MODULE-1: Conduction and Breakdown in Gases

Syllabus

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1.10 Conduction and Breakdown in Liquid Dielectrics: Liquids as Insulators, Pure Liquids and Commercial Liquids, Conduction and Breakdown in Pure Liquids, Conduction and Breakdown in Commercial Liquids.

1.11 Breakdown in Solid Dielectrics: Introduction, Intrinsic Breakdown, Electromechanical Breakdown, Thermal Breakdown.

Course Objectives

1. To discuss conduction and breakdown in gases, liquid dielectrics.
2. To discuss breakdown in solid dielectrics.

1. Introduction

1. Dielectric material is a poor conductor of electricity.
2. But it can be conducted by applying high electric field.
3. It is an efficient supporter of electric field.
4. Whenever we are applying electric field the position of ions get changed and support for electricity conduction.
5. Examples of dielectric materials are mica, glass, ceramics etc.

a) Dielectric Strength

•The dielectric strength of an insulating material is defined as the maximum dielectric stress with the material can withstand.

b) Factors affecting Dielectric strength

1. Pressure
2. Temperature
3. Humidity
4. Nature of applied voltage
5. Imperfection of material

c) Types of Dielectrics

1. Gas or Vacuum Dielectrics
2. Liquid Dielectrics
3. Solid Dielectrics
4. Composite Dielectrics

1. Gas or Vacuum Dielectrics

1. It has high dielectric strength (10^7 V/cm)
2. Breakdown occur in the gas or vacuum is due to collisional ionization. (Ionization by collision)
3. If the applied voltage is sufficiently large electrons are multiplied in an exponential manner & breakdown will be occurred.
4. Examples- Sulphar Hexa Fluoride, CO_2 etc

2. Liquid Dielectrics

1. The liquid dielectric are used in HV equipment for dual purpose of insulation & heat dissipation.
2. Temporary failure can be quickly re-insulated by the liquid flow to the affected area.
3. Highly purified liquid is more suitable to serve as a dielectric medium.
4. Dielectric strength is up to 1 MV/cm
5. Breakdown strength reduces due to impurities.
6. Selection of liquid dielectric is based on dielectric strength, viscosity, stability, flash point, gas constant etc
7. Examples- Petroleum, transformer oil (Mineral oil) etc
8. **Applications**- Area where equipments is continuously operated like Distribution Transformer.

3. Solid Dielectrics

1. It has good mechanical strength & bonding capability.
2. Dielectric strength – 10MV/cm
3. Examples- Inorganic materials (Ceramics, glass etc) , Organic materials(PVC, Polyethylene, natural rubber etc)
4. Application- Electrical apparatus

4. Composite Dielectrics

1. Combination of more than two kinds of insulators
2. Chemically stable
3. Long life span
4. But dielectric constant of two material should match
5. Two insulators never react together.
6. Examples – Oil impregnated paper, Oil impregnated metalized plastic film.

1. 1 Gases as Insulating Media

1. The simplest and the most commonly found dielectrics are gases.

2. Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as **Nitrogen (N2), Carbon dioxide (CO2), Freon (CCl2F2) and Sulphur hexafluoride (SF6**) are also used.

3. Various phenomena occur in gaseous dielectrics when a voltage is applied.

4. When the applied voltage is low, small current flow between the conducting electrodes and the insulation keep its electrical properties.

5. Whereas if applied voltage is large, the current flowing through the insulation increases very sharply, and an electrical breakdown occurs.

6. A strongly conducting spark formed during breakdown practically produces a short-circuit between the electrodes.

7. The maximum voltage applied to the insulation at the moment of breakdown is called the **breakdown voltage.**

8. Two types of electrical discharge in gases: **(1) Non-sustaining discharges and (2) Self-sustaining types**.

1.2. Collision Process: Ionization Processes

1. At normal temperature and pressure, a gas acts as good insulating materials.
2. When high voltage applied between the two electrodes immersed in gaseous medium, the gas becomes a conductor an **electrical breakdown** occurs.
3. Ionization by collisions are two type:
    a. **Elastic collisions:** An elastic collision is a collision in which there is no net loss in kinetic energy in the system as a result of the collision.
    b. **Inelastic collisions:** A collision in which the total kinetic energy of the colliding bodies or particles is not the same after the collision as it was before (opposed to elastic collision).

The processes that are primarily responsible for the breakdown of gas are

1. **Primary ionization process**
2. **secondary ionization process**

1. Primary ionization process

1. Ionization by collision
2. Photo ionization

2. Secondary Ionization Process

1. Electron emission due to positive ion impact
2. Thermal ionisation
3. Ionization by interaction of meta stable with neutral atoms
4. Electron detachment

1.2.1. Primary Ionisation

a) Ionization by collision

1. **Ionization is defined as a process** of leaving free electron from a gas molecule with the continuous generation of positive ion.
2. In the process of ionization by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion.
3. If we consider a low-pressure gas column in which an electric field E is applied across two plane parallel electrodes, as shown in Fig. 2.1.
4. If the energy (E) gained during this travel between collision exceeds the ionization potential, Vi, which is the energy required to remove an electron from its atomic shell, then ionization take place. This process can be represented as :

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

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

5. A few electron produce at the cathode by some external means, say by ultra-violet light falling on the cathode, ionize neutral gas particles producing positive ions and additional electrons.
6. The additional electrons, then, themselves make ‘ionizing collisions’ and thus the process repeats itself.

b) Photo ionisation

The ionization caused by cosmic radiation or photons is called **photo-ionization.**

Photo-ionization occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionization 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, and**

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

This reversible process can be expressed as,

$$h\nu + A \rightleftarrows A^{+} + e^{-}$$

E > Ai; Condition of breakdown Where E = hγ = hc/λ

h – planks constant, c – velocity of light and λ- wave length of radiation

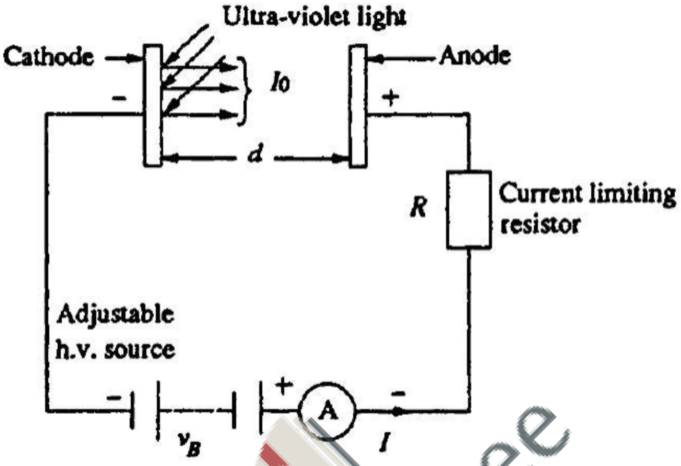


Figure 1.1 :Parallel plate capacitor

The higher the ionization energy, the shorter will be the wavelength of the radiation capable of causing ionization.

Note : It was observed experimentally that a radiation having a wavelength of 1250 Å is capable of causing photo-ionization of almost all gases.

1.2.2 Secondary Ionization

"The process of formation of secondary electrons after completion of ionization by collision & photo ionization"

(a)Electron emission due to positive ion impact

1. Positive ion formation is due to either ionization by collision or photo ionization.
2. Positive ions moves towards cathode
3. The secondary ion is forms such a way that "Total energy >2*work function"
   Where Total energy= KE+ Ionization energy

When positively and negatively charged particles present recombination take place.

This Recombination process is the reverse process of photo ionization and symbolically represented as :

$A^+ + e^- \rightarrow A + hv$

Where,

A^+= positive ion

e^- = an electron or negative ion.

The photon energy released (hv) would be absorbed by a third body C present.

The third body C may be another heavy particle or electron and represented as

$$A^+ + C + e^- \rightarrow A^* + C \rightarrow A + C + hv \frac{d\eta}{dt} = K\eta^2$$

(b) Thermal Ionisation

1. At high electrical stress, the gas filling the gap between the electrodes is heated up.
2. The gases at high temperature some of the gas molecules acquire high kinetic energy.
3. The collision between molecules creates ions due to release of electron from the neutral particles.
4. The electrons and other high speed molecules in- turn collide with each other and release more electrons. Thus the gas gets ionized.

(c)Electron emission due to meta-stable & neutral atoms

1. In the atmosphere, there are some elements or atoms whose life time extends to few seconds, in certain electronic states. Such atoms are called meta-stable atoms.
2. They have high potential energy.
3. Therefore, meta-stable atoms are able to ionize neutral particle.
4. It can be represented by following reaction of intersection:

$A + B^m = A^+ + e^- + B$

Where,

A = the atom to be ionized

B^m = metastable particle

A^+ = positive ion of atom

e^- = negatively charged electron

d) Deionization by Attachment (Electron Detachment)

1. Electrons can combine with neutral atoms or molecules to form negative ions, in certain gases.
2. Some of the Gases have a characteristics that are lacking one or two electrons in their outer surface known as electronegative gases.
3. **Electronegative gases** have very high dielectric strength due to formation of negative ion during deionization process.
4. The reaction represented symbolically as

$$AB + e \rightarrow (AB^-) + hv$$

It may also be happen that the atom AB will be dissociate into A^+ and B^- ion which will be represented by as below

$$AB + e \rightarrow (AB)^* + e \rightarrow A^+ + B^- + e$$

1.3 Townsend's Current Growth Equation, Current Growth in the Presence of Secondary Processes, Townsend's Criterion for Breakdown

Why Townsend's theory…………….?

