are used when peak values of the voltage are only needed and also for calibration purposes.

Series Impedance Voltmeters

For power frequency a.c. measurements the series impedance may be a pure resistance or a reactance. Since resistances involve power losses, often a capacitor is preferred as a series reactance. Moreover, for high resistances, the variation of resistance with temperature is a problem, and the residual inductance of the resistance gives rise to an impedance different from its ohmic resistance. High resistance units for high voltages have stray capacitances and hence a unit resistance will have an equivalent circuit as shown. At any frequency CD of the a.c. voltage, the impedance of the resistance *R* is

$$Z = \frac{(R+j\omega C)}{(1-\omega^2 \; LC)+(j\omega CR)}$$



Simplified lumped parameter equivalent circuit of a high ohmic resistance *R*

If ωL and ωC are small compared to *R*

$$Z = R\{1 + j\left(\frac{\omega_L}{R} - \omega CR\right)\}$$

and the total phase angle is

$$\varnothing = \left(\frac{\omega_L}{R} - \omega CR\right)$$

This can be made zero and independent of frequency If $L/C=R^2$

For extended and large dimensioned resistors, this equivalent circuit is not valid and each elemental resistor has to be approximated with this equivalent circuit. The entire resistor unit then has to be taken as a transmission line equivalent, for calculating the effective resistance. Also, the ground or stray capacitance of each element influences the current flowing in the unit, and the indication of the meter results in an error.

Series Capacitance Voltmeter

To avoid the drawbacks pointed out earlier, a series capacitor is used instead of a resistor for a.c. high voltage measurements. The schematic diagram is shown in Fig. The current/c through the meter is $I_C = j\omega CV$.

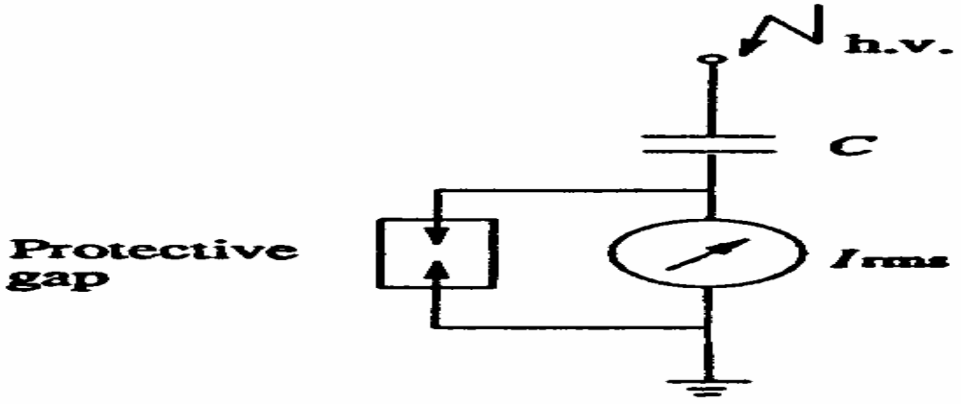
where, C = capacitance of the series capacitor,

ω = angular frequency, and V = applied a.c. voltage.

If the a.c. voltage contains harmonics, error due to changes in series impedance occurs. The rms value of the voltage V with harmonics is given by

$V = \sqrt{V_1^2 + V_2^2 + \text{------} V_n^2}$ where V_1 V_2 V_n represent the rms value of the fundamental, second... And nth harmonics. The currents due to these harmonics are

$I_1 = \omega CV_1$, $I_2 = 2\omega CV_2$, $I_n = n\omega CV_n$



The resultant r.m.s value of current is

$$I = \omega C(V_1^2 + 4V_2^2 + \text{--------} + n^2 V_n^2)^{1/2}$$

With a 10% fifth harmonic only, the current is 11.2% higher, and hence the error is 11.2% in the voltage measurement. This method is not recommended when a.c. voltages are not pure sinusoidal waves but contain considerable harmonics. Series capacitance voltmeters were used with cascade transformers for measuring rmsvalues up to 1000 kV. The series capacitance was formed as a parallel plate capacitor between the high voltage terminal of the transformer and a ground plate suspended above it. A rectifier ammeter was used as an indicating instrument and was directly calibrated in high voltage rms value. The meter was usually a (0-100) µA moving coil meter and the over all error was about 2%.

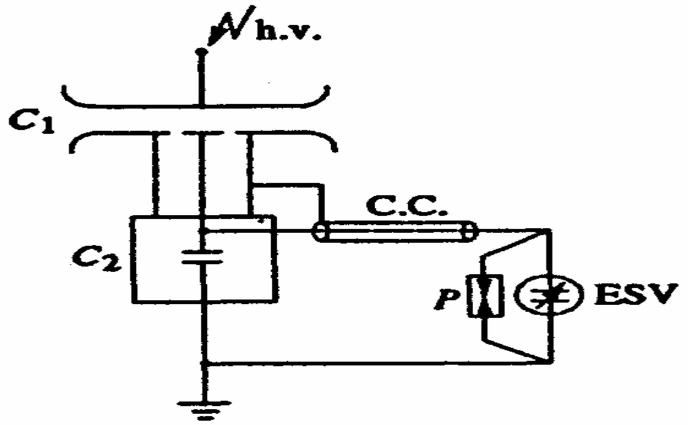
Capacitance Voltage Transformer—CVT

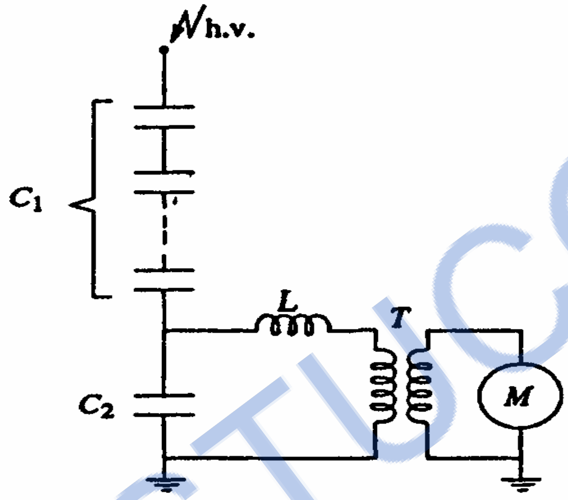
Capacitance divider with a suitable matching or isolating potential transformer tuned for resonance condition is often used in power systems for voltage measurements. This is often referred to as CVT. In contrast to simple capacitance divider which requires a high impedance meter like a V.T.V.M. or an electrostatic voltmeter, a CVT can be connected to a low impedance device like a wattmeter pressure coil or a relay coil. CVT can supply a load of few VA. capacitance will be around a few thousand pico farads as against a gas filled standard condenser of about 100 pF. A matching transformer is connected between the load or meter *M* and *C2.* The transformer ratio is chosen on economic grounds, and the h.v. winding rating may be 10 to 30 kV with the Lv. winding rated from 100 to 500 V. The value of the tuning choke *L* is chosen to make the equivalent circuit of the CVT purely resistive or to bring resonance condition. This condition is satisfied when

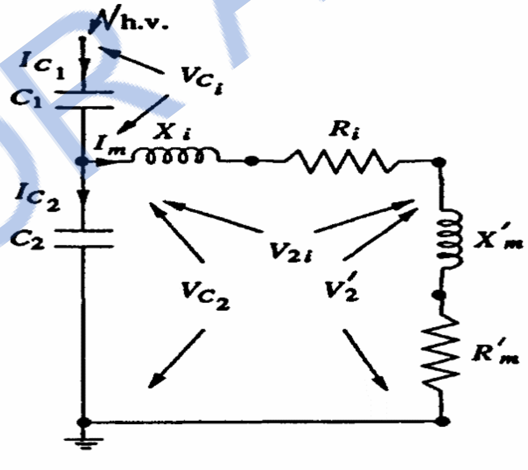
$$\omega\,(L + L_T) = \frac{1}{\omega(C_1 + C_2)}$$

L= inductance of the choke, and L_T = equivalent inductance of the transformer referred to h.v. side.

The voltage *V2* (meter voltage) will be in phase with the input voltage *V1*







Capacitive voltage transformer (CVT) Equivalent circuit

The phasor diagram of CVT under resonant conditions is shown in Fig

The meter is taken as a resistive load, and Xm′ is neglected. The voltage across the load referred to the divider side will be $V_2' = (I_m' + R_m')$ and $V_{C2} = V_2' + I_m (X_e + R_e)$. It is clear from the phasor diagram that V_1 (input voltage) = $(V_{C1} + V_{C2})$ and is in phase with V_2', the voltage across the meter. Re and X_e the potential transformer resistance and leakage reactance. Under this condition, the voltage ratio becomes

$a = (V_1 / V_2) = (V_{c1} + V_{Ri} + V_2')/V_2'$

Advantages of a CVT

Simple design and easy installation

Can be used both as a voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.

Frequency independent voltage distribution along elements as against conventional magnetic potential transformers which require additional insulation design against surges

Provides isolation between the high voltage terminal and low voltage metering.

Disadvantages

The voltage ratio is susceptible to temperature variations, and
The problem of inducing ferro-resonance in power systems.

Potential Transformers

Magnetic potential transformers are the oldest devices for ax. Measurements .They are simple in construction and can be designed for any voltage. For very high voltages, cascading of the transformers is possible. The voltage ratio is $\frac{V_1}{V_2} = \frac{N_1}{N_2}$

where *V1* and *V2* are the primary and secondary voltages, and *N1* and N2 the respective turns in the windings. These devices suffer from the ratio and phase angle errors caused by the magnetizing and leakage impedances of the transformer windings. The errors are compensated by adjusting the turns ratio with the tappings on the high voltage side under load conditions. Potential transformers (PT) do not permit fast rising transient or high frequency voltages along with the normal supply frequency, but harmonic voltages are usually measured with sufficient accuracy. With high voltage testing transformers, no separate potential transformer is used, but a PT winding is incorporated with the high voltage windings of the testing transformer. With test objects like insulators, cables, etc. which are capacitive in nature, a voltage rise occurs on load with the testing transformer, and the potential transformer winding gives voltage values less than the actual voltages applied to the test object If the percentage impedance of the testing transformer is known, the following correction can be applied to the voltage measured by the PT winding of the transformer.

$V_2 = V_{20}(1+ 0.0lvxC/C_N)$

V2O = OPencircuit voltage of the PT winding,

C_N=as load capacitance used for testing,

C = test object capacitance ($C \ll C_N$) and

Vx=% reactance drop in the transformer.

Electrostatic Voltmeters

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

$$F = \frac{1}{2} \epsilon_0 \, V^2 \frac{A}{S^2} \; = \; \frac{1}{2} \epsilon_0 \; A \left(\frac{V}{S}\right)^2$$

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

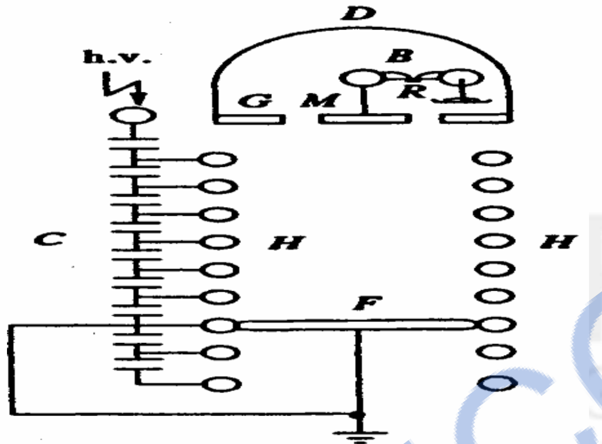
W1= work done in displacing a plate

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 millimetreto a few millimetresis 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.

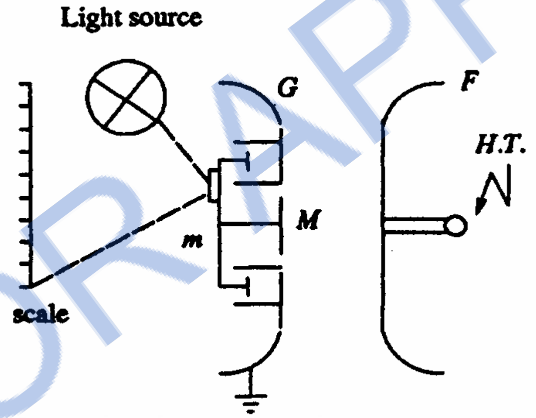
Electrostatic voltmeters are made with parallel plate configuration using guard rings to avoid corona and field fringing at the edges. An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight. Usually the electrostatic voltmeters have a small capacitance (5 to 50 pF) and high insulation resistance ($R > 10^{13}\Omega$). Hence they are considered as devices with high input impedance. The upper frequency limit for a.c. applications is determined from the following considerations:

- natural frequency of the moving system,
- resonant frequency of the lead and stray inductances with meter capacitance, and
- the *R-C* behavior of the retaining or control spring (due to the frictional resistance and elastance).

An upper frequency limit of about one MHz is achieved in careful designs. The accuracy for a.c. voltage measurements is better than ±0.25%, and for d.c. voltage measurements it may be ±0.1% or less.



Absolute electrostatic voltmeter



m — mirror Light beam arrangement

M —Mounting plate
B —Balance
G —Guard plate
C —Capacitance divider
F — Fixed plate
D — Dome
H —Guard hoops or rings
R — Balancing weight

The schematic diagram of an absolute electrostatic voltmeter or electrometer is given in Fig.. 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.

The main difference between several forms of voltmeters lies in the manner in which the restoring force is obtained. For conventional versions of meters, a simple spring control is used, which actuates a pointer to move on the scale of the instruments. In more versatile instruments, only small movements of the moving electrodes is allowed, and the movement is amplified through optical means (lamp and scale arrangement as used with moving coil galvanometers). Two air vane dampers are used to reduce vibrational tendencies in the moving system, and the 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. Multi-range instruments are constructed for 600 W rms and above The constructional details of an absolute electrostatic voltmeter is given in Fig. 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 di sc.

The balance beam carries a mirror which reflects a beam of light. The movement of the disc is thereby magnified. 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 in space by a capacitance divider ensuring a uniform special potential distribution Some instruments are constructed in an enclosed structure containing compressed air, carbon dioxide, or nitrogen. The gas pressure may be of the order of I5 atm. Working stresses as high as 100 kV/cm may be used in an electrostatic meter in vacuum. With compressed gas or vacuum as medium, the meter is compact and much smaller in size.

Series *Capacitor Peak Voltmeter or* Chubb-Frotscue method

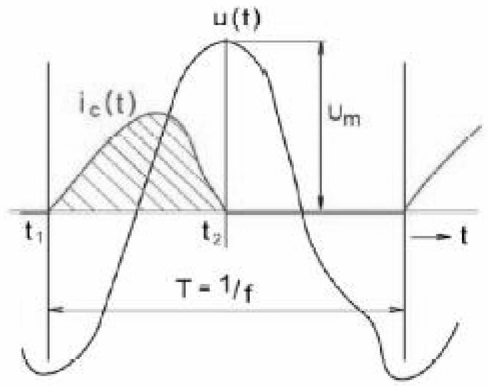
When a capacitor is connected to a sinusoidal voltage source, the charging current i $=\int_0^t V\,dt = j\,\omega CV$, where V is the rms value of the voltage and $\omega$is the angular frequency. If a half wave rectifier is used, the arithmetic mean of the rectifier current is proportional to the peak value of the a.c. voltage. The schematic diagram of the circuit arrangement is shown in Fig. . The d.c. meter reading is proportional to the peak value of the value *Vm*or Vm = 1/2Type equation here.where I is the d.c. current read by the meter and C is the capacitance of the capacitor. This method is known as the Chubb-Frotscue method for peak voltage measurement. The diode *D1* is used to rectify the a.c. current in one half cycle while D2 by-passes in the other half cycle. This arrangement is suitable only for positive or negative half cycles and hence is valid only when both half cycles are symmetrical and equal.

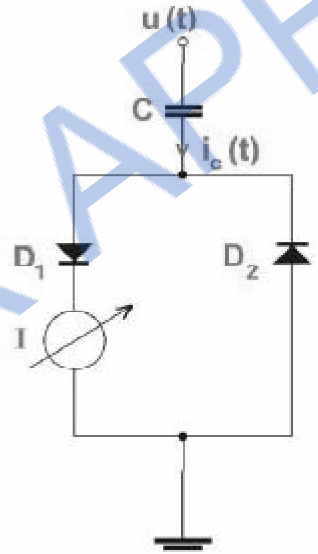
This method is not suitable when the voltage waveform is not sinusoidal but contains more than one peak or maximum as shown in Fig. . The charging current through the capacitor changes its polarity within one half cycle itself. The shaded areas in Fig. give the reverse current in any one of the half cycles and the current within that period subtracts from the net current. Hence the reading of the meter will be less and is not proportional to *Vm*as the current flowing during the intervals *(t1* - t2)etc will not be included in the mean value. The 'second* or the false maxima is easily spotted out by observing the waveform of the charging current on an oscilloscope. Under normal conditions with a.c. testing, such waveforms do not occur and as such do not give rise to errors. But pre-discharge currents within the test circuits cause very short duration voltage drops which may introduce errors. This problem can also be overcome by using a resistance *R* in series with capacitor *C* such that *CR* « 1/co for 50 Hz application. The error due to the resistance is

$\frac{\Delta V}{V} = \frac{V-V_m}{V} = \left(1 - \frac{1}{1+\omega^2 C^2 R^2}\right)$ V = actual value, and *Vm* = measured value

- In determining the error, the actual value of the angular frequency co has to be determined.
- The different sources that contribute to the error are the effective value of the capacitance being different from the measured value of C
- Imperfect rectifiers which allow small reverse currents
- Non-sinusoidal voltage waveforms with more than one peak or maxima per half cycle

Deviation of the frequency from that of the value used for calibration





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*C and 760 torr pressure occurs for a sphere gap . 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 sphere gap method of measuring high voltage is the most reliable and is used as the standard for calibration purposes. The breakdown strength of a gas depends on the ionization of the gas molecules, and on the density of the gas. As such, the breakdown voltage varies with the gap spacing; and for a uniform field gap, a high consistency could be obtained, so that the sphere gap is very useful as a measuring device. By precise experiments, the breakdown voltage variation with gap spacing, for different diameters and distances, have been calculated and represented in charts. In the measuring device, two metal spheres are used, separated by a gas-gap. The potential difference between the spheres is raised until a spark passes between them. The breakdown strength of a gas depends on the size of the spheres, their distance apart and a number of other factors.

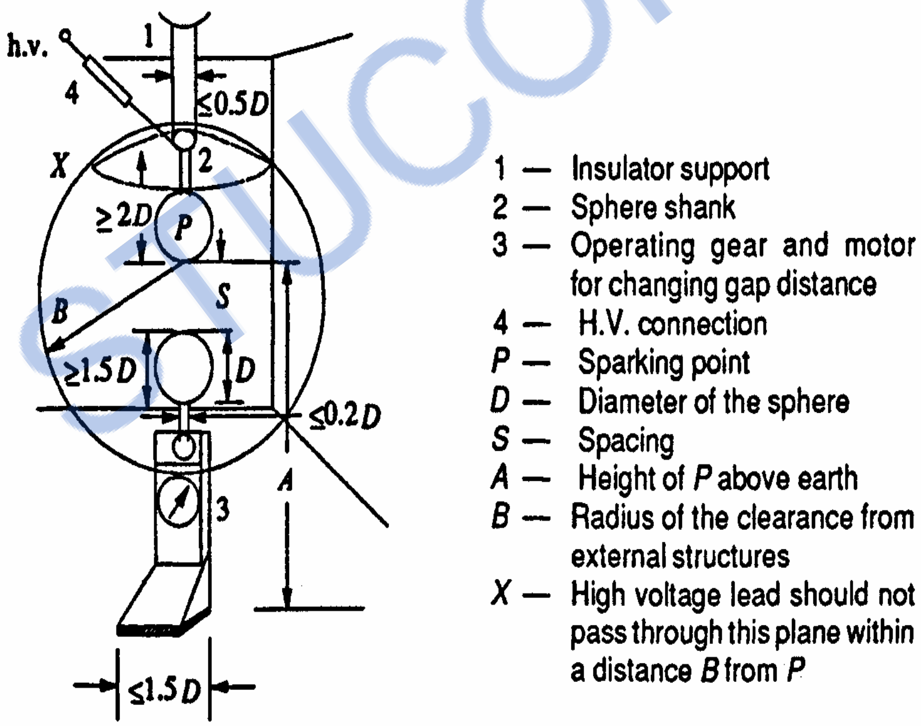
A spark gap may be used for the determination of the peak value of a voltage wave, and for the checking and calibrating of voltmeters and other voltage measuring devices. The density of the gas (generally air) affects the spark-over voltage for a given gap setting. Thus the correction for any air density change must be made. The air density correction factor $\delta=0.386P/(273+t)$ .The spark over voltage for a given gap setting under the standard conditions (760 torr pressure and at 20*C) must be multiplied by the correction factor to obtain the actual spark-over voltage.

The breakdown voltage of the sphere gap is almost independent of humidity of the atmosphere, but the presence of dew on the surface lowers the breakdown voltage and hence invalidates the calibrations.

The breakdown voltage characteristic has been determined for similar pairs of spheres (diameters 62.5 mm, 125 mm, 250 mm, 500 mm, 1 m and 2 m) When the gap distance is increased, the uniform field between the spheres becomes distorted, and accuracy falls.

The limits of accuracy are dependent on the ratio of the spacing **d** to the sphere diameter **D**, as follows. d < 0.5 D, accuracy = ± 3 %; 0.75 D > d > 0.5 D, accuracy = ± 5 % For accurate measurement purposes, gap distances in excess of 0.75D are not used.

The breakdown voltage characteristic is also dependent on the polarity of the high voltage sphere in the case of asymmetrical gaps (i.e. gaps where one electrode is at high voltage and the other at a low voltage or earth potential). If both electrodes are at equal high voltage of opposite polarity (i.e. + ½ V and - ½ V), as in a symmetrical gap, then the polarity has no effect. The fig shows these breakdown voltage variations. In the case of the symmetrical gap, there are two breakdown characteristics; one for the positive high voltage and the other for the negative high voltage. Since the breakdown is caused by the flow of electrons, when the high voltage electrode is positive, a higher voltage is generally necessary for breakdown than when the high voltage electrode is negative. However, when the gaps are very far apart, then the positive and the negative characteristics cross over due to various space charge effects. But this occurs well beyond the useful operating region. Under alternating voltage conditions, breakdown will occur corresponding to the lower curve (i.e. in the negative half cycle under normal gap spacing's). Thus under normal conditions, the a.c. characteristic is the same as the negative characteristic.



(a) Vertical arrangement of sphere gap

In sphere gaps used in measurement, to obtain high accuracy, the minimum clearance to be maintained between the spheres and the neighboring bodies and the diameter of shafts are also specified, since these also affect the accuracy (figure). There is also a tolerance specified for the radius of curvature of the spheres. "The length of any diameter shall not differ from the correct value by more than 1% for spheres of diameter up to 100 cm or more than 2% for larger spheres". Peak values of voltages may be measured from 2 kV up to about 2500 kV by means of spheres. One sphere may be earthed with the other being the high voltage electrode, or both may be supplied with equal positive and negative voltages with respect to earth (symmetrical gap). When spark gaps are to be calibrated using a standard sphere gap, the two gaps should not be connected in parallel. Equivalent spacing should be determined by comparing each gap in turn with a suitable indicating instrument.

Needle gaps may also be used in the measurement of voltages up to about 50 kV, but errors are caused by the variation of the sharpness of the needle gaps, and by the corona forming at the points before the gap actually sparks over. Also the effect of the variation of the humidity of the atmosphere on such gaps is much greater. Usually, a resistance is used in series with the sphere gap, of about 1ohm/V spark over conditions to about a maximum of 1 A

However for impulse measurements, a series resistance must not be used since this causes a large drop across the resistance. In measuring impulse voltages, since the breakdown does not occur at exactly the same value of voltage each time, what is generally specified is the 50 % breakdown value. A number of impulses of the same value is applied and a record is kept of the number of times breakdown occurs, and a histogram is plotted with the peak value of the impulse voltage and the percentage of breakdown

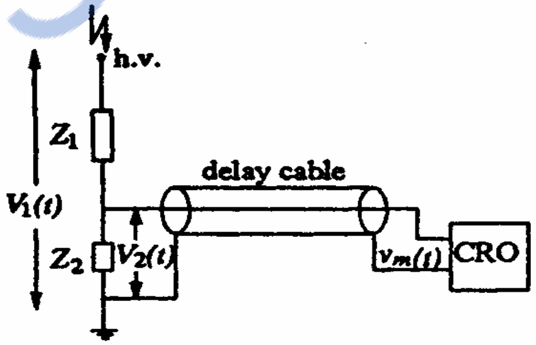
Factors Influencing the Spark over Voltage of Sphere Gaps

Various factors that affect the spark over voltage of a sphere gap are:

- nearby earthed objects,
- atmospheric conditions and humidity,
- irradiation, and
- polarity and rise time of voltage waveforms

Potential Dividers for Impulse Voltage Measurements

Potential or voltage dividers for high voltage impulse measurements, high frequency max. measurements, or for fast rising transient voltage measurements are usually either resistive or capacitive *or* mixed element type. The low voltage arm of the divider is usually connected to a fast recording oscillograph or a peak reading instrument through a delay cable. A schematic diagram of a potential divider with its terminating equipment is given in Fig. . *Z 1*is usually a resistor or a series of resistors in case of a resistance potential divider, or a single or a number of capacitors in case of a capacitance divider. It can also be a combination of both resistors and capacitors. Z2 will be a resistor or a capacitor or an *R-C* impedance depending upon the type of the divider. Each element in the divider, in case of high voltage dividers, has a self resistance or capacitance. In addition, the resistive elements have residual inductances, a terminal stray capacitance to ground, and terminal



Schematic diagram of a potential divider with a delay cable and oscilloscope

When a step or fast rising voltage is applied at the high voltage terminal, the voltage developed across the element *Z2* will not have the true waveform as that of the applied voltage. The cable can also introduce distortion in the wave shape. The following elements mainly constitute the different errors in the measurement:

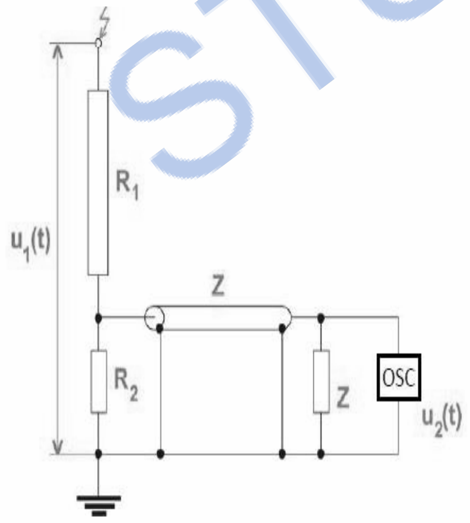
- residual inductance in the elements;
- stray capacitance occurring

  between the elements,
- from sections and terminals of the elements to ground,
- from the high voltage lead to the elements or sections;

  the impedance errors due to

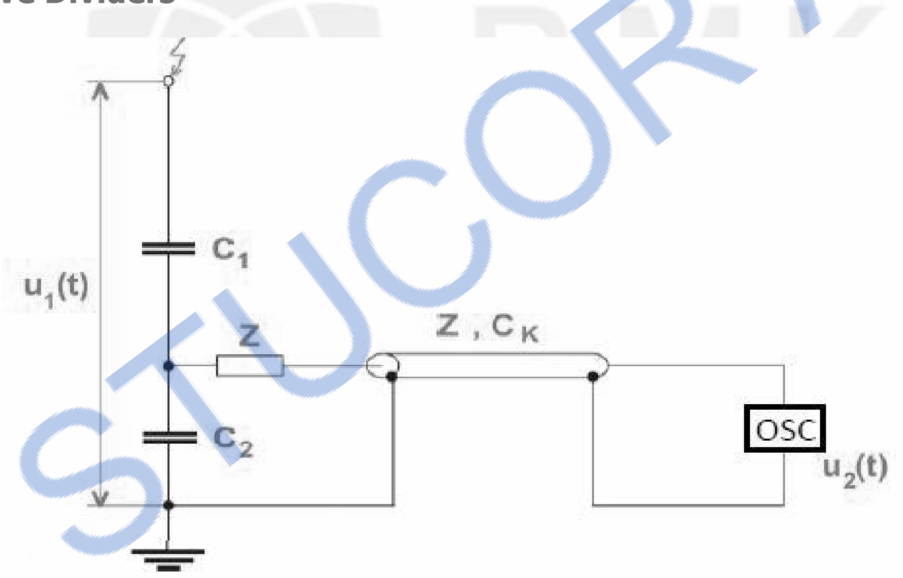
  connecting leads between the divider and the test objects, and
- ground return leads and extraneous current in ground leads; and
- parasitic oscillations due to lead and cable inductances and capacitance of high voltage terminal to ground.

Resistive Dividers



The resistance potential dividers are the first to 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 upon two or three factors. The maximum voltage to be measured is the first 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 *R*1 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.