1. We can measure the probability of secondary electron formation by using Townsend's theory
2. Analysis of 'ionization by collision' is carried out by Townsend's theory
3. It is applicable for primary & secondary ionization.

1.3.1 Townsend's first ionization coefficient (α)

1. **α :** is defined as the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field
2. 'α' depends upon Pressure (P) and Electric field in V/cm (E)
3. **<u>' α 'proportional to (E/P)</u>**

- Let us consider a parallel plate capacitor having gas as in insulating medium and separated by a distance as shown in Fig.

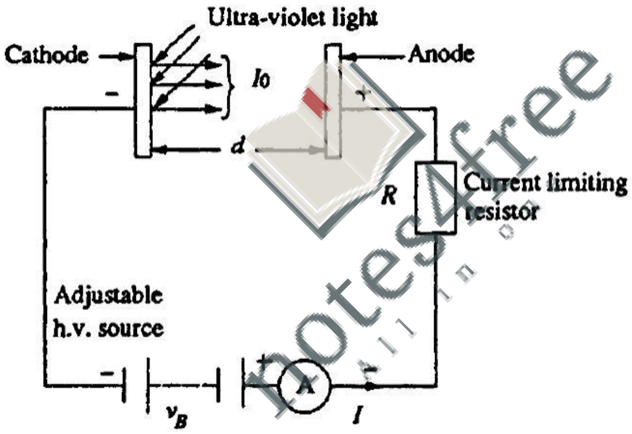
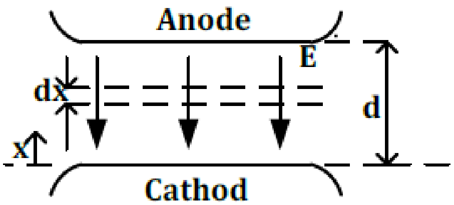


Fig1.2: Parallel plate capacitor



(a) gap arrangment

- Let us assume that **n_0 electrons** are emitted from the cathode.
- When one electron collides with a neutral particle, a positive ion and an electron are formed. This is called an ionizing collision.
- Let α be the average number of ionizing collisions made by an electron per centimeter distance travel in the direction of the field (α depends on gas pressure p and E/p, and is called the Townsend's first ionization coefficient).

- Fig. 1.2 illustrates the breakdown phenomenon of a gas and the growth of current in the gas which is responsible for breakdown.
- The curve has three regions:
    1. Ohmic region
    2. Saturation region
    3. Townsend's discharge region

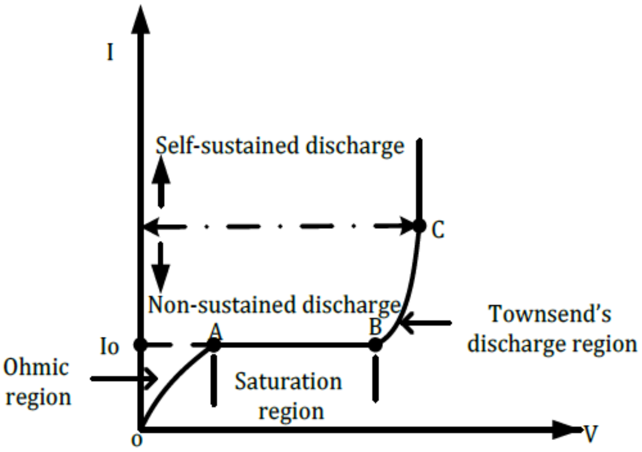


Fig 1.2 : Typical current growth curve In Townsend discharge

- It is observed from the figure that the current at first increases proportionally with the increases in field or voltage. This region is called **ohmic region.**
- After this state, a situation comes when current become constant I_0 even if voltage is increased. The constant current **I_0 is called the saturation current.**
- At still higher voltage, the current increases exponentially.

The exponential increase in current is due to ionization of gas by electron collision with gas molecules.

As the voltage increase, electric field intensity V/d increases and hence the electrons are accelerated more and more and the electron get higher kinetic energy and therefore, knock out more and more electrons.

At any distance x from the cathode, let the number of electrons be n_x.

When these n_x electrons travel a further distance of dx they give rise to ($\alpha n_x dx$) electrons.

$$dn_x = \alpha n_x dx$$

$$\frac{dn_x}{n} = \alpha dx$$

$$\ln n = \alpha x + A \text{..............................(i)}$$

$$(at(x = 0), n_x = n_0)$$

$$\therefore A = \ln n_0 \; put \text{ in equation (i)}$$

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

$$\therefore \ln n - \ln n_0 = \alpha x$$

$$\therefore \ln\left(\frac{n}{n_0}\right) = \alpha x$$

$$\therefore \left(\frac{n}{n_0}\right) = e^{\alpha d}, \text{ at x=d distance,}$$

$$\therefore \text{n} = n_0 e^{\alpha d}$$

The average current in the gap, which is equal to the number of electrons travelling from the above equation per second will be

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

Where $e^{\alpha d}$ =electron avalanche, I_o =initial current Ampere

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Q. **In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8} A at 8 kV at a distance of 0.4 cm between the plane electrodes. Keeping the field constant and reducing the distance to 0.1 cm results in a current of 5.5×10^{-9}A. Calculate Townsend's primary ionization coefficient α.**

Solution: The current at the anode *I* is given by

$$I = I_0 \exp(\alpha d)$$

where I_0 is the initial current and d is the gap distance.
Given,

$$d_1 = 0.4 \text{ cm} \qquad d_2 = 0.1 \text{ cm}$$

$$I_1 = 5.5 \times 10^{-8} A \qquad I_2 = 5.5 \times 10^{-9} A$$

$$\frac{I_1}{I_2} = \exp \alpha(d_1 - d_2)$$

i.e., $$10 = \exp(\alpha \times 0.3)$$

i.e., $$0.3\alpha = \ln(10)$$

$\therefore$ $$\alpha = 7.676/\text{cm . torr}$$

1.3.2 Townsend's Second Ionization Co-efficient

1. The single avalanche process described in the previous section becomes complete when the initial set of electrons reaches the anode.
2. The probability amplification of the electrons being release in the gap by other mechanisms increases, and these new electrons create further avalanches.
3. The other mechanisms are
   (i) The positive ions released may have sufficient energy to cause liberation of electrons from the cathode when they impose on it.
   (ii) The excited atoms or molecules in avalanches may emit photon, and this will lead to the emission of electrons due to photo-emission.
   (iii) The meta-stable particles may diffuse back causing electron emission.
4. The electrons produced by these processes are called secondary electrons.

The secondary ionization coefficient γ is defined in the same way as α , as the net number of secondary electrons produced per incident positive ion, photon, exited particle, or metastable particle, and the total value of γ is the sum of the individual coefficients due to the three different processes, i.e. $\gamma = \gamma_1 + \gamma_2 + \gamma_3$.

γ is called Townsend's secondary ionization coefficient and is a function of the gas pressure p and E/p.

Following Townsend's procedure for current growth, let us assume

n_+ = number of secondary electrons produced due to secondary (γ) processes.

($n_0 + n_+$)= total number of electron leaving the cathode.

The total number of electron n reaching the anode becomes,

$$n = (\mathrm{n}_0 + \mathrm{n}_+)\,\mathrm{e}^{\alpha d} \,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

$$\mathrm{n}_+ = \gamma\left[n - (\mathrm{n}_0 + \mathrm{n}_+)\right]$$

$$n_+ = \gamma n - \gamma n_0 - \gamma n_+$$

$$(1+\gamma)n_+ = \gamma(\mathrm{n} - \mathrm{n}_0)$$

$$\mathrm{n}_+ = \frac{\gamma(\mathrm{n} - \mathrm{n}_0)}{1+\gamma}$$

Substituting n_+ value in equation (i)

$$n = \left[n_0 + \frac{\gamma(\mathrm{n} - \mathrm{n}_0)}{1+\gamma}\right]\mathrm{e}^{\alpha d}$$

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

$$n = \left[\frac{n_0 + \gamma n}{1+\gamma}\right]e^{\alpha d}$$

$$n(1+\gamma) = (n_0 + \gamma n)e^{\alpha d}$$

$$n + \gamma n = n_0 e^{\alpha d} + \gamma n e^{\alpha d}$$

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

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

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

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

$$or\ \mathrm{I} = \frac{I_0 e^{\alpha d}}{\left[1 - \gamma(e^{\alpha d} - 1)\right]}$$

This is Townsend’s current growth equation due to primary and secondary ionization

1.3.3 Limitation of Townsend's theory

Townsend theory or Townsend's mechanism applied to gas-discharge phenomenon was found to have some drawback or limitations.

(i) First drawback is that according to Townsend's theory, the current growth occurs as a result of ionization process only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap.

(ii) Secondary, the Townsend's mechanism predicts the time-lag of the order of 10 $^{-5}$seconds. While in practice, the breakdown was observed to occur at very short time of the order of 10 $^{-8}$ sec.

(iii) Townsend's mechanism predicts the very diffused from of discharge but in practice, it was found to be filament and irregular.

iv) It is applicable for pd value below 1000 torr-cm.

1.4 Condition for Gaseous dielectric breakdown

We know that

$$I=\frac{I_0 e^{\alpha d}}{\left[1-\gamma(e^{\alpha d}-1)\right]}$$

Where, I=current at anode

α =Townsend's first ionization coefficient

γ =Townsend's second ionization coefficient

d = gap-length of electrodes

The current becomes ∞ if

$$1-\gamma\left(e^{\alpha d}-1\right)=0$$

$$\gamma\left(e^{\alpha d}-1\right)=1$$

$$e^{\alpha d}\gg 1$$

$\gamma e^{\alpha d}=1$ defines condition for begining of spark formation.

Three possible condition:

(1) if $\gamma e^{\alpha d}=1$: In this condition, the discharge is said to be Self-sustained because, discharge will sustain itself even if source producing I_0(as shown in fig.)is removed.

(2) if $\gamma e^{\alpha d}>1$: In this case, the ionization produced by successive avalanche is cumulative. The spark discharge grows more rapidly.

(3) if $\gamma e^{\alpha d}<1$: In this condition, the current is not self-sustained. because, removal of source, the current I_0 is only remain constant.

1.5 Breakdown in Electronegative Gases

- Electronegative gases are the gases that have similarity towards electrons. When electron comes into contact with these gas molecules, the gas molecule attracts the electrons and becomes negative ion.
- The gases, which are lacking in one or two electrons in their outer shell are known as **electronegative gases.**
- The most common attachment processes encountered in gases are :
  a. Direct Attachment: In which an electron directly attaches to form a negative ion.

  $$AB + e^- \rightarrow AB^- + hv$$

  b. Dissociative Attachment: In which gas molecules split into their constituent atoms and

  Electronegative atoms from negative ions.

  $$AB + e \rightarrow A + B^- + e$$

- A simple gas of this types is oxygen. Other gases are Sulphur hexafluoride, Freon, carbon dioxide, and fluorocarbons.
- In this gases, ‘A’ is usually Sulphur or carbon atom, and ‘B’ is oxygen atom or one of the halogen atoms or molecules.
- With such gases, the Townsend current growth equation is modified to include ionization and attachment.

An attachment coefficient (η) is defined, similar to α as the number of attaching collisions made by one electron drifting one centimeter in the direction of the filed.

Under these conditions, the current reaching the anode, can be written as

$$I = I_0 \frac{\left[\{\alpha/(\alpha-\eta)\} e^{(\alpha-\eta)d}\right] - \left[\eta/(\alpha-\eta)\right]}{1-\left\{\gamma \frac{\alpha}{(\alpha-\eta)}\left[\left\{e^{(\alpha-\eta)d}\right\}-1\right]\right\}} \text{...(i)}$$

Townsend breakdown criterion for attaching gases can also be find out by equating the denominator in equation (i)

$$\gamma \frac{\alpha}{(\alpha-\eta)}\left[e^{(\alpha-\eta)d} - 1\right] = 1 \text{...(ii)}$$

This shown that for $\alpha > \eta$, breakdown is always possible irrespective of the values of $\alpha, \eta,$ and γ.

If on the other hand, $\eta > \alpha$ equation approaches an asymptotic from with increasing value of d,

$$\gamma\frac{\alpha}{(\alpha-\eta)}=1$$

$$\therefore \gamma\alpha=\alpha-\eta$$

$$\therefore \quad \eta=\alpha-\gamma\alpha$$

$$\therefore \quad \alpha=\frac{\eta}{(1-\gamma)}$$

$$\alpha=\eta \quad (\gamma \text{ is very small } \leq 10^{-4})$$

If the pressure is constant then this condition put the limit of value of E below which no breakdown is possible irrespective of the value of 'd' and the limit value is critical E for that pressure. eg. For SF_6 117V cm^{-1} $torr^{-1}$ at $20^{\circ} C$

1.6 Time Lag of Breakdown

1. Theoretically the mechanism of spark breakdown is considered as a function of ionization processes under **uniform field conditions.**
2. In practical engineering designs, the breakdown due to rapidly changing voltage or impulse voltage is of great importance.
3. Actually there is a time difference in the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself. This time difference is called as the **time lag.**
4. The Townsend criterion for breakdown is satisfied only if at least one electron is present in the gap between the electrodes as in the case of applied d.c. or slowly varying (50Hz a.c.) voltages. This is no difficulty in satisfying this condition.
5. With rapidly varying voltage of short duration ($\approx 10^{-6}$ s), the initiatory electron may not be present in the gap then the breakdown cannot occur due to not available free electron.

i. Statistical time-lag(ts): is defined as the time lapsed between the application of voltage sufficient to cause breakdown and the appearance of initiating electron is called as statistical time lag.

1. The Statistical time lag depends upon the amount of pre-ionization present in the gap.
2. This in turn depends on the size of the gap and the quantity of radiation that produces the primary electrons.
3. The techniques generally used for irradiating the gaps include ultraviolet radiation, radioactive materials and light sources.

ii. Formative time-lag(tf): After the appearance of electron, the time tf required for the ionization process to develop fully to cause to the breakdown of gap is called as formative time-lag.

The formative time lags depend mostly on the mechanism of the avalanche growth in the gap.

iii. Total time-lag (t): is define as the sum total of Statistical time-lag and formative time-lag T= ts + tf

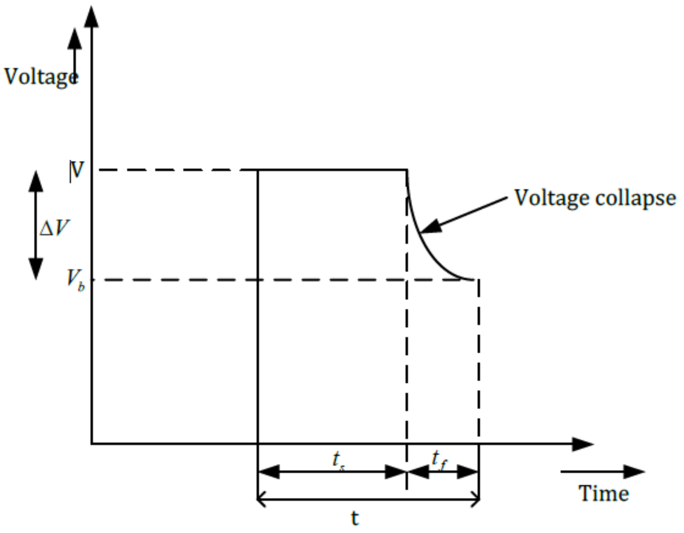


Fig 1.4 : 5Breakdown with a step function voltage pulse

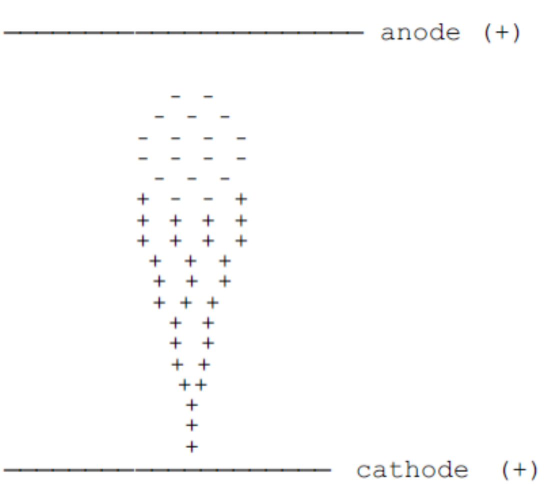
1.7 Streamer or Kanal Mechanism of Breakdown of Spark:

1. The streamer Mechanism of Breakdown is also known as **"<u>Kanal" mechanism of breakdown.</u>**
2. The Streamer theory removes the limitation and drawbacks of Townsend's theory.
3. We know that the charges in between the electrodes separated by a distance d increase by a factor
4. $e^{\alpha d}$ when field between electrodes is uniform
5. This is valid only if we assume that the field $\mathbf{E_0 = V/d}$ is not affected by the space charges of electrons and positive ions.
6. Whenever the concentration exceeds 10^8, the avalanche current is followed by steep rise in current and breakdown of the gap takes place.
7. 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.

Streamer theory of breakdown for gas or Avalanche breakdown :

1. Avalanche breakdown or streamer breakdown is a phenomenon that can occur in both insulating and semiconducting materials.
2. It is a form of electric current multiplication that can allow very large currents within materials & causes dielectric breakdown.
3. Formation of finger like discharge is called as streamer.