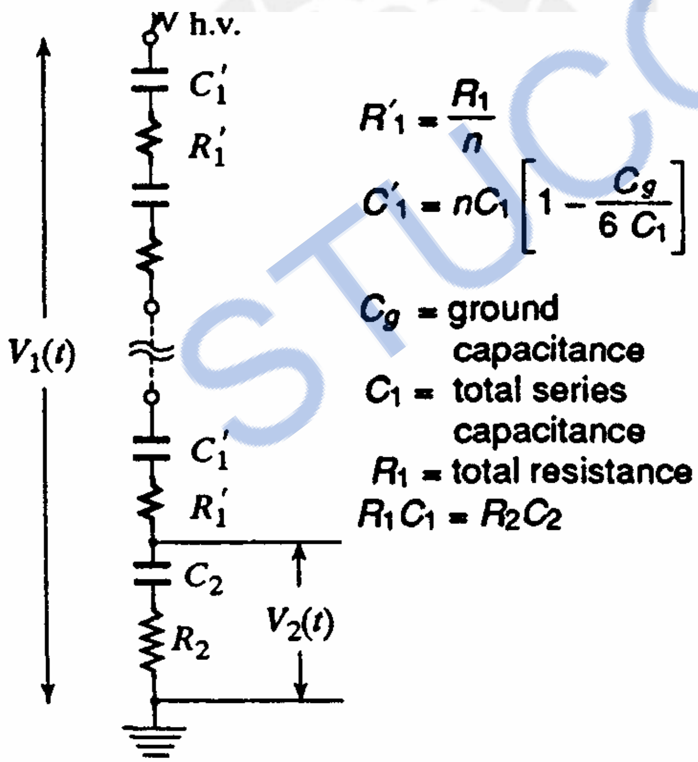
Capacitive Dividers



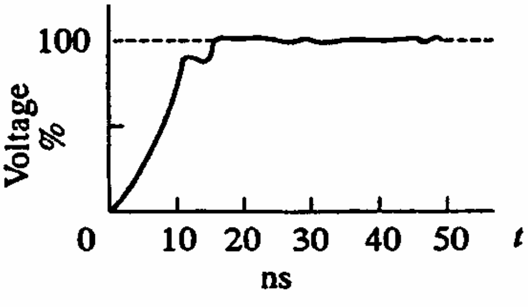
Capacitance potential dividers are more complex than the resistance type. For measurement of impulse voltages not exceeding 1 MV capacitance dividers can be both portable and transportable. In general, for measurement of 1 MV and over, the capacitance divider is a laboratory fixture. The capacitance dividers are usually made of capacitor units mounted one above the other and bolted together.

It is this failure which makes the small dividers portable. A screening box similar to that described earlier can be used for housing both the low voltage capacitor unit $C2$ and the matching resistor if required. The low voltage capacitor $C2$ should be non-inductive. A form of capacitor which has given excellent results is of mica and tin foil plate, construction, each foil having connecting tags coming out at opposite corners. This ensures that the current cannot pass from the high voltage circuit to the delay cable without actually going through the foil electrodes. It is also important that the coupling between the high and low voltage arms of the divider be purely capacitive. Hence, the low voltage arm should contain one capacitor only; two or more capacitors in parallel must be avoided because of appreciable inductance that would thus be introduced. Further, the tappings to the delay cable must be taken off as close as possible to the terminals of $C2$.

Mixed R-C Potential Dividers



(a) Equivalent circuit



(b) Step response determined with low voltage step pulse

Mixed potential dividers use *R-C* elements in series or in parallel. One method is to connect capacitance in parallel with each *R'*| element This is successfully employed for voltage dividers of rating 2 MV and above. A better construction is to make an *R-C* series element connection. The equivalent circuit of such a construction is shown in Fig. Such dividers are made for 5 MV with response times less than 30 n s. The low voltage arm R2 is given "L peaking" by connecting a variable inductance L in series with R2- The step response of the divider and the schematic connection of low voltage arm are shown in Fig. . However, for a correctly designed voltage divider L peaking will not be necessary.

Measurement of High Direct Currents

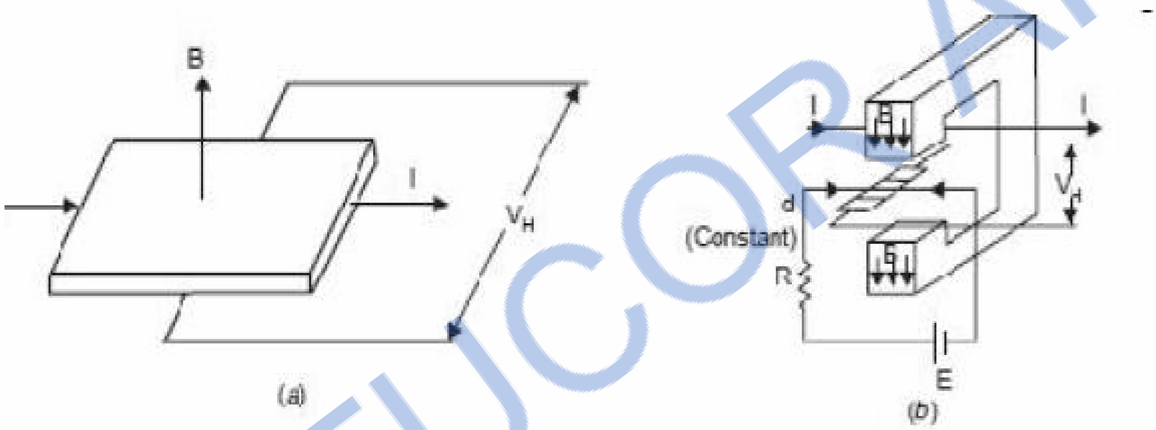
High currents are used in power system for testing circuit breakers, cables lightning arresters etc. and high currents are encountered during lightning discharges, switching transients and shunt faults. These currents require special techniques for their measurements.

High Direct Currents

Low resistance shunts are used for measurement of these currents. The voltage drop across the shunt resistance is measured with the help of a milli-voltmeter. 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.

Hall Generators* for D.C. *Current Measurements

Hall effect is used to measure very high direct current. Whenever electric current flows through a metal plate placed in a magnetic field perpendicular to it, Lorenz force will deflect the electrons in the metal structure in a direction perpendicular to the direction of both the magnetic field and the flow of current. The charge displacement results in an e.m.f. in the perpendicular direction called the Hall voltage. The Hall voltage is proportional to the current I, the magnetic flux density B and inversely proportional to the plate thickness d *i.e.,* $VH = RBI/d$ where R is the Hall coefficient which depends upon the material of the plate and temperature of the plate. For metals the Hall coefficient is very small and hence semiconductor materials are used for which the Hall coefficient is high.



When large d.c. currents are to be measured the current carrying conductor is passed through an iron cored magnetic circuit (Fig. (*b*)). The magnetic field intensity produced by the conductor in the air gap at a depth d is given by $H = 1/(2\pi d)$ The Hall element is placed in the air gap and a small constant d.c. current is passed through the element. The voltage developed across the Hall element is measured and by using the expression for Hall voltage the flux density B is calculated and hence the value of current I is obtained.

High Power Frequency Currents

High Power frequency currents are normally measured using current transformers as use of low resistance shunts involves unnecessary power loss. Besides, the current transformers provide isolation from high voltage circuits and thus it is safer to work on *HV* circuits Fig. below shows a scheme for current measurements using current transformers and electro-optical technique.

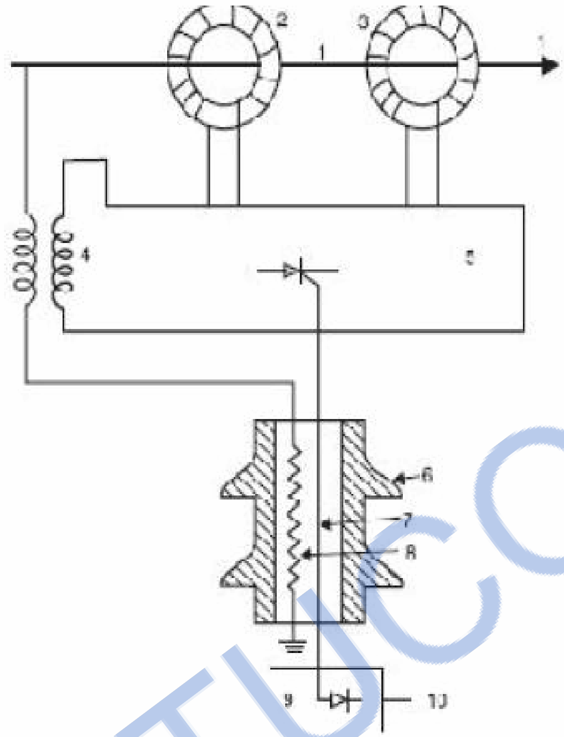


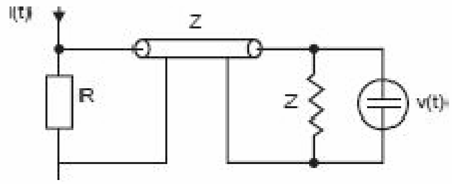
Fig. Current transformers and electro-optical system for high a.c. current measurements

- A voltage signal proportional to the current to be measured is produced and is transmitted to the ground through the electro-optical device. Light pulses proportional to the voltage signal are transmitted by a glass optical fibre bundle to a photo detector and converted back into an analog voltage signal. The required power for the signal convertor and optical device are obtained from suitable current and voltage transformers.

High Frequency and Impulse Currents

In power system the amplitude of currents may vary between a few amperes to a few hundred kilo amperes and the rate of rise of currents can be as high as 10^{10} *A*/sec and the rise time can vary between a few micro seconds to a few macro seconds. Therefore, the device to be used for measuring such currents should be capable of having a good frequency response over a very wide frequency band. The methods normally employed are—(*i*) resistive shunts; (*ii*) elements using induction effects; (*iii*) Faraday and Hall effect devices. With these methods the accuracy of measurement varies between 1 to 10%. Fig. shows the circuit diagram of the most commonly used method for high impulse current measurement

The voltage across the shunt resistance *R* due to impulse current $i(t)$ is fed to the oscilloscope through a delay cable *D*. The delay cable is terminated through an impedance *Z* equal to the surge impedance of the cable to avoid reflection of the voltage to be measured and thus true measurement of the voltage is obtained. Since the dimension of the resistive element is large, it will have residual inductance *L* and stray capacitance *C*. The inductance could be neglected at low frequencies but at higher frequencies the inductive reactance would be comparable with the resistance of the shunt. The effect of inductance and capacitance above 1 MHz usually should be considered. The resistance values range between 10 micro ohm to a few milliohms and the voltage drop is of the order of few volts. The resistive shunts used for measurements of impulse currents of large duration is achieved only at considerable expense for thermal reasons. The resistive shunts for impulse current of short duration can be built with rise time of a few nano seconds of magnitude. The resistance element can be made of parallel carbon film resistors or low inductance wire resistors of parallel resistance wires or resistance foils

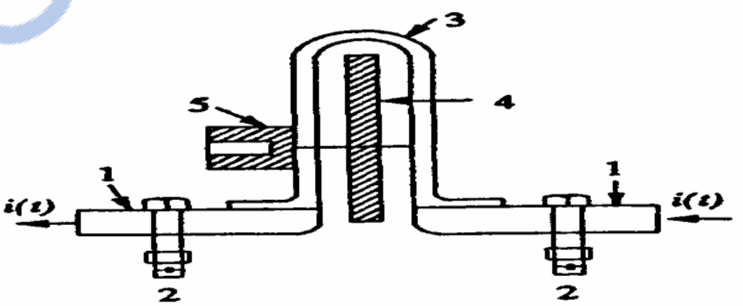


Assuming the stray capacitance to be negligibly small the voltage drop across the shunt in complex frequency domain may be written as $V(s) = I(s)[R + Ls]$ It is to be noted that in order to have flat frequency response of the resistive element the stray inductance and capacitance associated with the element must be made as small as possible. In order to minimize the stray field effects following designs of the resistive elements have been suggested and used

- Bifilar flat strip shunt.
- Co-axial tube or Park's shunt
- Co-axial squirrel cage shunt.

Bifilar Strip Shunt

The bifilar design (Fig.) consists of resistor elements wound in opposite directions and folded back, with both ends insulated by a teflon or other high quality insulation. The voltage signal is picked up through a ultra high frequency (UHF) coaxial connector. The shunt suffers from stray inductance associated with the resistance element, and its potential leads are linked to a small pan of the magnetic flux generated by the current that is measured. To overcome these problems, coaxial shunts are chosen.

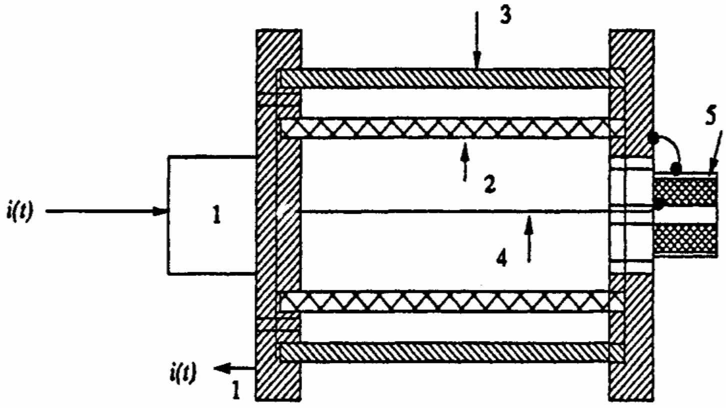


(a) Schematic arrangement

1. Metal base
2. Current terminals (C_1 and C_2)
3. Bifilar resistance strip
4. Insulating spacer (teflon or bakelite)
5. Coaxial UHF connector

P_1. P_2 — Potential terminals

Coaxial Tubular or Park's Shunt



1. Current terminals
2. Coaxial cylindrical resistive element
3. Coaxial cylindrical return conductor (copper or brass tube)
4. Potential pick up lead
5. UHF coaxial connector

In the coaxial ... iner cylinder or resistive element and is made to return through an outer conducting cylinder of copper or brass. The voltage drop across the resistive element is measured between the potential pick-up point and the outer case. The space between the inner and the outer cylinder is air and hence acts like a pure insulator. With this construction, the maximum frequency limit is about 1000 MHz and the response time is a few nanoseconds. The upper frequency limit is governed by the skin effect in the resistive element. The coaxial tubular shunts were constructed for current peaks up to 2OO kA; shunts constructed for current peaks as high as 200 kA with *di/dt* of about 5x 10^{10} A/s have induced voltages less than 5OVand the voltage drop across the shunt was about 100 V.

Elements using Induction Effects(Rogowski coil)

If the current to be measured is flowing through a conductor which is surrounded by a coil as shown in Fig., and *M* is the mutual inductance between the coil and the conductor, the voltage across the coil terminals will be: $v(t) = M(di/dt)$ Usually the coil is wound on a non-magnetic former in the form of a toroid and has a large number of turns, to have sufficient voltage induced which could be recorded. The coil is wound criss-cross to reduce the leakage inductance. If *M* is the number of turns of the coil, *A* the coil area and *lm* its mean length, the mutual inductance is given by *M* =µ0NA/lm

Usually an integrating circuit *RC* is employed as shown in Fig. to obtain the output voltage proportional to the current to be measured. The output voltage is given by $v0(t)$ =Mi(t)/(RC) Integration of $v(t)$ can be carried out more elegantly by using an appropriately wired operational amplifier. The frequency response of the Rogowski coil is flat upto 100 MHz but beyond that it is affected by the stray electric and magnetic fields and also by the skin effect.