"**<u>A streamer discharge</u>**, also known as filamentary discharge, is a type of transient electrical discharge. Streamer discharges can form when an insulating medium (for example air) is exposed to a large potential difference."



Process :

1. Streamer breakdown occur when the dielectric medium is exposed to a high voltage difference.
2. First step is the formation of **avalanche.**
3. Formation avalanche creates **space charge** (collection of charge or cloud of charge).
4. Space charge leads additional electric field.
5. **The electric field** enhance the growth of **new avalanche.**
6. Ionised region grows quickly & expand.
7. Applicable for **non-uniform electric field**
8. **When the energy gained by the electrons greater than lattice ionization potential formation of streamer takes palace. (Condition for streamer breakdown)**
9. Breakdown occur when avalanche exceeds critical size & formation of many avalanche.
10. Streamer ionise the path & production of large current. Breakdown will be occurred.

Detailed Procedure:

Fig. 1.5 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.

A. 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.
B. It can be seen from Fig. 1.5 that the filed at the head of the avalanche is strengthened.
C. The field between the two assumed charge Centre's i.e., the electrons and positive ions is decreased as the field due to the charge centres opposes the main field E0 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.
D. It has been observed that if the charge carrier number exceeds 10^6, the field distortion becomes noticeable.
E. 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 a significance on the discharge phenomenon.
F. 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.**

G. The space charge field, therefore, plays a very important role in the mechanism of electric discharge in a non-uniform gap.

H. This photon falls on the molecules and again electrons are release which is called photoionization. Photoionization of gas molecules is the secondary mechanism of ionization responsible for breakdown.

I. On the whole, it is observed that due to (i)Enhancement of field (ii)Primary ionization (iii) Photoionization

   A. Size of the electron avalanche is gradually increased and the avalanches are transformed into channels of ionization which proceeds towards the anode.

   B. Such channels are called the **<u>steamer (anode streamer).</u>**

   C. Finally the gas breakdown, at the moment of breakdown the avalanche has got specific size which is called **critical size of avalanche**.

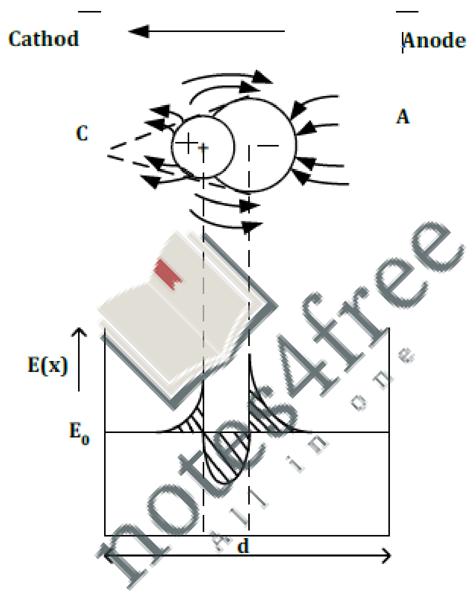


Fig 1.5 : Breakdown with a step function voltage pulse

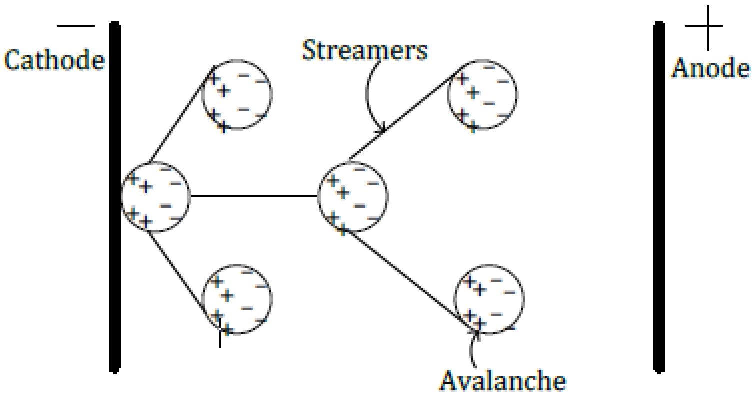


Fig: 1.6 Formation of secondary avalanches due to photo-ionization

Streamer breakdown classification:

- Positive streamer
1. Low electric field
2. Positive streamers propagate in the opposite direction.
- Negative streamer
1. Negative streamers propagate against the direction of the electric field
2. Negative streamers require higher electric fields

Areas of application

1. Ozone production
2. Air purification
3. Plasma medicine

1.8 Paschen's Law

1. Paschen's theory is one of the most important theories related to breakdown of gaseous insulating material.
2. It is widely used in the design of extra high voltage equipments.
3. The gas to be used in the apparatus is matched and studied with operating voltage of the system.
4. The breakdown voltage must be greater than the operating voltage of the system.

Paschen's Law: The law essentially sates that, at higher pressures (above a few torr) the breakdown characteristics of a gap are function (generally not linear) of the product of the gas pressure(p) and gap length(d), usually written as V_b= f(P.d)

The above relation does not imply that breakdown voltage Vb is directly proportional to product the product of p and d.

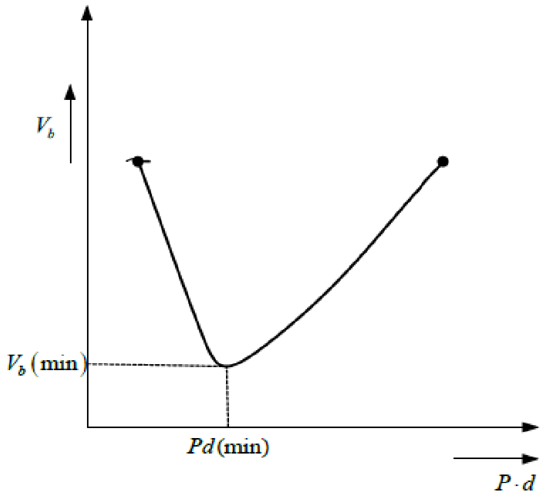
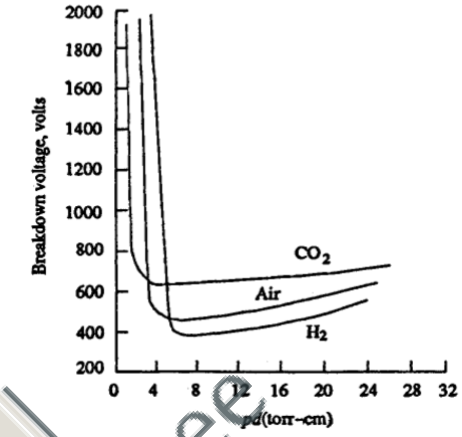


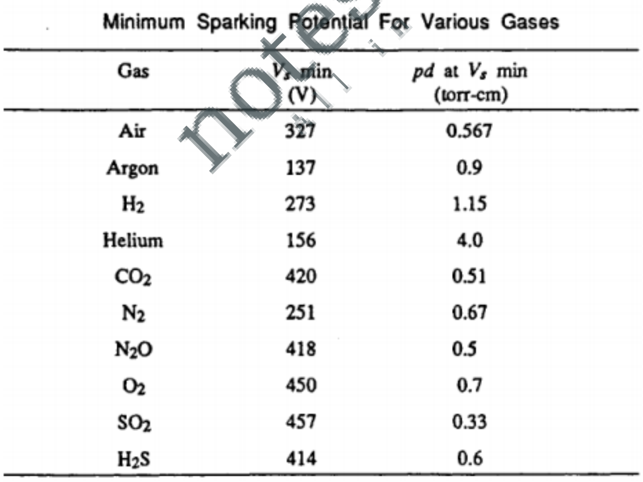
Fig1.7: V_b varies non-linearly with the product Pd

1. Paschen, a scientist studied the breakdown voltage of various gases between the parallel metal plates as the **pressure & distance** where varied.
2. Paschen found that Voltage is a function only of the product of the pressure & gap length(distance).
3. The equation V= f(pd) is called as Paschen's law
4. At higher pressure and air gap length, the breakdown voltage is approximately proportional to product of pressure & air gap.
5. The curve which shows the voltage versus the pressure gap length is called Paschen's curve.
6. Paschen law will be helpful for finding the minimum breakdown voltage of a gas.
7. The minimum pd value for air is 0.567 and 367V.

Paschen's curve



8. Application – based on Paschen's law, we can find the minimum sparking voltage (Breakdown voltage)of various gas.



Minimum Sparking Potential For Various Gases

Gas	V_s min (V)	pd at V_s min (torr-cm)
Air	327	0.567
Argon	137	0.9
H_2	273	1.15
Helium	156	4.0
CO_2	420	0.51
N_2	251	0.67
N_2O	418	0.5
O_2	450	0.7
SO_2	457	0.33
H_2S	414	0.6

1.8.1 Derive an expression for Paschen’s Law

pd(min) and Vb(min):

1. The Paschen's curve, the relationship between V and pd is shown in above graph for three gases CO_2, air and H_2. It is seen that the relationship between V and pd is not linear and has a minimum value for any gas.
2. This means that a breakdown voltage of a uniform field gap is a unique function of the product of p, the gas pressure and d, the electrode gap, for a particular gas and for a given electrode material.

The breakdown criterion in gases is given as

$$\gamma\,[\exp(\alpha d) - 1] = 1$$

where the coefficients α and γ are functions of *E*/*p*, i.e

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right)$$

and
$$\gamma = f_2\left(\frac{E}{p}\right)$$

Also
$$E = \frac{V}{d}$$

Substituting for E in the expressions for a and y and rewriting Equation

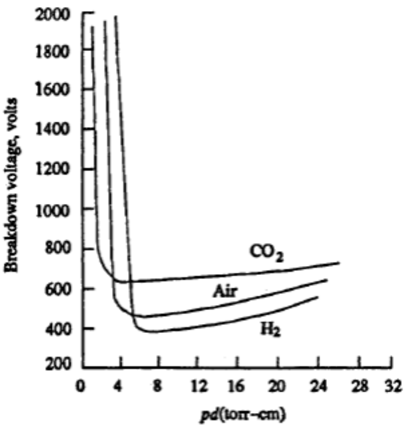
$$f_2\left(\frac{V}{pd}\right)[\exp\left\{pdf_1\left(\frac{V}{pd}\right)\right\} - 1] = 1$$

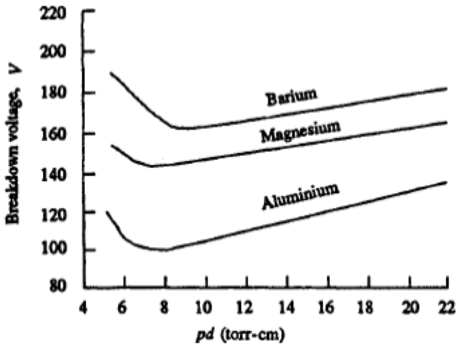
This equation shows a relationship between *V* and *pd*, and implies that the breakdown voltage varies as the product *pd* varies. Knowing the nature of functions f_1 and f_2 we can rewrite

$$V = f(pd)$$

This equation is known as Paschen's law and has been experimentally established for many gases, and it is a very important law in high voltage engineering.

Paschen’s curve for different dielectrics





a) Mathematical Analysis

From the definitions of Townsend's first ionization constant, $\frac{\alpha}{p}$ is the function of $\frac{E}{p}$.

That is
$$\frac{\alpha}{p} = f[E/\mathrm{p}]$$
$$\therefore \alpha = f[E/\mathrm{p}] \times p$$

And Townsend's criterion for Breakdown is

$$\gamma\left[e^{\alpha d} - 1\right] = 1$$
$$\gamma e^{\alpha d} - \gamma = 1$$
$$\gamma e^{\alpha d} = 1 + \gamma$$
$$e^{\alpha d} = \frac{1+\gamma}{\gamma} = \left(1 + \frac{1}{\gamma}\right)$$
$$\ln\left(e^{\alpha d}\right) = \ln\left(1 + \frac{1}{\gamma}\right)$$
$$\alpha \cdot d = \ln\left(1 + \frac{1}{\gamma}\right)$$
$$f\left[\frac{E}{p}\right] \cdot p \cdot d = \ln\left(1 + \frac{1}{\gamma}\right) = K$$
$$f\left(\frac{V_b}{p \cdot d}\right) \cdot p \cdot d = K \quad \left(\because E = \frac{V_b}{d}\right)$$
$$f\left(\frac{V_b}{p \cdot d}\right) = \frac{K}{p \cdot d}$$
$$V_b = f\left(p \cdot d\right)$$

This is called Paschen's law

NOTE:

Penning effect:

1. Paschen's law does not hold good for many gaseous mixtures. A typical example is that of mixture of Argon in neon.
2. A small percentage of Argon in Neon reduces substantially the dielectric strength of pure Neon.
3. In fact, the dielectric strength is smaller than the dielectric strengths of either pure Neon or Argon.
4. The lowering of dielectric strength is due to the fact that the lowest excited stage of neon is meta-stable and its excitation potential (16eV) is about 0.9eV greater than the ionization potential of Argon.

5. The meta-stable atoms have a long life in neon gas, and on hitting Argon atoms there is a very high probability of ionization them.
6. This phenomenon is known as Penning Effect.

1.9 Breakdown in Non-Uniform Fields and Corona Discharges

1. It is an electric discharge mainly occurring at non uniform electric field
2. Visual and audible discharge
3. The corona will occur when the strength of the electric field around a conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects.
4. It is often seen as a bluish (or other color) glow in the air adjacent to pointed metal conductors carrying high voltages, and emits light by the same property as a gas discharge lamp.
5. Potential difference between two electrodes should be greater than threshold value (30kV).

Corona Discharge:

1. 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.
2. However, in non-uniform fields, before the spark or breakdown of the medium takes place, there are many sign in the form of visual and audible discharges. These discharges are known as **Corona discharges**.
3. This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone.
4. Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges.
5. Corona also gives rise to radio interference.
6. 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

$$E_w = 30md\left[1 + \frac{0.301}{\sqrt{dr}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

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

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

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 $^{\circ}C$,d = 1 at 760 torr and 250C. The expressions were found to hold good from atmospheric pressure down to a pressure of several torr.

Fig. 1.8 shows the corona inception and breakdown voltages of the sphere-plane arrangement. From the figure, it is clear that—

(i) For small spacing (Zone–I), the field is uniform and the breakdown voltage depends mainly on the gap spacing.

(ii) In zone–II, where the spacing is relatively larger, the electric field is non-uniform and the breakdown voltage depends on both the sphere diameter and the spacing. (iii) For still larger spacing.

(iii) at large spacing(zone-III) the field is non-uniform and the breakdown is preceded by corona and is controlled only by the spacing. The corona inception voltage mainly depends on the sphere diameter.

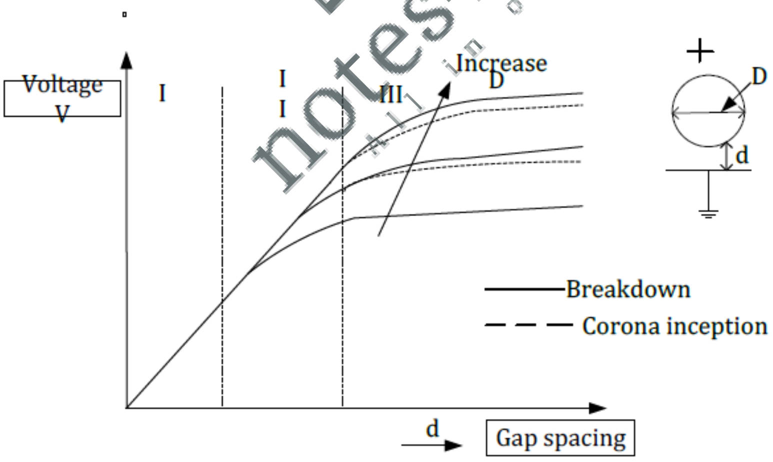


Fig 1.8 :Breakdown and corona inception characteristics for spheres of different diameter in Sphere - plane gap geometry

Results of corona

a. Power loss
b. Hissing noise
c. Ozone formation
d. Chemical activities

Factors affecting corona

a. Air desnsity & Humidity are inversely proportional to corona.
b. Surface conduction is proportional to corona.

Problems associated with corona

a. Ozone (O_3) , Nitric acid & Nitrogen oxide (NO_x) production
b. Electromagnetic interference
c. Audible noise
d. Insulation losses

1.10 Solid Dielectrics

- Solid dielectrics are commonly used all kinds of **electric circuit and devices.**

- Provide insulation for current carrying conductors.

Properties of good solid dielectric material

1. Good mechanical strength
2. Free from gaseous inclusion
3. Free from moisture
4. Resistant to thermal and chemical deterioration
5. Low dielectric loss

Types of breakdown mechanism

(a) Intrinsic or ionic breakdown

1. Electronic breakdown
2. Avalanche breakdown

(b) Electromechanical breakdown

(c) Failure due to treeing and tracking

(d) Thermal breakdown

(e) Electrochemical breakdown

(J) Breakdown due to internal discharges

Types of breakdown mechanism

Intrinsic breakdown

1. Usually a small number of conduction electrons (free electrons) present in the solid dielectric dielectric material.
2. The following reasons such as
   i) Small number of impurities &
   ii) Structural imperfection of dielectric material are responsible for intrinsic breakdown.
3. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of **electric fields and temperatures.**
4. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process.
5. Presence of free electrons which are capable of migration through the lattice of the dielectrics.
6. Process will be repeated until the completion of dielectric breakdown of solid dielectric material.