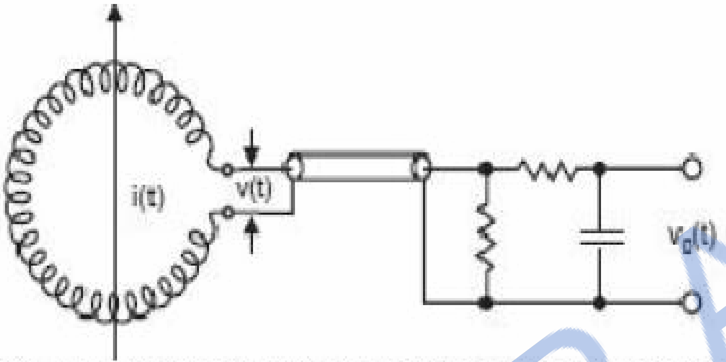


Fig. Rogowski coil for high impulse current measurements

Magnetic Links

These are used for the measurement of peak magnitude of the current flowing in a conductor. These links consist of a small number of short steel strips on high retentivity. The link is mounted at a known distance from the current carrying conductor. It has been found through experiments that the remanant magnetism of the link after impulse current of 0.5/5 micro sec shape passes through the conductor is same as that caused by a direct current of the same peak value. Measurement of the remanance possessed by the link after the impulse current has passed through the conductor enables to calculate the peak value of the current. For accurate measurements, it is usual to mount two or more links at different distances from the same conductor. Because of its relative simplicity, the method has been used for measurement of lightning current especially on transmission towers.

Other Techniques for Impulse Current Measurements

Hall Generators

The high amplitude a.c. and impulse currents can be measured by Hall Generator described earlier. For the Hall Generator, though a constant control current flows which is permeated by the magnetic field of the current to be measured, the Hall voltage is directly proportional to the measuring current. This method became popular with the development of semi-conductor with sufficient high value of Hall constant. The band width of such devices is found to be about 50 MHz with suitable compensating devices and feedback.

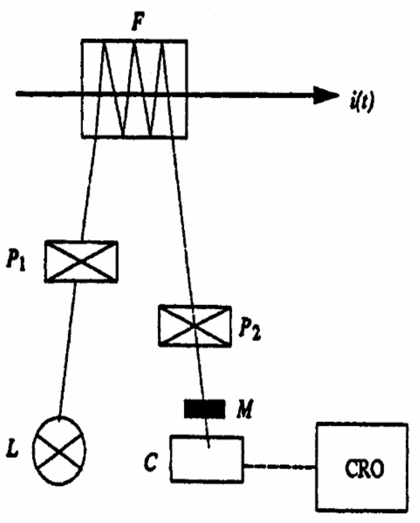
Faraday Generator or Ammeter

When a linearly polarized light beam passes through a transparent crystal in the presence of a magnetic field, the plane of polarization of the light beam undergoes rotation. The angle of rotation a is given by $\alpha = VBl$

where, V= a constant of the crystal which depends on the wavelength of the light,

B = magnetic flux density, and

l= length of the crystal.



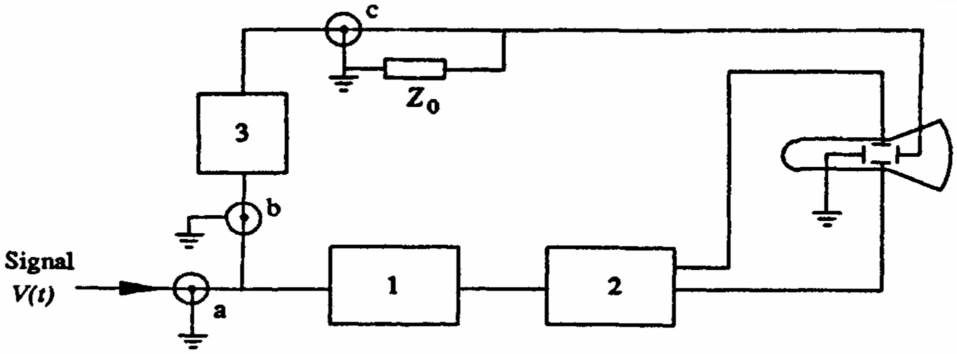
L — Light source
P1 — Polarizer
P2 — Analyser
F — Crystal
CRO — Recording oscillograph
M — Filter
C — Photo-multiplier

To measure the waveform of a large current in a EHV system an arrangement shown in Fig. may be employed. A beam of light from a stabilized light source is passed through a polarizer *P1* to fall on a crystal *F* placed parallel to the magnetic field produced by the current I. The light beam undergoes rotation of its plane of polarization. After passing through the analyzer, the beam is focused on a photomultiplier the output of which is fed to a CRO. The output beam is filtered through a filter M, which allows only the monochromatic light The relation between the oscillograph display and the current to be measured are complex but can be determined. The advantages of this method are that 1) there is no electric connection between the source and the device, (2) no thermal problems even for large currents of several kilo amperes, and (3) as the signal transmission is through an optical system, no insulation problems or difficulties arise for EHV systems. However, this device does not operate for d.c. currents.

CATHODE RAY OSCILLOGRAPHS FOR IMPULSE VOLTAGE AND CURRENT MEASUREMENTS

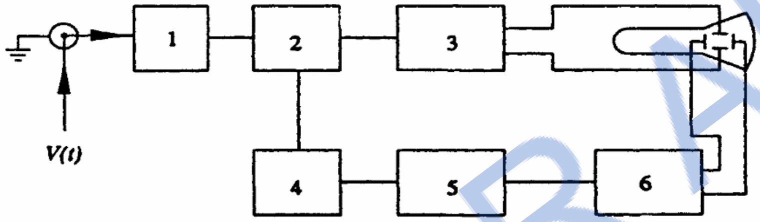
Modern oscillo graphs are sealed tube hot cathode oscilloscopes with photographic arrangement for recording the waveforms. The cathode ray oscilloscope for impulse work normally has input voltage range from *5* m V/cm to about 20 V/cm. In addition, there are probes and attenuators to handle signals up 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 With rapidly changing signals, it is necessary to initiate or start the oscilloscope time base before the signal reaches the oscilloscope deflecting plates, otherwise a portion of the signal may be missed. Such measurements require an accurate initiation of the horizontal time base and is known as triggering. Oscilloscopes are normally provided with both internal and external triggering facility. When external triggering is used, as with recording of impulses, the signal is directly fed to actuate the time base and then applied to the vertical or *Y* deflecting plates through a delay line. The delay is usually 0.1 to *0.5* s. The delay is obtained by:

- A long interconnecting coaxial cable 20 to 50 m long. The required triggering is obtained from an antenna whose induced voltage is applied to the external trigger terminal.
- The measuring signal is transmitted to the CRO by a normal coaxial cable.
- The delay is obtained by an externally connected coaxial long cable to give the necessary delay. This arrangement is shown in Fig.
- The impulse generator and the time base of the CRO are triggered from an electronic tripping device. A first pulse from the device starts the CRO time base and after a predetermined time a second pulse triggers the impulse generator.



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



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

Problems

Example 7.1: A generating voltmeter has to be designed so that it can have a range from 20 to 200 kV d.c. If the indicating meter reads a minimum current of 2 μA and maximum current of 25 μA, what should the capacitance of the generating voltmeter be ?

Solution: Assume that the driving motor has a synchronous speed of 1500 rpm.

$$I_{rms} = \frac{VC_m}{\sqrt{2}}\omega$$

where, $V =$ applied voltage,

$C_m =$ capacitance of the meter, and

$\omega =$ angular speed of the drive

Substituting,

$$2 \times 10^{-6} = \frac{20 \times 10^3 \times C_m}{\sqrt{2}} \times \frac{1500}{60} \times 2\pi$$

$\therefore$ $C_m = 0.9$ p.F

At $200 \text{ kV}, I_{rms} = \dfrac{200 \times 10^3 \times 0.9 \times 10^{-12} \times 1500}{\sqrt{2} \times 60} 2\pi$

$= 20.0$ μA

The capacitance of the meter should be 0.9 pF. The meter will indicate 20 kV at a current 2 μA and 200 kV at a current of 20 μA.

Problems

Example 7.7: A Rogowski coil is to be designed to measure impulse currents of 10 kA having a rate of change of current of 10^{11} A/s. The current is read by a VTVM as a potential drop across the integrating circuit connected to the secondary. Estimate the values of mutual inductance, resistance, and capacitance to be connected, if the meter reading is to be 10 V for full-scale deflection.

Solution: $V_m(t) = \frac{M}{CR} I(t)$ for $\frac{1}{CR} << \omega$ (Eq. 7.42),

taking the peak values

$$\frac{M}{CR} = \frac{V_m(t)}{I(t)} = \frac{10}{10^4} = 10^{-3}$$

The time interval of the change of current assuming sinusoidal variation is

$$\frac{10^4}{10^{11}} = 10^{-7}\ \text{s} = \frac{1}{4} \text{ of a cycle}$$

$\therefore$ frequency $= \frac{10^7}{4}$ Hz

and, $\omega = 2\pi f = \frac{\pi}{2} \times 10^7$

Taking $\frac{1}{CR} = \frac{\omega}{10\pi} = \frac{10^6}{2}$

$$CR = \frac{2}{10^6}$$

$$M = 10^{-3} CR = 10^{-3} \frac{2}{10^6}$$

$$= 2 \times 10^{-9} \text{ H or } 2 \text{ n H.}$$

Taking $R = 2 \times 10^3\ \Omega$,

$$C = \frac{CR}{R} = 2 \times 10^{-6}/20 \times 10^2$$

$$= 10^{-9} \text{ F or } 1000 \text{ pF}$$

(It should be noted that for a given frequency, $X_c << R$; otherwise the low frequency response will be poor. Here X_c at $f = 10^7/4$ is 60Ω only.)

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Two Mark Questions

1.What is the Specialty of high voltage / current measurement? [CO4 K1]

- Safety of men & materials.
- Accuracy
- Induction of over voltage, due to stray coupling.
- Proper location.
- Linear extrapolation not valid.
- Electro magnetic interference.

2. Explain Different devices used for High DC voltages [CO4 K2]

- Series resistance micro ammeter.

  Resistance potential dividers

- Generating of Voltmeters

  Sphere gap & Spark gaps.

3. **What are the various methods used for measurement of power frequency AC voltages. [CO4 K1]**

  Series impedance ammeter.
- Potential dividers, resistance or capacitive Type.
- Potential Transformers electromagnetic or C. V. T.

4.What is the method available for measurement & High frequency AC voltages or Impulse voltages or other rapidly rising voltages? [CO4 K1]

  Potential dividers, resistance Type or capacitance Type with CRO.

  Peak Voltmeter.
- Sphere gaps.

5.What are the various methods available for measurement of High direct currents? [CO4 K1]

- Resistive shunt with mille ammeter

  Hall effect generators,

  Magnetic links

6.What are the methods available for measurement of High alternating current? [CO4 K1]

  Resistive shunts with milli ammeters

  Electro magnetic current Transformers.

7.What are the Various methods of measurement of High Impulse currents or High frequency ac or fast rising ac? [CO4 K1]

- Resistive shunts
- Magnetic pot cut meter.
- Magnetic links
- Hall Effect generators.
- Faraday generators

8. **What are the limitations of resistance potential dividers? [CO4 K1]**

- Power dissipation
- Source loading
- Temperature effect & long term stately
- Sensitivity to Mechanical strain.
- Direct connection to HV terminals

9. What is the principle of generating voltmeters? [CO4 K1]

It is a variable capacitance electrostatic voltage generator, generating current proportional to the applied voltage. It does not absorb power from the voltage measuring source. It is driven by external synchronous / constant speed motor.

10.What are the advantages of generating voltmeters? [CO4 K1]

- No source loading
- No direct contact with HV terminals.
- Scale is linear & extension easy.
- Very convenient, to measure voltages for Van de graff generators.

11.What are the limitations of generating voltmeters? [CO4 K1]

- They require calibrations
- Careful construction necessary
- Disturbance in mounting make calibrations invalid.

12.What is the principle of a 'Sphere gap' for measurement of High voltages? [CO4 K1]

A uniform field sphere gap will always have a spark over voltage within known tolerance under constant atmospheric conditions. Hence it can be used for measurement of the voltage wave form and hence suitable for all types of wave forms, from dc to Impulse voltages of short 1MHz frequency.

13.What are the factors influencing the spark over voltage of a sphere gap? [CO4 K1]

- Nearby earthed object
- Atmospheric conditions and humidity
  irradiation
- Polarity and rise time of voltage wave forms.

14.What are advantages of faraday generators [CO4 K1]

No electric connection between source and load

No thermal problems

Transmission is done through optical system. So no insulation problems

15.What are problems associated with impulse and very high frequency voltage Measurements? [CO4 K1]

- The magnitude of impulse voltages and currents are high
- Their rise time is less

Part B

1. Explain various methods of high DC voltage measurements? **[CO4 K1]**
2. Explain the methods to measure High AC voltages? **[CO4 K1]**
3. Explain the Peak Voltmeters with Potential Dividers **[CO4 K1]**
4. Explain the methods to measure impulse voltages? **[CO4 K1]**

5. Explain in detail about CRO for impulse voltage and current measurement. **[CO4 K1]**

6.Explain various digital methods to measure high voltages **[CO4 K1]**

7. Explain how a sphere gap can measure the peak voltages? **[CO4 K1]**

8. Explain generating voltmeters in detail? **[CO4 K1]**

9. Explain how a CVT can be used to measure high AC voltages? **[CO4 K1]**

Part C

1.A generating voltmeter is to read 250 kV with an indicating meter having a range of (O - 20) μ.A calibrated accordingly. Calculate the capacitance of the generating voltmeter when the driving motor rotates at a constant speed of 1500 r.p.m.

[CO4 K2]

2. Explain the necessity of earthing and shielding arrangements in impulse measurements and in high voltage laboratories. Give a sketch of the multiple shielding arrangements used for impulse voltage and current measurements.

[CO4 K1]

3. What are the usual sources of errors in measuring high impulse voltages by resistance potential dividers? How are they eliminated? An impulse resistance divider has a high voltage arm with a 5000 ohm resistance and the L.V. arm with a 5 ohm resistance. If the oscilloscope is connected to the secondary arm through a cable of surge impedance 75 ohms, determine, (i) the terminating resistance, and (ii) the effective voltage ratio.

[CO4 K2]

Assignment

1. Analyse the characteristic and limitations of different resistive shunts used for impulse current measurements [CO4 K3]

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Protection and control of high voltage power circuit

Real time Applications in day to day life and to Industry

In industrial testing and research laboratories, it is essential to measure the voltages and currents accurately, ensuring perfect safety to the personnel and equipment. Hence a person handling the equipment as well as the metering devices must be protected against over voltages and also against any induced voltages due to stray coupling. Therefore, the location and layout of the devices are important. Secondly, linear extrapolation of the devices beyond their ranges are not valid for high voltage meters and measuring instruments, and they have to be calibrated for the full range. Electromagnetic interference is a serious problem in impulse voltage and current measurements, and it has to be avoided or minimized. Therefore, even though the principles of measurements may be same, the devices and instruments for measurement of high voltages and currents differ vastly from the low voltage and low current devices.

Thank you

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HIGH VOLTAGE ENGINEERING

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INSTITUTIONS

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Course Objectives

To impart knowledge on the following Topics

1. Various types of over voltages in power system and protection methods.
2. Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.
3. Generation of over voltages in laboratories.
4. Measurement of over voltages.
5. Testing of power apparatus
6. insulation coordination

Pre Requisites (Course Names with Code)

EE8402- Transmission and Distribution
EE8501 Power System Analysis
EE8602 Protection and Switchgear

SYLLABUS

EE8701 HIGH VOLTAGE ENGINEERING **L T P C**

3 0 0 3

OBJECTIVES:

To impart knowledge on the following Topics

•Various types of over voltages in power system and protection methods.