Types of Intrinsic breakdown

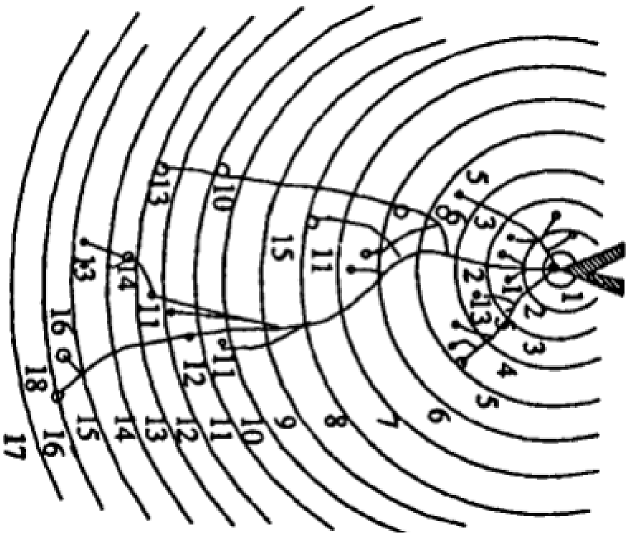
1. Electronic breakdown
2. Avalanche breakdown

(1) Electronic breakdown

1. Due to the presence of large density free electrons in a solid dielectrics
2. Whenever a high voltage is applied, collision between large free electrons will take place.
3. As a result electrons gain energy from the electric field and cross the forbidden energy gap from the valance to the conduction band.
4. Eventually dielectric breakdown takes place

(2) Avalanche or streamer breakdown

1. Similar to the breakdown in gaseous dielectric
2. Avalanche breakdown or streamer breakdown is a phenomenon that can occur in both insulating and semiconducting materials.
3. It is a form of electric current multiplication that can allow very large currents within materials & causes dielectric breakdown.
4. First step is the formation of avalanche.
5. Formation avalanche creates space charge (collection of charge or cloud of charge).
6. Space charge leads additional electric field.
7. The electric field enhance the growth of new avalanche.
8. Ionized region grows quickly & expand.
9. When the energy gained by the electrons greater than lattice ionization potential formation of **avalanche** takes palace. (Condition for avalanche breakdown)
10. Breakdown occur when avalanche exceeds critical size & formation of many avalanche, Breakdown will be occurred



(b) Electro mechanical breakdown

1. Consider the following reasons
   (i) solid dielectrics are subjected to high electric fields
   (ii) electrostatic compressive forces which can exceed the mechanical compressive strength.
2. How do you calculate the 'maximum value of electric field strength' before the breakdown'..?
3. Consider a solid dielectric material
4. The thickness of solid dielectric material=do
5. Applied voltage = V
6. Thickness after the applied voltage = d . That means material is compressed.

$$\varepsilon_0 \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \qquad (1)$$

7. Equation (1) represents electrically developed compressive stress in equilibrium.
   where Y is the Young's modulus. From (1) find the voltage V^2

$$V^2 = d^2\left[\frac{2Y}{\varepsilon_0 \varepsilon_r}\right]\ln\left[\frac{d_0}{d}\right] \qquad (2)$$

- Usually, mechanical instability occurs when

d/do = 0.6 or do/d= 1.67 ***(3)***

- ***Substitute (3) in (2)***

8. The highest apparent electric stress or maximum value of electric field before breakdown is given by

$$E_{\max} = \frac{V}{d_0}$$

$$E_{\max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}}$$

(C) Thermal breakdown

1. Most of the insulation failures in high voltage power apparatus occur due to thermal breakdown.
2. When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material.
3. The current heats up the specimen and the temperature rises.
4. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces.

Mathematical expression

- The heat generated under d.c. stress E is given as

$$W_{d.c.} = E^2\sigma \qquad \text{W/cm}^3 \qquad (1)$$

Where ‘σ’ is the D.C. conductivity of the specimen.

Under A.C. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8\times 10^{12}} \qquad \text{W/cm}^3 \qquad (2)$$

$f =$ frequency in Hz,

$\delta =$ loss angle of the dielectric material, and

The heat dissipated (WT) is given by

$$W_T = C_V \frac{dT}{dt} + \text{div}\,(K \text{ grad } T) \qquad (3)$$

where, $C_V =$ specific heat of the specimen,

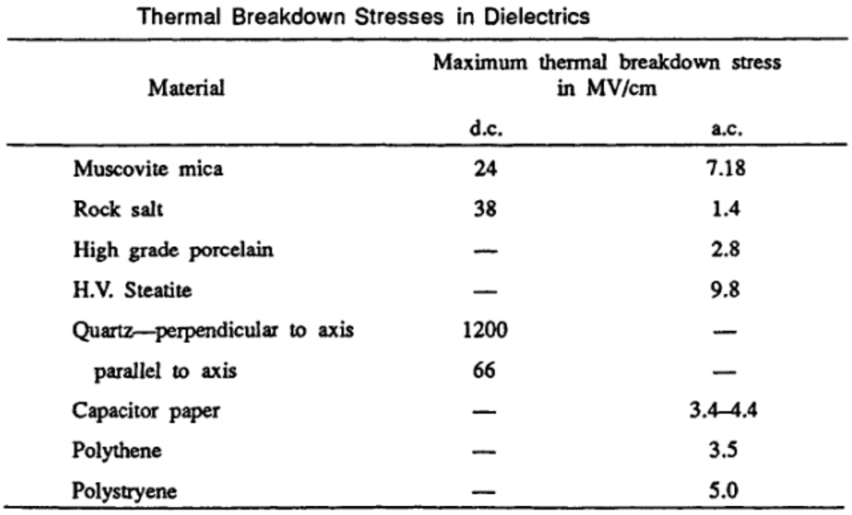
$T =$ temperature of the specimen,

$K =$ thermal conductivity of the specimen, and

$t =$ time over which the heat is dissipated.

- Normally Wac or Wdc equals to WT

- Breakdown occur when Wac or Wdc Greater than WT



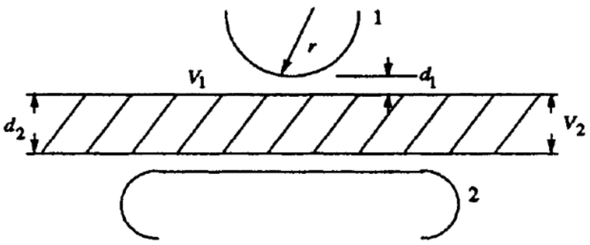
Thermal Breakdown Stresses in Dielectrics

Material	Maximum thermal breakdown stress in MV/cm	
	d.c.	a.c.
Muscovite mica	24	7.18
Rock salt	38	1.4
High grade porcelain	—	2.8
H.V. Steatite	—	9.8
Quartz—perpendicular to axis	1200	—
parallel to axis	66	—
Capacitor paper	—	3.4–4.4
Polythene	—	3.5
Polystryene	—	5.0

c) Breakdown due to treeing & tracking

1. This type of breakdown occurs when a solid dielectric material subjected to electric stress for a long time.
2. Presence of conducting path inside solid dielectric material due to moisture.
3. A mechanism whereby leakage current passes through the conducting path finally leading to the formation of a spark.
4. Insulation deterioration occurs as a result of these sparks, sparks erodes the surface, generates heat & surface becomes dry.
5. The spreading of spark channels said to be **tracking**, in the form of the branches of a tree is called **treeing**
6. As time passes, breakdown 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.
7. Usually, tracking occurs even at very low voltages of the order of about 100 V, whereas treeing requires high voltage.
8. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes.
9. This phenomena happening the layers of Bakelite, paper, cables and similar dielectrics built of laminates.

Breakdown due to treeing & tracking



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

Breakdown due to treeing & tracking

1. When a dielectric material lies between two electrodes as shown in Fig. There is a possibility for two different dielectric media, the air and the dielectric, to come in series.
2. The voltages across the two media are as shown (V_1 across the air gap, and V_2 across the dielectric). The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2}$$

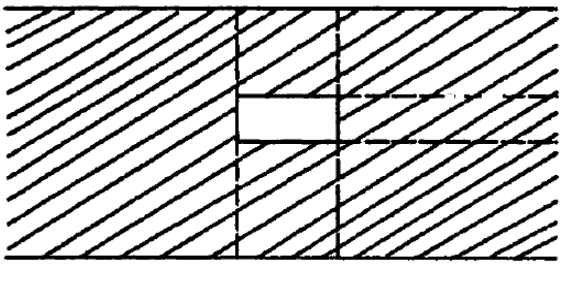
How to prevent treeing & tracking??

1. Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment.
2. The materials chosen should be resistant to tracking.
3. Sometimes moisture repellant greases are used. But this needs frequent cleaning and regressing.
4. Increasing creepage distances should prevent tracking, but in practice the presence of moisture films defeat the purpose.
5. 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 discharge

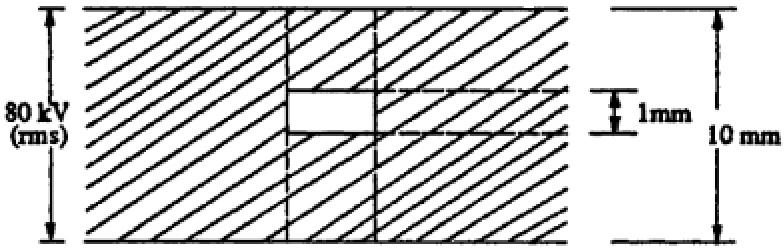
1. Due to voids or cavities present inside the insulating materials.
2. These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation.
3. Hence, the electric field strength in the voids is higher than that across the dielectric.
4. Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur.