•Generation of over voltages in laboratories.

•Measurement of over voltages.

•Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.

•Testing of power apparatus and insulation coordination

UNIT I OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS

Causes of over voltages and its effects on power system – Lightning, switching surges and temporary over voltages, Corona and its effects – Bewley lattice diagram- Protection against over voltages.

UNIT II DIELECTRIC BREAKDOWN

Properties of Dielectric materials - Gaseous breakdown in uniform and non-uniform fields – Corona discharges – Vacuum breakdown – Conduction and breakdown in pure and commercial liquids, Maintenance of oil Quality – Breakdown mechanisms in solid and composite dielectrics- Applications of insulating materials in electrical equipments.

UNIT III GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

Generation of High DC voltage: Rectifiers, voltage multipliers, vandigraff generator: generation of high impulse voltage: single and multistage Marx circuits – generation of high AC voltages: cascaded transformers, resonant transformer and tesla coil- generation of switching surges – generation of impulse currents - Triggering and control of impulse generators.

UNIT IV MEASUREMENT OF HIGH VOLTAGES AND HIGH CURRENTS

High Resistance with series ammeter – Dividers, Resistance, Capacitance and Mixed dividers - Peak Voltmeter, Generating Voltmeters - Capacitance Voltage Transformers, Electrostatic Voltmeters – Sphere Gaps - High current shunts- Digital techniques in high voltage measurement.

UNIT V HIGH VOLTAGE TESTING & INSULATION COORDINATION

High voltage testing of electrical power apparatus as per International and Indian standards – Power frequency, impulse voltage and DC testing of Insulators, circuit breakers, bushing, isolators and transformers- Insulation Coordination& testing of cabilitys.

TOTAL : 45 PERIODS

COURSE OUTCOME

Course Outcome		Level of Knowledge
CO1	To impart knowledge on the following Topic Understand Various types of over voltages in power system and protection methods.	K1
CO2	Breakdown Mechanism in Gases, Liquids, Solids	K1
CO3	Generation of over voltages in laboratories.	K2
CO4	Measurement of over voltages.	K2
CO5	Testing of power apparatus	K2
CO6	insulation coordination	K2

PROGRAM OUTCOMES (POs)

a.Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

b.Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

c.Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

d.Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

e.Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

f.The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

g.Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

h.Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

i.Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

j.Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

k.Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary **environments.**

l.Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES (PSOs)

PSO 1: Analyze, design and implement control, instrumentation and power systems for satisfying industry needs.

PSO 2 : Use modern tools and appropriate solutions for the real time problems for promoting energy conservation and sustainability.

PSO 3 : Possess the capacity to embrace new opportunities of emerging technologies, leadership and teamwork opportunities, all affording sustainable engineering career in Electrical and Electronics related fields.

COs - POs/PSOs MATRICES

COs	PO												PSO		
	a	b	c	d	e	f	g	h	i	j	k	l	1	2	3
CO1	3	3	2	3	2	2	2	-	-	-	-	2	3	2	2
CO2	3	2	1	2	1	2	2	-	-	-	-	2	3	2	-
CO3	3	2	2	3	3	2	2	-	-	-	-	2	3	2	2
CO4	3	2	2	3	3	2	2	-	-	-	-	2	3	2	2
CO5	3	2	2	3	3	2	2	-	-	-	-	2	3	2	2
CO6	3	2	2	3	3	2	2	-	-	-	-	2	3	2	2

Relevance: 1: Slight (Low)   2: Moderate (Medium) 3: Substantial (High)

UNIT-I
LECTURE PLAN

S. NO	TOPIC	No. of Periods	Proposed date	Actual Lecture Date	Pertaining CO	Taxonomy level	Mode of Delivery
1	High voltage testing of electrical power apparatus as per International and Indian standards				CO4	K1	Power Point Presentation
2	Power frequency, impulse voltage and DC testing of Insulators,				CO4	K2	Power Point Presentation
3	Testing of bushing				CO4	K2	Power Point Presentation
4	Testing of isolators and circuit breakers				CO4	K1	Power Point Presentation
5	Testing of transformers				CO4	K2	Power Point Presentation
6	Insulation Coordination				CO4	K2	Power Point Presentation

E Books

1. https://b-ok.asia/book/541362/93a5bb

   High voltage engineering , by C.L Wadhwa

2. https://b-ok.asia/book/593383/a732c8

   High voltage engineering by MS.Naidu &V.Kamaraju

3. https://b-ok.asia/book/462609/d72278

   High Voltage Engineering Fundamentals, by E. Kuffel and W.S. Zaengl, J.Kuffel

4. https://b-ok.asia/book/1132470/e51f4c

   High-voltage engineering: theory and practice, by Mazen Abdel – Salam, Hussein Anis, Ahdab A-Morshedy, Roshday Radwan

VIDEO LINKS

TITLE	LINK
High voltage testing of electrical power apparatus as per International and Indian standards	https://dir.indiamart.com/impcat/high-voltage-tester.html
Power frequency, impulse voltage and DC testing of Insulators,	https://www.youtube.com/watch?v=4pTWi8jgqd0
Testing of bushing	https://www.youtube.com/watch?v=4pTWi8jgqd0
Testing of isolators and circuit breakers	https://testguy.net/content/257-high-voltage-bushing-maintenance-techniques
Testing of transformers	https://www.youtube.com/watch?v=U-xA6yvp1Wk
Insulation Coordination	https://www.youtube.com/watch?v=vCcvDZCJ6Ik

UNIT -5

HIGH VOLTAGE TESTING & INSULATION COORDINATION

5. High Voltage Testing of Electrical Apparatus

5.1 Introduction

In High voltage operation, its mandatory to ensure that the electrical apparatus is capable of withstanding over voltages. So testing of electrical equipment for overvoltage is necessary.

The general terminology of the technical terms used is high voltage testing

(a) Disruptive Discharge Voltage

This is defined as the voltage which produces the loss of dielectric strength of an insulation. It is that voltage at which the electrical stress in the insulation causes a failure which includes the collapse of voltage and passage of current. In solids, this causes a permanent loss of strength, and in liquids or gases only temporary loss may be caused. When a discharge takes place between two electrodes in a gas or a liquid or over a solid surface in air, it is called flashover. If the discharge occurs through a solid insulation, it is called puncture.

(b) Withstand Voltage

The voltage which has to be applied to a test object under specified conditions in a withstand test is called the withstand voltage.

(c) Fifty Per Cent Flashover Voltage

This is the voltage which has a probability of 50% flashover, when applied to a test object. This is normally applied in impulse tests in which the loss of insulation strength is temporary.

(d)Hundred Per Cent Flashover Voltage

The voltage that causes a flashover at each of its applications under specified conditions when applied to test objects is specified as hundred per cent flashover voltage.

(e) Creepage Distance

It is the shortest distance on the contour of the external surface of the insulator unit or between two metal fittings on the insulator.

(f) a.c Test Voltages

Alternating test voltages of power frequency should have a frequency range of 40 to 60 Hz and should be approximately sinusoidal. The deviation allowed from the standard sine curve is about 7%. The deviation is checked by measuring instantaneous values over specified intervals and computing the rms value, the average value, and the form factor.

(g) Impulse Voltages

Impulse voltages are characterized by polarity, peak value, time to front (tf), and time to half the peak value after the peak (tt). The time to front is defined as 1.67 times to time between 30% and 90% of the peak value in the rising portion of the wave.

According to IS: 2071 (1973), standard impulse is defined as one with tf = 1.2μs, tt = 50μs (called 1/50μs wave). The tolerances allowed are ±3% on the peak value, ±30% in the front time (tf), and ±20% in the tail time (tt).

(h) Reference Atmospheric Conditions

The electrical characteristics of the insulators and other apparatus are normally referred to the reference atmospheric conditions. According to the Indian Standard Specifications, they are:

Temperature	: 270C
Pressure	: 1013 millibars (or 760 torr)
Absolute humidity	: 17 gm/m3

Since it is not always possible to do tests under these reference conditions, correction factors have to be applied. In some cases, the following test conditions are also used as reference (British Standard Specifications) conditions.

Temperature	: 2O0C
Pressure	: 1013 millibars (760 Torr)
Absolute humidity	: 11 g/m3 (65% relative humidity at 2O0C)

5.2 Tests on Insulators

The tests that are normally conducted are usually subdivided as
Type tests, and
Routine tests.

Type tests are intended to prove or check the design features and the quality. The routine tests are intended to check the quality of the individual test piece.
Type tests are done on samples when new designs or design changes are introduced, whereas the routine tests are done to ensure the reliability of the individual test objects and quality and consistency of the materials used in their manufacture.

High voltage tests include
Power frequency tests, and
Impulse tests.

All the insulators are tested for both categories of test.

5.2.1 Power Frequency Tests

Dry and Wet Flashover Tests: In these tests the a.c. voltage of power frequency is applied across the insulator and increased at a uniform rate of about 2 per cent per second of 75% of the estimated test voltage, to such a value that a breakdown occurs along the surface of the insulator. If the, test is conducted under normal conditions without any rain or precipitation, it is called "dry flashover test". If the test is done under conditions of rain, it is called "wet flashover test". In general, wet tests are not intended to reproduce the actual operating conditions, but only to provide a criterion based on experience that a satisfactory service operation will be obtained. The test object is subjected to a spray of water of given conductivity by means of nozzles. The spray is arranged such that the water drops fall approximately at an inclination of 45° to the vertical. The test object is sprayed for at least one minute before the voltage application, and the spray is continued during the voltage application.

Wet and Dry Withstand Tests (One Minute) In these tests, the voltage specified in the relevant specification is applied under dry or wet conditions for a period of one minute with an insulator mounted as in service conditions. The test piece should withstand the specified voltage.

5.2.2. Impulse Tests

(a) Impulse Withstand Voltage Test: This test is done by applying standard impulse voltage of specified value under dry conditions with both positive and negative polarities of the wave. If five consecutive waves do not cause a flashover or puncture, the insulator is deemed to have passed the test. If two applications cause flashover, the object is deemed to have failed. If there is only one failure, additional ten applications of the voltage wave are made. If the test object has withstood the subsequent applications, it is said to have passed the test.

(b) Impulse Flashover Test: The test is done as above with the specified voltage. Usually, the probability of failure is determined for 40% and 60% failure values or 20% and 80% failure values, since it is difficult to adjust the test voltage for the exact 50% flashover values. The average value of the upper and the lower limits is taken. The insulator surface should not be damaged by these tests, but slight marking on its surface or chipping off of the cement is allowed.

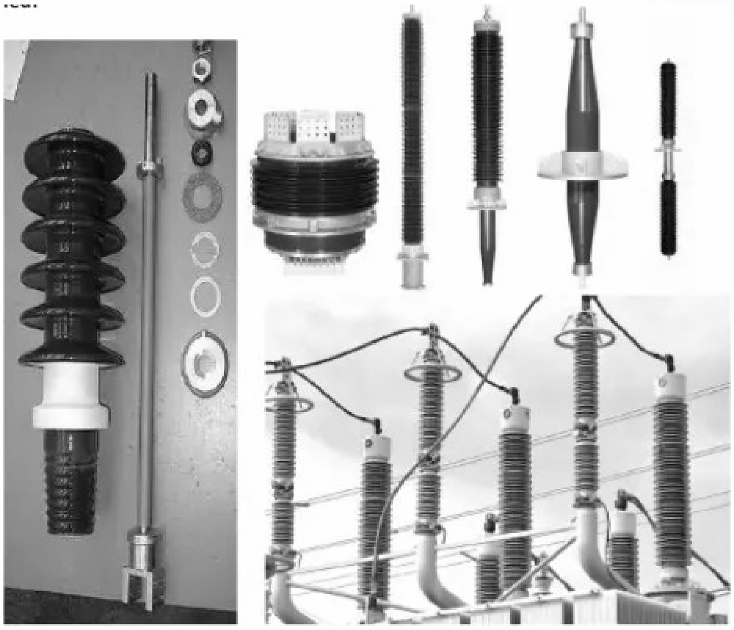
(c) Pollution Testing: Because of the problem of pollution of outdoor electrical insulation and consequent problems of the maintenance of electrical power systems, pollution testing is gaining importance.

The normal types of pollution are dust, micro-organisms, bird secretions, flies, etc., industrial pollution like smoke, petroleum vapours, dust, and other deposits, coastal pollution in which corrosive and hygroscopic salt layers are deposited on the insulator surfaces, desert pollution in which sand storms cause deposition of sand and dust layers, ice and fog deposits at high altitudes and in polar countries.

These pollutions cause corrosion, non-uniform gradients along the insulator strings and surface of insulators and also cause deterioration of the material. Also, pollution causes partial discharges and radio interference. Hence, pollution testing is important for extra high voltage systems.

At present there is no standard pollution test available. The popular test that is normally done is the salt fog test. In this test, the maximum normal withstand voltage is applied on the insulator and then artificial salt fog is created around the insulator by jets of salt water and compressed air. If the flashover occurs within one hour, the test is repeated with fog of lower salinity, otherwise, with a fog of higher salinity. The maximum salinity at which the insulator withstands three out of four tests without flashover is taken as the representative figure.

5.3 Testing of Bushings



5.3.1 Power Frequency Tests

(a) Power Factor—Voltage Test: In this test, the bushing is set up as in service or immersed in oil. It is connected such that the line conductor goes to the high voltage side and the tank or earth portion goes to the detector side of the high voltage Schering bridge. Voltage is applied up to the line value in increasing steps and then reduced. The capacitance and power factor (or tan δ) are recorded at each step. The characteristic of power factor or tan δ versus applied voltage is drawn. This is a normal routine test but sometimes may be conducted on percentage basis.

(b) Internal or Partial Discharge Test: This test is intended to find the deterioration or failure due to internal discharges caused in the composite insulation of the bushing. This is done by using internal or partial discharge arrangement. The voltage versus discharge magnitude as well as the quadratic rate gives an excellent record of the performance of the bushing in service. This is now a routine test for high voltage bushings.

(c) Momentary Withstand Test at Power Frequency: This is done as per the Indian Standard Specifications, IS: 2099, applied to bushings. The test voltage is specified in the specifications. The bushing has to withstand without flashover or puncture for a minimum time (~30s) to measure the voltage. At present this test is replaced by the impulse withstand test.

(d) One Minute Wet Withstand Test at Power Frequency: The most common and routine tests used for all electrical apparatuses are the one minute wet, and dry voltage withstand tests. In wet test, voltage specified is applied to the bushing mounted as in service with the rain arrangement as described earlier. A properly designed bushing has to withstand the voltage without flashover for one minute. This test really does not give any information for its satisfactory performance in service, while impulse and partial discharge tests give more information.

(e) Visible Discharge Test at Power Frequency: This test is intended for determining whether the bushing is likely to give radio interference in service, when the voltage specified in IS: 2099 is applied. No discharge other than that from the arcing horns or grading rings should be visible to the observers in a dark room. The test arrangement is the same as that of the withstand test, but the test is conducted in a dark room.