Breakdown due to internal discharge



Numerical

A solid dielectric specimen of dielectric constant of 4.0 shown in the figure has an internal void of thickness 1 mm. The specimen is 1 cm thick and is subjected to a voltage of 80 kV (rms). If the void is filled with air and if the breakdown strength of air can be taken as 30 k V (peak)/cm, find the voltage at which an internal discharge can occur



Answer:

- The voltage that appears across the void is given as

$$V_1 = \frac{Vd_1}{\left(d_1 + \frac{\varepsilon_0}{\varepsilon_1} d_2\right)}$$

$d_1 = 1$ mm

$d_2 = 9$ mm

$\varepsilon_0 = 8.89 \times 10^{-12}$ F/m

$\varepsilon_1 = \varepsilon_r \varepsilon_0 = 4.0\,\varepsilon_0$

$$V_1 = \frac{V \times 1}{\left(1 + \frac{9}{4}\right)} = \left(\frac{4V}{13}\right)$$

V- Voltage for the occurrence of Internal discharge.
V1- Voltage require to cause The breakdown in air.

The voltage at which the air void of 1 mm thickness breaks down is 3 kV/mm × 1 mm = 3 kV

$$\therefore V_1 = \frac{13V}{4} = \frac{13 \times 3}{4} = \frac{39}{4}$$

$$= 9.75 \text{ kV (peak)}$$

The internal discharges appear in the sinusoidal voltage 80 sin ωt kV when the voltage reaches a value of 9.75 kV

1.11 Liquid Dielectrics

Properties of **good liquid dielectric material**

1. High density
2. High dielectric strength
3. Should free from moisture
4. Should free from oxidation
5. High resistivity
6. High heat transfer characteristics
7. Chemically stable
8. Applications- Transformer oil, Silicon oil, Synthetic hydro carbon(power cable) & chlorinated hydro carbon

Breakdown in liquid dielectrics

1. Impurities like gas bubbles, suspended particles etc will reason for dielectric breakdown.
2. Breakdown mechanism depends upon nature of electrodes, physical properties of the liquid dielectrics, presence of impurities & gas present in the liquid

Theories supported for dielectric breakdown in **Liquid dielectric material**

1. Suspended particle theory
2. Cavitation & bubble mechanism
3. Electro convection breakdown
4. Electronic breakdown

1. Suspended particle theory

1. Commercial liquids will always contain solid impurities like fibers or dispersed solid particles & gaseous bubbles.
2. Consider the permittivity of liquid dielectrics ε_1 & permittivity of solid impurities being ε_2.
3. $\varepsilon_2 > \varepsilon_1$
4. When the electric field is applied the force is directed towards areas of maximum stress case of the presence of solid particles like paper (solid impurities) in the liquid.
5. On the other hand, if only gas bubbles are present in the liquid ($\varepsilon_2 < \varepsilon_1$).
6. If we consider these impunities (solid or gas) to be spherical particles of radius ‘r’, and if the applied field is ‘E’ then the particles experience a force ‘F’

$$F = \frac{1}{2r^3} \frac{(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2} \text{grad } E^2$$

7. The process of Liquid dielectric breakdown depends up on the size & number of external impurities (either solid or gaseous impurities)
8. If the field exceeds the breakdown strength of the liquids, liquid dielectric breakdown will occur.
9. If the number of impurities 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.

2. Cavitations (Bubble's theory) theory

1. Theory states that dielectric strength of liquid dielectric material depends up on hydrostatic pressure.
2. Hydrostatic pressure proportional to higher electric field strength & it is responsible for changing the phase of liquid dielectrics & results in liquid dielectric breakdown.
3. A kind of small vapor bubble formed inside the liquid dielectrics reason for dielectric breakdown.
4. The following reasons responsible for the bubble's formation in liquid dielectric material - Gas pockets in the electrode surface - Irregular surface of electrodes - Change in temperature & pressure - Dissociation of product by electron collision
5. Condition of breakdown- " Voltage drop along the length of bubble equals to minimum value of voltage in the Paschen's curve".
6. The value of breakdown field is given by

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r}\left\{\frac{\pi}{4}\sqrt{\left(\frac{V_b}{2rE_0}\right)} - 1\right\}\right]^{\frac{1}{2}}$$

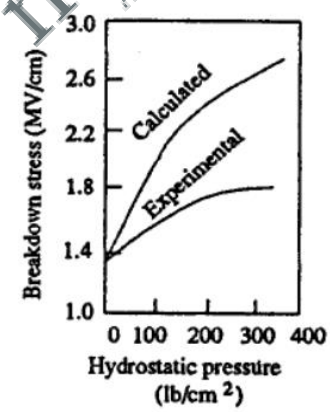
Where σ = surface tension of the liquid, Ɛ1=permittivity of liquid, Ɛ2= permittivity of gaseous bubble, r=initial radios of gas bubble Vb= Voltage drop in the bubble corresponding to the minimum value in the pachen's curve.

1. Breakdown strength depends upon initial size of bubble's, which influence by hydrostatic pressure & temperature.

Limitations

- This theory doesn't mention about the formation of initial bubbles.

- Theoretical & experimental calculation of breakdown strength are different.



3.Electronic breakdown

1. Once the voltage is applied in between two electrodes, electrons are injected to the liquid
2. Electron gains energy from the electric field • Starts the collision process in between other electrons
3. Electrons are accelerated under electric field & would gain a sufficient energy to knock out an electron & beginning the process of avalanche.
4. Condition of breakdown is referred as "Threshold condition"

5. Threshold condition achieved when the energy gained by the electron equals to energy lost during ionisation. • $e*\lambda*E = C* h *\mu$ C=constant

4. Electro-convection breakdown

1. Breakdown in pure insulating fluid under high voltage
2. Charge carrier injected to liquid surface
3. Resulting the formation of space charge region
4. Increase the columbic force
5. Reason for hydrodynamic instability
6. Formation of convection current
7. The interaction between the space charge & the electric field give rise to eddy motion of liquid.

Conclusion

1. It is clear that no single theory can explain all the experimental observation satisfactorily.
2. All the above theories do not consider dependence of breakdown strength on the gap length.
3. Experimental evidence showed that the breakdown strength of liquids depends on the gap length.

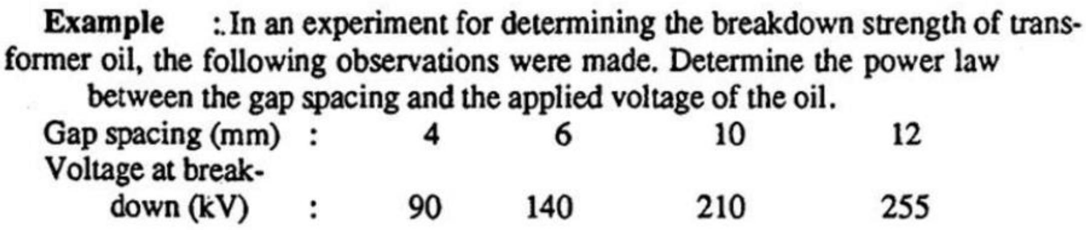
Note : Power law

$$V_b = Ad^n$$

d = gap length,
A = constant, and
n = constant, always less than 1.

1. The above equation is termed as ‘power law’ equation.
2. The breakdown voltage depends on nature of voltage, mode in which the voltage is applied, Gap distance between electrodes & time of application.

Numerical



Example :.In an experiment for determining the breakdown strength of transformer oil, the following observations were made. Determine the power law between the gap spacing and the applied voltage of the oil.

Gap spacing (mm)	:	4	6	10	12
Voltage at breakdown (kV)	:	90	140	210	255

The relationship between the breakdown voltage and gap is normally given as

$$V = Kd^n$$

or, $$\log V = \log K + n \log d$$

i.e., $$\log V - \log K = n \log d$$

or, $$n = \frac{\log V - \log K}{\log d}$$

$$= \text{slope of the straight line as shown in Fig. E.3.1.}$$

$$= 0.947$$

From Fig. E.3.1.,

$$K = 24.5$$

∴ Relationship between the breakdown voltage and the gap spacing for the transformer oil studied is

$$V = 24.5\, d^{0.947}$$

where *V is in kV and d is in mm.*

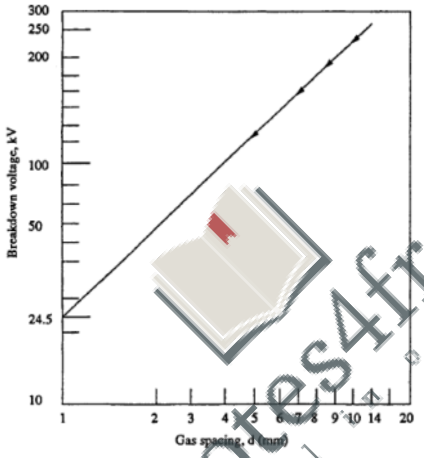


Fig. E.3.1 Breakdown voltage as a function of gap spacing

Note: Solve all numericals solved in class

Course Outcome

At the end of the course the student will be able to:

1. Explain conduction and breakdown phenomenon in gases, liquid dielectrics and in solid dielectrics.

MODULE -2 Generation of High Voltages and Currents

Syllabus

2.1 Generation of High Direct Current Voltages

2.2 Generation of High Alternating Voltages

2.3 Generation of Impulse Voltages

2.4 Tripping and Control of Impulse Generators.

2.5 Generation of Impulse Currents

Course Objectives

To discuss generation of high voltages and currents and their measurement

2. Introduction

Need for HV Generation

- Importance of High voltage DC & AC: High voltage dc require for industry, medical sciences, HVDC transmission etc.
- Applications of high voltage DC: Electrostatic precipitator (EPS) in thermal power plant for the ash handling unit, electrostatic paint, cement industry etc.
- Applications of high voltage AC: Power transmission.