5.3.2 Impulse Voltage

(a) Full Wave Withstand Test: The bushing is tested for either polarity voltages as per the specifications. Five consecutive full waves of standard waveform are applied, and, if two of them cause flashover, the bushing is said to have failed in the test. If only one flashover occurs, ten additional applications are done. The bushing is considered to have passed the test if no flashover occurs in subsequent applications.

(b) Chopped Wave Withstand and Switching Surge Tests: The chopped wave test is sometimes done for high voltage bushings (220 kV and 400 kV and above). Switching surge flashover test of specified value is now-a-days included for high voltage bushings. The tests are carried out similar to full wave withstand tests.

5.3.3 Thermal Tests

Temperature Rise and Thermal Stability Tests: The purpose of these tests is to ensure that the bushing in service for long does not have an excessive temperature rise and also does not go into the "thermal runaway" condition of the insulation used. Temperature rise test is carried out in free air with an ambient temperature below 40OC at a rated power frequency (50Hz) a.c. current. The steady temperature rise above the ambient air temperature at any part of the bushing should not exceed 45OC. The test is carried out for such a long time till the temperature is substantially constant, i.e. the increase in temperature rate is less than l°C/hr. Sometimes, the bushings have to be operated along with transformers, of which the temperature reached may exceed 80OC. This temperature is high enough to produce large dielectric losses and thermal instability. For high voltage bushings this is particularly important, and hence the thermal stability test is done for bushings rated for 132kV and above. The test is carried out with the bushing immersed in oil at a maximum temperature as in service, and the voltage applied is 86% of the nominal system voltage. This is approximately √2 times the working voltage of the bushing and hence the dielectric losses are about double the normal value. The additional losses account for the conductor ohmic losses. It has been considered unnecessary to specify the thermal stability test for oil-impregnated paper bushings of low ratings; but for the large high voltage bushings (1600 A, 400 kV transformer bushings, etc.), the losses in the conductor may be high enough to outweigh the dielectric losses.

It may be pointed out here, that the thermal stability tests are type tests. But in the case of large sized high voltage bushings, it may be necessary to make them routine tests.

5.4 TESTING OF ISOLATORS AND CIRCUIT BREAKERS

5.4.1 Introduction

In this section, the testing of isolators and circuit breakers is covered, giving common characteristics for both. While these characteristics are directly relevant to the testing of circuit breakers, they are not much relevant as far as 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 k V and below) which may be the capacitive currents of bushings, bus bars etc. In fact, the definition of an Isolator or a Disconnector as per IS: 9921 (Pan 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.

Thus, most of the discussion here refers to the testing of circuit breakers. Testing of circuit breakers is intended to evaluate (a) the constructional and operational characteristics, and (b) the electrical characteristics of the circuit which the switch or the breaker has to interrupt or make. The different characteristics of a circuit breaker or a switch may be summarized as per the following groups.

(i) (a) The electrical characteristics which determine the arcing voltage, the current chopping characteristics, the residual current, the rate of decrease of conductance of the arc space and the plasma, and the shunting effects in interruption.

(b) Other physical characteristics including the media in which the arc is extinguished, the pressure developed or impressed at the point of interruption, the speed of the contact travel, the number of breaks, the size of the arcing chamber, and the materials and configuration of the circuit interruption.

(ii) The characteristics of the circuit include the degree of electrical loading, the normally generated or applied voltage, the type of fault in the system which the breaker has to clear, the time of interruption, the time constant, the natural frequency and the power factor of the circuit, the rate of rise of recovery voltage, the restriking voltage, the decrease in the a.c. component of the short circuit current, and the degree of asymmetry and the d.c. component of the short circuit current.

To assess the above factors, the main tests conducted on the circuit breakers and isolator switches are
(i) the dielectric tests or overvoltage tests,
(ii) the temperature rise tests,
(iii) the mechanical tests, and
(iv) the short circuit tests

Dielectric tests consist of overvoltage withstand tests of power frequency, lightning and switching impulse voltages. Tests are done for both internal and external insulation with the switch or circuit breaker in both the open and closed positions. In the open position, the test voltage levels are 15% higher than the test voltages used when the breaker is in closed position. As such there is always the possibility of line to ground flashover. To avoid this, the circuit breaker is mounted on insulators above the ground, and hence the insulation level of the body of the circuit breaker is raised.

The impulse tests with the lightning impulse wave of standard shape are done in a similar manner as in the case of insulators. In addition, the switching surge tests with switching overvoltages are done on circuit breakers and isolators to assess their performance under overvoltages due to switching operations.Temperature rise and mechanical tests are tube tests on circuit breakers and are done according to the specifications.

5.4.2 Short Circuit Tests

The most important tests carried out on circuit breakers arc short circuit tests, since these tests assess the primary performance of these devices, i.e. their ability to safely interrupt the fault currents. These tests consists of determining the making and breaking capacities at various load currents and rated voltages. In the case of isolators, the short circuit tests are conducted only with the limited purpose to determine their capacity to carry the rated short circuit current for a given duration; and no breaking or making current test is done.
The different methods of conducting short circuit tests are
(I) Direct Tests
(a) using a short circuit generator as the source
(b) using the power utility system or network as the source.
(II) Synthetic Tests
(a) Direct Testing in the Networks or in the Fields Circuit breakers are sometimes tested for their ability to make or break the circuit under normal load conditions or under short circuit conditions in the network itself. This is done during period of limited energy consumption or when the electrical energy is diverted to other sections of the network which are not connected to the circuit under test.

The advantages of field tests are:
(i) The circuit breaker is tested under actual conditions like those that occur in a given network.
(ii) Special occasions like breaking of charging currents of long lines, very short line faults, interruption of small inductive currents, etc. can be tested by direct testing only.
(iii) to assess the thermal and dynamics effects of short circuit currents, to study applications of safety devices, and to revise the performance test procedures, etc.

The disadvantages are:
(i) The circuit breaker can be tested at only a given rated voltage and network capacity.
(ii) The necessity to interrupt the normal services and to test only at light load conditions.
(iii) Extra inconvenience and expenses in installation of controlling and measuring equipment in the Held.

(b) Direct Testing in Short Circuit Test Laboratories in order to test the circuit breakers at different voltages and at different short circuit currents, short circuit laboratories are provided. The schematic layout of a short circuit testing laboratory is given in Fig. 5.4. It consists of a short circuit generator in association with a master circuit breaker, resistors, reactors and measuring devices. A make switch initiates the short circuit and the master circuit breaker isolates the test device from the source at the end of a predetermined time set on a test sequence controller. Also, the master circuit breaker can be tripped if the test device fails to operate properly. Short circuit generators with induction motors as prime movers are also available.

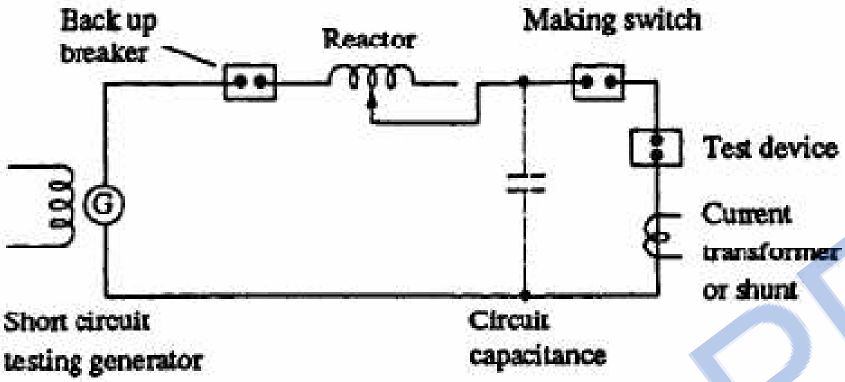
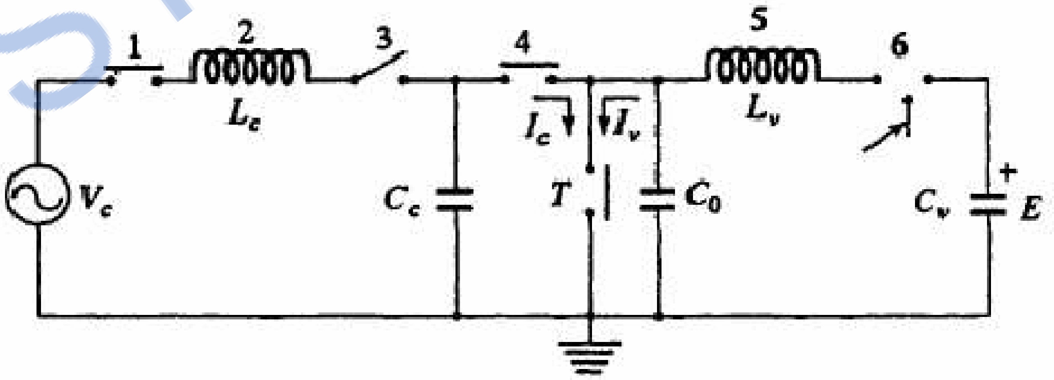


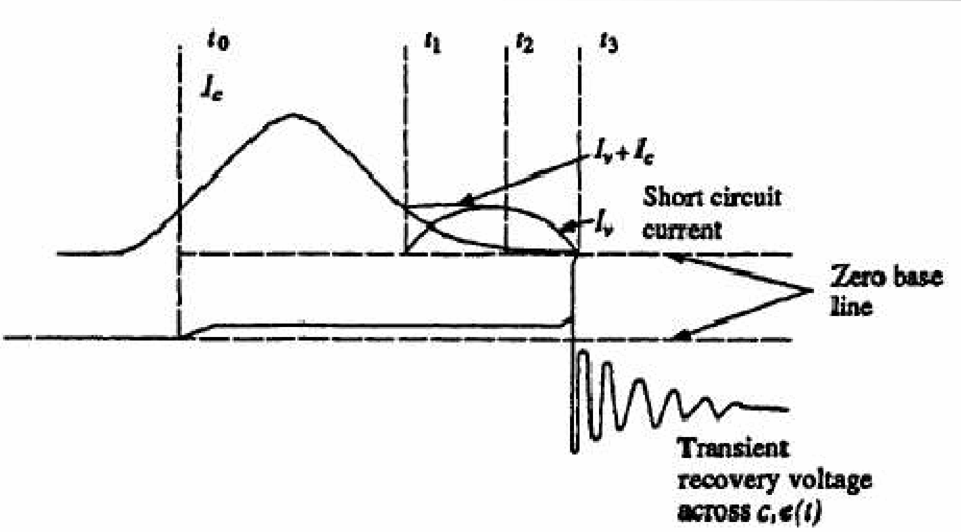
Fig. 5.4 Schematic diagram showing basic elements of a short circuit testing laboratory

(c) Synthetic Testing of Circuit Breakers: Due to very high interrupting capacities of circuit breakers, it is not economical to have a single source to provide the required short circuit and the rated voltage. Hence, the effect of a short circuit is obtained as regards to the intensity of the current and the recovery voltage as a combination of the effects of two sources, one of which supplies the a.c. current and the other the high voltage.

In the initial period of the short circuit test, the a.c. current source supplies the heavy current at a low voltage, and then the recovery voltage is simulated by a source of comparatively high voltage of small current capacity. A schematic diagram of a synthetic testing station is shown in Fig.5.5.



Schematic diagram of synthetic testing of circuit breakers



Current and recovery voltage waveforms across the test circuit breaker

With the auxiliary breaker (3) and the test breaker (T) closed, the closing of the making switch (1) causes the current to flow in the test circuit breaker. At some instant say to, the test circuit breaker (T) begins to operate and the master circuit breaker (1) becomes ready to clear the generator circuit. At some times t1, just before the zero of the generator current, the trigger gap (6) closes and the higher frequency current from
the discharging capacitor Cv also flows through the arc. At time t2, when the generator current is zero, the circuit breaker (1) clears that circuit, leaving only the current from Cv which has the required rate of change of current at its zero flowing in the test circuit breaker. At the zero of this current/full test voltage will be available. The closing of gap (6) would be a little earlier in time than shown in Fig. 10.4, but it has been drawn as shown for clarity at current zeros. It is important to see that the high-current source is disconnected and a high-voltage source applied with absolute precision (by means of an auxiliary circuit breaker) at the instant of circuit breaking.

(d) Composite Testing In this method, the breaker is first tested for its rated breaking capacity at a reduced voltage and afterwards for rated voltage at a low current. This method does not give a proper estimate of the breaker performance.

(e) Unit Testing When large circuit breakers of very high voltage rating (220 kV and above) are to be tested and where more than one break is provided per pole, the breaker is tested for one break at its rated current and the estimated voltage. In actual practice, the conditions of arc in each gap may not be identical and the voltage distribution along several breaks may be uneven. Hence, certain uncertainty prevails in the testing of one break.

(f) Testing Procedure The circuit breakers are tested for their (i) breaking capacity B, and (ii) making capacity M. The circuit breaker, after the calibration of the short circuit generator, is tested for the following duty cycle.
(1) B-3-B-3-B at 10% of the rated symmetrical breaking capacity
(2) B-3-J3-3-B at 30% of the rated symmetrical breaking capacity
(3) B-3-J3-3-B at 60% of the rated symmetrical breaking capacity
(4) B-3-MB-3MB-MB at 100% breaking capacity with the recovery voltage not less than 95% of the rated service voltage.

The power factor in these tests is generally between 0.15 and 0.3. The numral 3 in the above duty cycle indicates the time interval in minutes between the tests.

(g) Asymmetrical Tests One test cycle is repeated for the asymmetrical breaking capacity in which the d.c. component at the instant of contact separation is not less than 50% of the a.c. component.

TESTING OF TRANSFORMERS

Transformers are very important and costly apparatus in power systems. Great care has to be exercised to see that the transformers are not damaged due to transient overvoltages of either lightning or power frequency. Hence, overvoltage tests become very important in the testing of transformers. Here, only the overvoltage tests are discussed, and other routine tests like the temperature rise tests, short circuit tests, etc. are not included and can be found in the relevant specifications.

(a) Induced Overvoltage Test

Transformers are tested for overvoltages by exciting the secondary of the transformer from a high frequency a.c. source (100 to 400 Hz) to about twice the rated voltage. This reduces the core saturation and also limits the charging current necessary in large power transformers. The insulation withstand strength can also be checked.

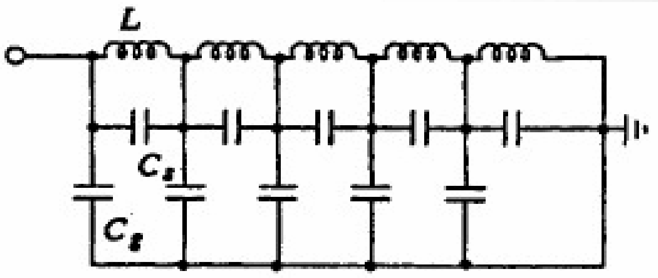
(b) Partial Discharge Tests

Partial discharge tests on the windings are done to assess the discharge magnitudes and the radio interference levels. The transformer is connected in a manner similar to any other equipment and the discharge measurements are made. The location of the fault or void is sometimes done by using the travelling wave technique similar to that for cables. So far, no method has been standardized as to where the discharge is to be measured. Multi-terminal partial discharge measurements are recommended. Under the application of power frequency voltage, the discharge magnitudes greater than 104pico coulomb are considered to be severe, and the transformer insulation should be such that the discharge magnitude will be far below this value.

Impulse Testing of Transformers

The purpose of the impulse tests is to determine the ability of the insulation of the transformers to withstand the transient voltages due to lightning, etc. Since the transients are impulses of short rise time, the voltage distribution along the transformer winding will not be uniform. The equivalent circuit of a transfomer winding for impulses is shown in Fig. . If an impulse wave is applied to such a network (shown in Fig.) the voltage distribution along the element will be uneven, and oscillations will be set in producing voltages much higher than the applied voltage.

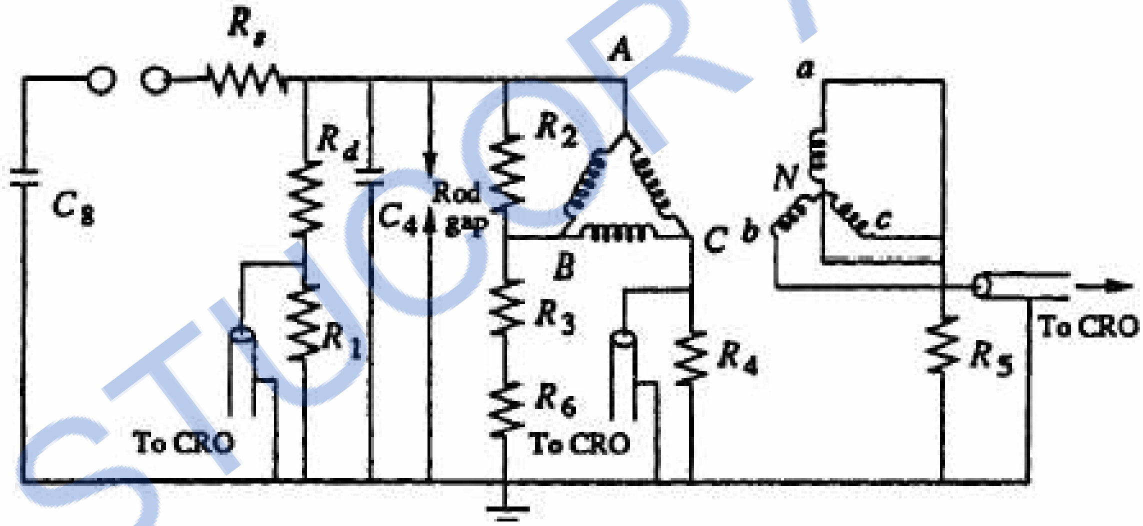
Impulse testing of transformers is done using both the full wave and the chopped wave of the standard impulse, produced by a rod gap with a chopping time of 3 to 6μs. To prevent large overvoltages being induced in the windings not under test, they are short circuited and connected to ground. But the short circuiting reduces the impedance of the transformer and hence poses problems in adjusting the standard wave shape of the impulse generators. It also reduces the sensitivity of detection.



Equivalent circuit of transformer winding for impulses

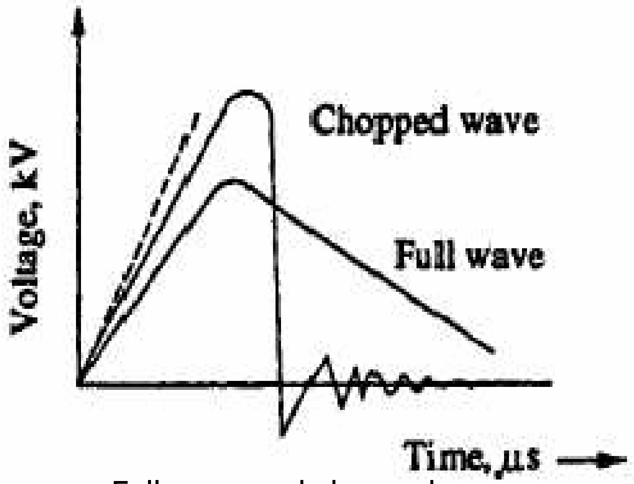
(a) Procedure for Impulse Testing

The schematic diagram of the transformer connection for impulse testing is shown in Fig. , and the wave- ground shapes of the full and chopped waves are shown in Fig. . In transformer testing it is essential to record the waveforms of the applied voltage and current through the windings under test. Sometimes, the transferred voltage in the secondary and the neutral current are also recorded.



Arrangement of transformer for impulse testing

Impulse testing is done in the following sequence:
(j) applying impulse voltage of magnitude 75% of the Basic Impulse Level (BIL) of the transformer under test,
(ii) one full wave voltage of 100% BIL,
(iii) two chopped waves of 100% BIL,
(iv) one full wave of 100% BIL, and
(v) one full wave of 75% BIL.
It is very important to see that the grounding is proper and the windings not under test are suitably terminated.



Full wave and chopped wave

(c)Detection and Location of Fault During Impulse Testing

The fault in a transformer insulation is located in impulse tests by any one of the following methods.

General observations: The fault can be located by general observations like noise in the tank or smoke or bubbles in breather. Voltage oscillogram method : Fault or failure appears as a partial or complete collapse of the applied voltage wave. Figure ... gives the typical waveform. The sensitivity of this method is low and does not detect faults which occur on less than 5% of the winding.

Neutral current method : In the neutral current method, a record of the impulse current flowing through a resistive shunt between the neutral and ground point is used for detecting the fault. The neutral current oscillogram consists of a high frequency oscillation, a low frequency disturbance, and a current rise due to reflections from the ground end of the windings. When a fault occurs such as arcing between the turns or from turn to the ground, a train of high frequency pulses similar to that in the front of the impulse current wave are observed in the oscillogram and the waveshape changes.

If the fault is local, like a partial discharge, only high frequency oscillations are observed without a change of waveshape. The sensitivity of the method decreases, if other windings not under test are grounded.

Transferred surge current method: In this method, the voltage across a resistive shunt connected between the low voltage winding and the ground is used for fault location. A short high frequency discharge oscillation is capacitively transferred at the event of failure and is recorded. Hence, faults at a further distance from the neutral are also clearly located. The waveshape is distorted depending on the location and type of fault, and hence can be more clearly detected.

After the location of the fault, the type of fault can be observed by dismantling the winding and looking for charred insulation or melted parts on the copper winding.

This is successful in the case of major faults. Local faults or partial discharges are selfhealing and escape observation.

INSULATION COORDINATION ON HIGH VOLTAGE

Insulation coordination means the correlation of the insulation of the various equipments in a power system to the insulation of the protective devices used for the protection of those equipments against overvoltages. In a power system various equipments like transformers, circuit breakers, bus supports etc. have different breakdown voltages and hence the volt-time characteristics. In order that all the equipments should be properly protected it is desired that the insulation of the various protective devices must be properly coordinated. The basic concept of insulation coordination is illustrated in Fig. . Curve A is the volt-time curve of the protective device and B the volt-time curve of the equipment to be protected. Fig. 7.27 shows the desired positions of the volt-time curves of the protecting device and the equipment to be protected. Thus, any insulation having a withstand voltage strength in excess of the insulation strength of curve B is protected by the protective device of curve A.

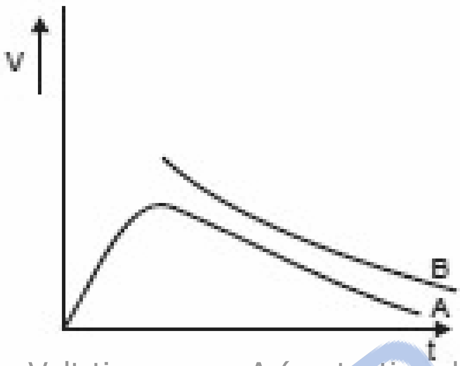


Fig: Volt-time curve A (protecting device and)
volt-time curve B (device to be protected)

The 'volt-time curve' expression will be used very frequently in this chapter. It is, therefore, necessary to understand the meaning of this expression.

Volt-Time Curve

The breakdown voltage for a particular insulation of flashover voltage for a gap is a function of both the magnitude of voltage and the time of application of the voltage. The volt-time curve is a graph showing the relation between the crest flashover voltages and the time to flashover for a series of impulse applications of a given wave shape. For the construction of volt-time curve the following procedure is adopted. Waves of the same shape but of different peak values are applied to the insulation whose volt-time curve is required. If flashover occurs on the front of the wave, the flashover point gives one point on the volt-time curve. The other possibility is that the flashover occurs just at the peak value of the wave; this gives another point on the V-T curve. The third possibility is that the flashover occurs on the tail side of the wave. In this case to find the point on the V-T curve, draw a horizontal line from the peak value of this wave and also draw a vertical line passing through the point where the flashover takes place. The intersection of the horizontal and vertical lines gives the point on the V-T curve. This procedure is nicely shown in Fig.

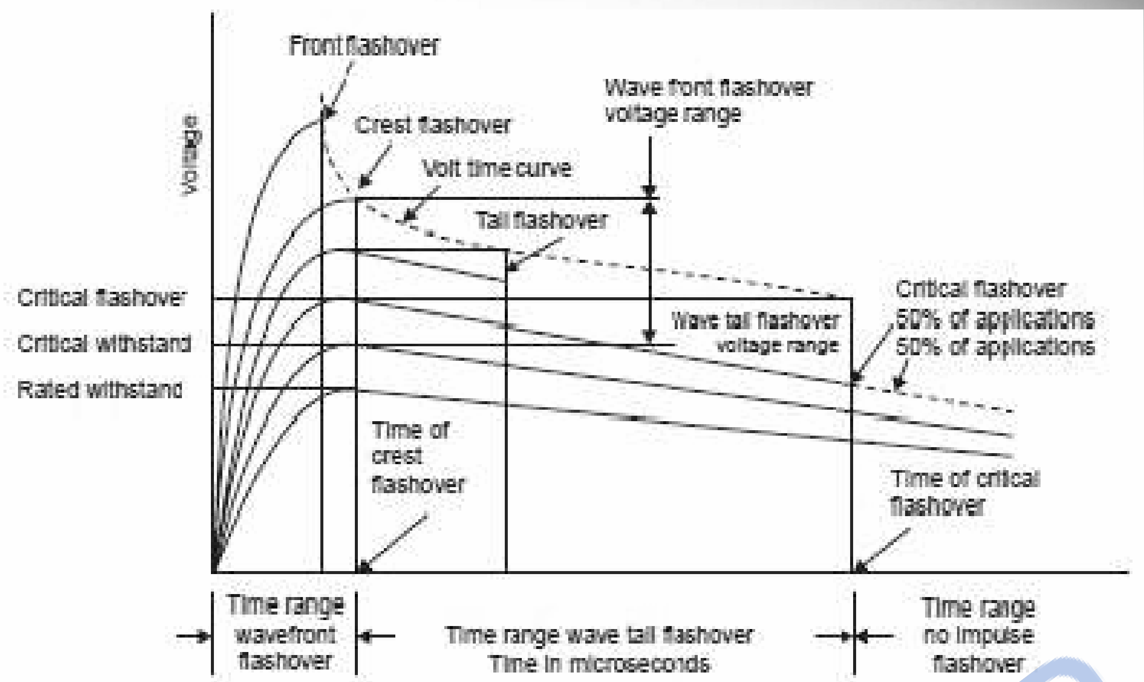


Fig: Volt-time curve (construction)

The overvoltages against which coordination is required could be caused on the system due to system faults, switching operation or lightning surges. For lower voltages, normally upto about 345 kV, over voltages caused by system faults or switching operations do not cause damage to equipment insulation although they may be detrimental to protective devices. Overvoltages caused by lightning are of sufficient magnitude to affect the equipment insulation whereas for voltages above 345 kV it is these switching surges which are more dangerous for the equipments than the lightning surges.

The problem of coordinating the insulation of the protective equipment involves not only guarding the equipment insulation but also it is desired that the protecting equipment should not be damaged.

To assist in the process of insulation coordination, standard insulation levels have been recommended. These insulation levels are defined as follows.

Basic impulse insulation levels (BIL) are reference levels expressed in impulse crest voltage with a standard wave not longer than 1.2/50 μ sec wave. Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the basic insulation level.

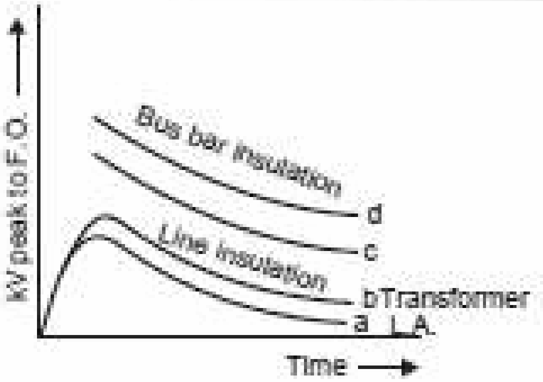
The problem of insulation coordination can be studied under three steps:

1. Selection of a suitable insulation which is a function of reference class voltage (i.e., 1.05 × operating voltage of the system). Table 5.1 gives the BIL for various reference class voltages.

Basic impulse insulation levels

Reference class kV	Standard Basic impulse level kV	Reduced insulation levels
23	150	
34.5	200	
46	250	
69	350	
92	450	
115	550	450
138	650	550
161	750	650
196	900	
230	1050	900
287	1300	1050
345	1550	1300

2. The design of the various equipments such that the breakdown or flashover strength of all insulation in the station equals or exceeds the selected level as in (1).
3. Selection of protective devices that will give the apparatus as good protection as can be justified economically.
The above procedure requires that the apparatus to be protected shall have a withstand test value not less than the kV magnitude given in the second column of Table 5…. irrespective of the polarity of the wave positive or negative and irrespective of how the system was grounded. The third column of the table gives the reduced insulation levels which are used for selecting insulation levels of solidly grounded systems and for systems operating above 345 kV where switching surges are of more importance than the lightning surges. At 345 kV, the switching voltage is considered to be 2.7 p.u., i.e., 345 × 2.7 = 931.5 kV which corresponds to the lightning level. At 500 kV, however, 2.7 p.u. will mean 2.7 × 500 = 1350 kV switching voltage which exceeds the lightning voltage level.
Therefore, the ratio of switching voltage to operating voltage is reduced by using the switching resistances between the C.B. contacts. For 500 kV it is has been possible to obtain this ratio as 2.0 and for 765 kV it is 1.7. With further increase in operating voltages, it is hoped that the ratio could be brought to 1.5. So, for switching voltages the reduced levels in third column are used i.e., for 345 kV, the standard BIL is 1550 kV but if the equipment can withstand even 1425 kV or 1300 kV it will serve the purpose.
Fig. 5.. gives the relative position of the volt-time curves of the various equipments in a substation for proper coordination. To illustrate the selection of the BIL of a transformer to be operated on a 138 kV system assume that the transformer is of large capacity and its star point is solidly grounded. The grounding is such that the line-to-ground voltage of the healthy phase during a ground fault on one of the phases is say 74% of the normal L-L voltage. Allowing for 5% overvoltage during operating conditions, the arrester rms operating voltage will be 1.05 × 0.74 × 138 = 107.2 kV. The nearest standard rating is 109 kV. The characteristic of such a L.A. is shown in Fig. 5….. From the figure the breakdown value of the arrester is 400 kV. Assuming a 15% margin plus 35 kV between the insulation levels of L.A. and the transformer, the insulation level of transformer should be at least equal to 400 + 0.15 × 400 + 35 = 495 kV. From Fig. 7.30 (or from the table the reduced level of transformer for 138 kV is 550 kV) the insulation level of transformer is 550 kV; therefore a lightning arrester of 109kV rating can be applied.



Volt-time curves

It is to be noted that low voltage lines are not as highly insulated as higher voltage lines so that lightning surges coming into the station would normally be much less than in a higher voltage station because the high voltage surges will flashover the line insulation of low voltage line and not reach the station.

The traditional approach to insulation coordination requires the evaluation of the highest overvoltages to which an equipment may be subjected during operation and selection of standardized value of withstand impulse voltage with suitable safety margin. However, it is realized that overvoltages are a random phenomenon and it is uneconomical to design plant with such a high degree of safety that they sustain the infrequent ones. It is also known that insulation designed on this basis does not give 100% protection and insulation failure may occur even in well designed plants and, therefore, it is desired to limit the frequency of insulation failures to the most economical value taking into account equipment cost and service continuity. Insulation coordination, therefore, should be based on evaluation and limitation of the risk of failure than on the prior choice of a safety margin.

The modern practice, therefore, is to make use of probabilistic concepts and statistical procedures especially for very high voltage equipments which might later on be extended to all cases where a close adjustment of insulation to system conditions proves economical. The statistical methods even though laborious are quite useful.

5….. Statistical Methods for Insulation Coordination

Both the over voltages due to lightning or switching and the breakdown strength of the insulating media are of statistical nature. Not all lightning or switching surges are dangerous to the insulation and particular specimen need not necessarily flashover or puncture at a particular voltage. Therefore, it is important to design the insulation of the various equipments to be protected and the devices used for protection not for worst possible condition but for worst probable condition as the cost of insulation for system of the voltage more than 380 kV are proportional to square of the voltage and, therefore any small saving in insulation will result in a large sums when considered for such large modern power system. This, however, would involve some level of risk failure. It is desired to accept some level of risk of failure than to design a risk-free but a very costly system.

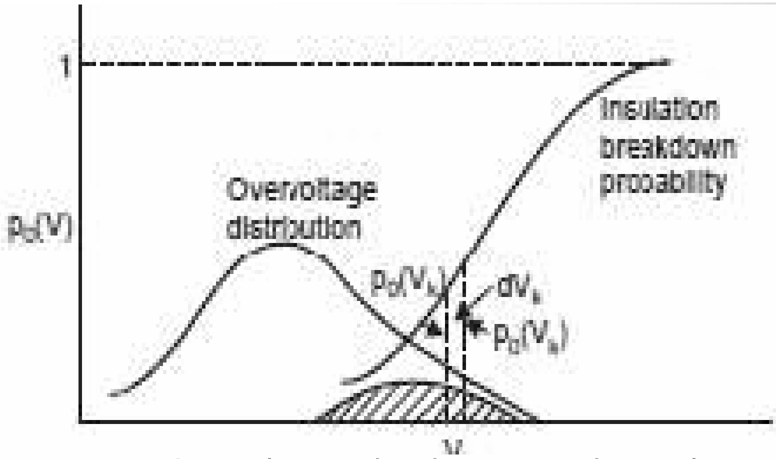


Fig: Overvoltage distribution and Insulation breakdown probability

The statistical methods, however, call for a very rigorous experimentation and analysis work so as to find probability of occurence of overvoltages and probability of failure of insulation. It is found that the distribution of breakdown for a given gap follows with some exceptions approximately normal or Gaussian distribution. Similarly the distribution of over voltages on the system also follows the Gaussian distribution. In order to coordinate electrical stresses due to overvoltages with the electrical strengths of the dielectric media, it has been found convenient to represent overvoltage distribution in the form of probability density function and the insulation breakdown probability by the cumulative distribution function as shown in Fig. The statistical methods, however, call for a very rigorous experimentation and analysis work so as to find probability of occurence of overvoltages and probability of failure of insulation. It is found that the distribution of breakdown for a given gap follows with some exceptions approximately normal or Gaussian distribution. Similarly the distribution of over voltages on the system also follows the Gaussian distribution. In order to coordinate electrical stresses due to overvoltages with the electrical strengths of the dielectric media, it has been found convenient to represent overvoltage distribution in the form of probability density function and the insulation breakdown probability by the cumulative distribution function as shown in Fig. 5..

Insulation Co-ordination in EHV and UHV Systems

The insulation design of EHV and UHV stations is based on the following principles stations have transformers and other valuable equipment that have non-self restoring insulation, and

the protective levels for lightning surges and switching surges are almost equal and even overlap. If the basic impulse level for the equipment or the system is chosen, then this level cannot give protection against the switching impulses.

Hence, a separate switching impulse level (SIL) has to be chosen. It is, therefore, desirable to use protective devices for limiting both lightning and switching overvoltages. As such, the switching impulse Insulation Coordination of Substation above the controlled switching surge level has to be adopted so that the surge arresters operate only rarely on switching overvoltages when the controls of the control devices for switching voltages fail. A general guideline that can be adopted for different EHV and UHV system for maximum switching surge levels are given in Table
.

Table 8.5 *Maximum Switching Surge Level at Different Line Voltages*

Highest system voltage (kV)	420	525	765	1150
Maximum switching surge level (kV) = highest system voltage multiplied by	2.5	2.25	2.0	1.8 to 1.9

It is now necessary to allow a suitable margin in the Insulation Coordination of Substation above the maximum switching surge overvoltage and also permit a little risk for failure in the interest of economical adoption of insulation levels. Usually statistical methods are adopted based on a given risk of flashover which is calculated by combining the flashover voltage distribution function of the insulation structures with the overvoltage probability density function.

Two Mark Questions

1. What are the necessities of High voltage testing?

   To check whether they are as per the design and as per specifications and standards.

   To ensure that the HV equipment is able to withstand over voltages produced naturally or within the system.

2. What is the specialty of HV Testing?

   The H.V. lab requires higher space.
   Special equipments are required.
   Special Techniques are required.

Name how standards for HV Testing

B I S - Bureau of Indian Standards.
I E C - International Electro Tech. Commission.
B S I - British Standard Institution.
I E E E - Instituting Electrical & Electronics Engineering.
I S O P - International Standards Organization.
A N S I - American Standards Institute
C I G R E - International council on large electrical system.
ISS - Indian Standard Specifications

3. What is disruptive discharge voltage?

The Voltage that produces loss of dielectric strength of equipment is called disruptive discharge voltage. In solid-it is called puncture. In liquid or air-it is called Flashover.

4. What is Flashover?

When a loss of dielectric strength occurs inside a liquid or gaseous insulation or along the surface of a solid Insulation, it is called flashover.

5. What is Puncture?

When a loss of dielectric strength occurs inside a solid it is called puncture.

6. What are self restoring and Non self restoring insulation?

Insulation which completely regains its dielectric strength after a disruptive Discharge is called a self restoring insulation. Insulation which does not regain its insulating property after a disruptive discharge is a Non self restoring insulation.

7. What is withstand voltage.

Withstand Test is a Test in which the specified voltage is applied to the test object under specified conditions to check whether the equipment withstands W/o. any discharge/ flash over . The test voltage which is applied to a Test object in a withstand Test is called withstand voltage. It is the voltage that the equipment is capable of withstanding under specified conditions.

8. What is withstand voltage 50% Flashover voltage

The Test voltage which has 50% probability for flashover is called 50% flashover voltage.

9. What is withstand voltage 100% Flashover voltage

The test voltage which causes flashover of the test object at each of its application.

10. How are the Testing of insulators classified

1. Type Test
   Done whenever a new brand is introduced and a new design is adopted.
1. Routine Test
   Whenever the quality of the individual equipment is to be established say at the time of purchase.

11. What is meant by atmospheric correction with reference to High Voltage Testing?

Normally HV Tests are done under Normal Temperature, pressure & humidity conditions and then the values are corrected to the following conditions.

Temp : 27oC

Pressure : 1013 Millibar 760 torr Absolute humidity : 17gram/m3

This is done by applying the following correction factors. h = humidity correction factor, d = air density correction factor

If Then

Va = Voltage under Test conditions

& Vs = Voltage under reference atmospheric candidate

Vs = Va x h/d

d = 0.289 b/ (273+t)

where

b = atmospheric Pressure in millibar t = atmospheric temp in degree C.

h = Can be obtained form graph.

(Humidity / Dry bulb thermometer reading)

12. What are the various HV Test done on Bushings?

Power frequency Tests

Power factor Test

Partial Discharge Test

1 Minute W.S. Test

Visible discharge Test

Impulse Voltage Test

Impulse with stand Test –

Full wave (Positive & Negative Polarity)

Impulse with stand Test

Chopped wave (Positive & Negative polarity)

Switching surge Flashover Test

Impulse Flash over Test under oil.

13. What are the steps for Impulse withstand Test on Power Transformer

Apply one full Impulse of 75% BIL of Power Transformer

Apply one full Impulse of 100% BIL of Power Transformer

Apply Two chopped wave of 100% BIL

Apply one full wave of 100% BIL

Apply one full wave of 75% BIL The Power Tr should stand. Then it passes the Test.

14. What are the various HV Tests done one circuit Breakers?
    Power frequency WS Test, 1 minute, dry.
    Power frequency WS Test, wet
    Impulse voltage WS Test dry.
    Switching impulse WS Test

15. What are the various Tests (HV Tests) done on surge diverters.
    Insulation withstand Test, power frequency both dry and wet.
    Power frequency voltage spark over Test.
    Standard Impulse voltage spark over Test.
    Front of wave voltage spark over Test.
    Switching Impulse voltage spark over Test.
    Residual voltage Test.
    Current Impulse withstand Test.
        High current
        Long duration.
    Pressure relief Test (When fitted)
    Pollution Tests

16. What is the necessity for measurement of RIV?
    Sometimes electrical equipment like power Transformer, conductors, rotating machines etc. produce unwanted electrical signals in the radio frequency range of 150k Hz to 30 M Hz, where as the power frequency being 50 Hz. These signals affect the communication systems & should be prevented. Hence RIV measurement is necessary.

17. What is meant by insulation co-ordination in EHV power system?
    Insulation co-ordination is the grading of the insulation level of
    Various equipments in a power system
    Various parts of the equipments
    Protection devices in such a way that, in the event of a serious over voltage, less vital, less important, less costlier, easy to repair equipment/part of equipment breaks down first and thereby avoiding major breakdown & interruption to consumers, cost of replacement etc.
    For e.g.
    In the event of an over voltage, a string insulator on Transmission line should breakdown before the bushing of a power Transformer.
    The bushing of the power Tr. should breakdown first before the Breakdown of the winding of the Power Transformer.

18. What is system protection level and its selection depend on what factors?
    In the power system, system protection level is established considering the,
    Location of the station
    Protection level of arrester
    Line shielding

19. What is BIL?
The basic insulation levels are reference levels fixed by standards for each voltage levels. Basic impulse levels are reference levels expressed in terms of impulse crest voltage(Vp) with a standard lightning impulse voltage(1.2/50 micro seconds wave) for any apparatus the insulation level as demonstrated by suitable tests should be greater than or equal to the BIL.

While selecting an equipment for a power system what should he its BIL. when compared to the system protection level.
For any equipment insulation level should be more than the BIL
For proper insulation coordination its insulation level should be greater than the system protection level over the margin determined by the following factor

Atmospheric Condition
Station Location
Protection level of arresters.
Importance of the equipments etc.

Hence the system protection level will be less than BIL

20. While selecting an equipment for a power system what should he its BIL.when compared to the system protection level.
For any equipment insulation level should be more than the BIL
For proper insulation coordination its insulation level should be greater than the system protection level over the margin determined by the following factor

Atmospheric Condition
Station Location
Protection level of arresters.
Importance of the equipments etc.

Hence the system protection level will be less than BIL

PART – B

1. With a neat sketch explain the impulse testing on the power transformer.
2. Discuss the various test carried out in a circuit breaker at HV labs.
3. What are the different power frequency tests done on bushings? Mention the procedure for testing.
4. Briefly discuss the various tests carried out the insulator.
5. What is meant by insulation coordination? How are the protective devices chosen for optimal insulation level in a power system?
6. Explain the terms:
(i) With stand voltage
(ii) Flash over voltage
(iii)50% flash over voltage
(iv)Wet and dry power frequency tests as referred to HV testing.
7. Explain the following terms used in HV testing as per the standards:
(i) Disruptive discharge voltage
(ii) Creepage distance
(iii)Impulse voltage
(iv)100% flash over voltage.
8. (i)What are the tests conducted on circuit breakers and isolator switches? Explain about any one of the tests.
(ii)What are different tests conducted on cables? Explain any one of them.

Part C

1. Explain the complete test procedure for conducting impulse voltage withstand test on 33KV post insulator. (15) [CO5 K2]

2. Explain the direct and synthetic testing of isolators and circuit breakers in detail. (15) [CO5 K2]

3. Explain the different high voltage tests done on bushing? (15) [CO5 K2]

4. What are the tests to be conducted on cables as IS10810. Explain them in detail. (15) [CO5 K1]

5. (i) Elaborately discuss about various types of standards for HV power apparatus testing of electrical power apparatus(8) (ii)write short notes on statistical methods for insulation Coordination(7) [CO6 K2]

Assignment

1. Explain in detail the testing of Transformer with Indian standard and International Standard [CO5 K3]
2. Explain in detail of Insulation coordination for various working voltages ranges with electrical power apparatus . [CO5 K3]

Supportive online Materials

https://dir.indiamart.com/impcat/high-voltage-tester.html

https://www.youtube.com/watch?v=4pTWi8jgqd0

https://www.youtube.com/watch?v=4pTWi8jgqd0

https://testguy.net/content/257-high-voltage-bushing-maintenance-techniques

https://www.youtube.com/watch?v=U-xA6yvp1Wk

https://www.youtube.com/watch?v=vCcvDZCJ6Ik

Real time Applications in day to day life and to Industry

In industrial testing and research laboratories, it is essential to measure the voltages and currents accurately, ensuring perfect safety to the personnel and equipment. Hence a person handling the equipment as well as the metering devices must be protected against over voltages and also against any induced voltages due to stray coupling. Therefore, the location and layout of the devices are important. Secondly, linear extrapolation of the devices beyond their ranges are not valid for high voltage meters and measuring instruments, and they have to be calibrated for the full range. Electromagnetic interference is a serious problem in impulse voltage and current measurements, and it has to be avoided or minimized. Therefore, even though the principles of measurements may be same, the devices and instruments for measurement of high voltages and currents differ vastly from the low voltage and low current devices.

Activity Based Learning

Create a concept Mapping to Understand the Various Techniques used for Measurement of High Voltages.

Steps For Building Concept Mapping

Step 1: List key concepts/terms related to the topic

Step 2: Build up concepts to elaborate key concepts

Step 3: Identify links between concepts

Template design:

https://creately.com/diagram/example/jd2ke4en1/Blank+Concept+Map+Template

Thank you

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