2.1 Generation of High voltage DC

1. Rectifier circuits

2. Van de Graff generators

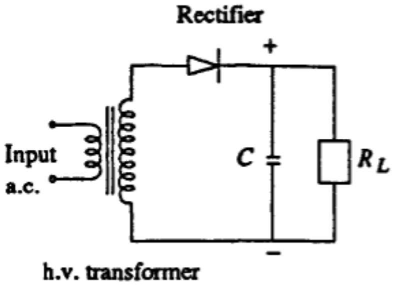
3. Cock croft- Walton type high voltage DC set

1. Rectifier circuits for producing high DC voltages from AC sources.

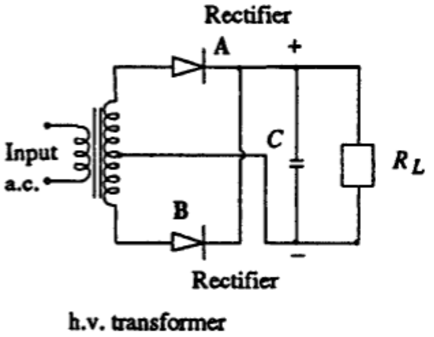
(a) Half wave rectifiers.

(b) Full wave rectifiers.

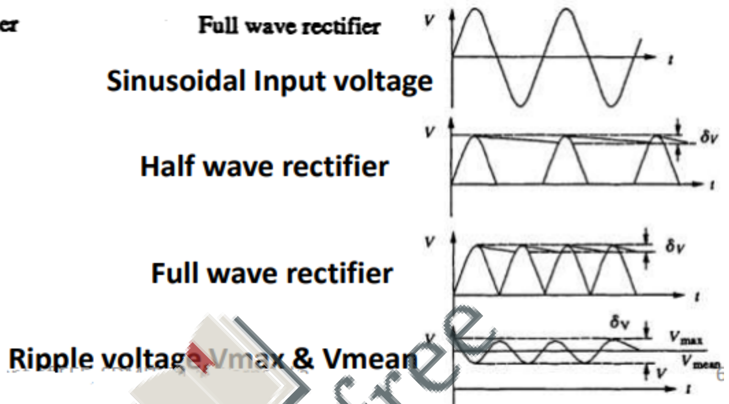
(c) Voltage doubler type rectifiers.

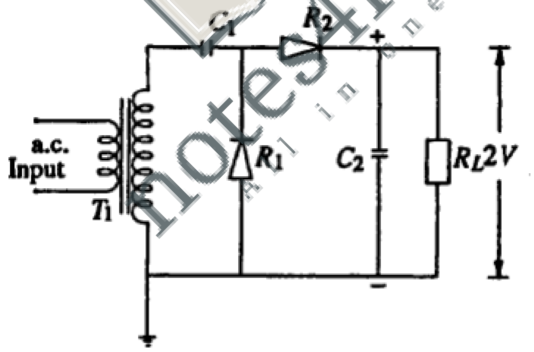


Half wave rectifier

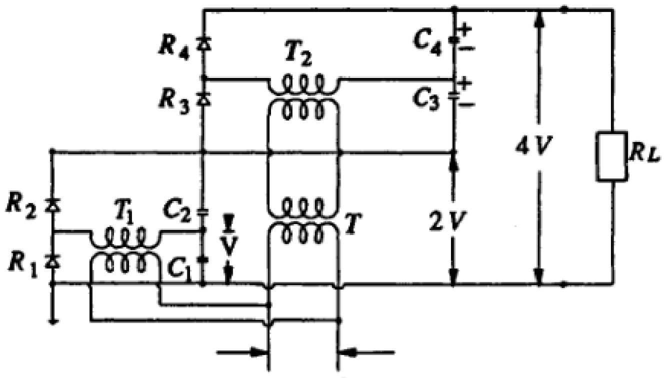


Full wave rectifier

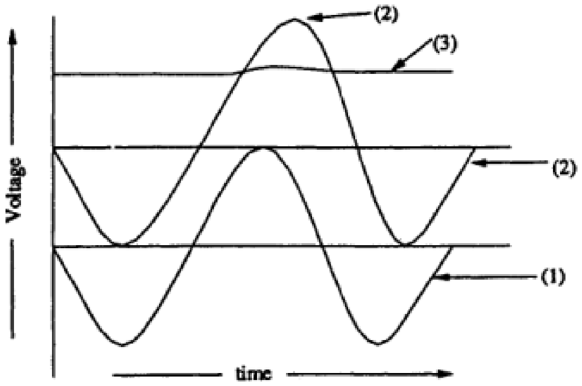




Simple voltage doubler



Cascaded voltage doubler



Waveforms of a.c. voltage and the d.c. output voltage on no-load of the voltage doubler shown in Fig

Fig2.1: 1. AC input voltage waveform 2.AC output voltage waveform without condenser filter

3.AC Output voltage waveform with condenser filter

2.1.1 Van de Graff generators

- It is a type of electrostatic generator
- It generates high potential differences
- Then the generated potential differences are used to speed up the particles like ions etc. So it is a "**particle accelerator**"
- **Application:** Nuclear physics experiments
- The potential difference achieved in modern Van de Graaff generators can reach 5 megavolts.

- A Van de Graaff generator operates by transferring electric charge from a moving belt to a terminal.
- The high voltages generated by the Van de Graaff generator can be used for accelerating subatomic particles to high speeds, making the Van de graaff generator a useful tool for fundamental Nuclear physics research.

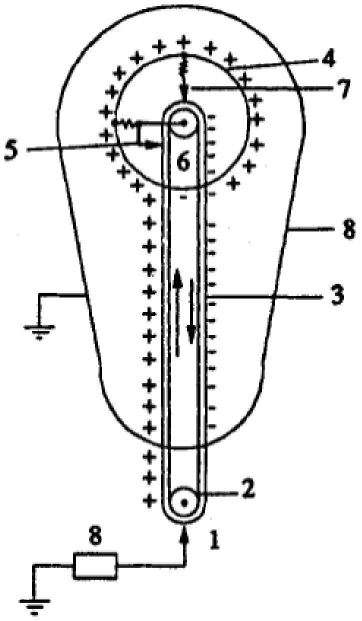
Working of the generator is based on two principles:

1. Discharging action of sharp points, ie., electric discharge takes place in air or gases readily, at pointed conductors.
2. If the charged conductor is brought in to internal contact with a hollow conductor, all of its charge transfers to the surface of the hollow conductor no matter how high the potential of the latter may be.

Applications

1. Accelerating electrons to sterilize food and process materials,
2. Accelerating protons for nuclear physics experiments,
3. Driving X-ray tubes, etc.

Construction



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

1. A simple Van de Graaff-generator consists of a belt of silk, or a similar flexible dielectric material, running over two metal pulleys etc
2. The generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure or in vacuum.
3. Charge is sprayed on to an insulating moving belt from corona points
4. Require the potential of 10 to 100 kV
5. The belt is driven by an electric motor at a speed of 1000 to 2000 rpm
6. Potential of high voltage electrode rises in the rate of

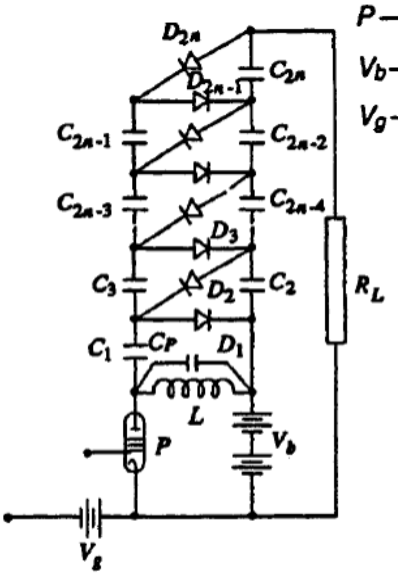
$$\frac{dV}{dt} = \frac{I}{C}\frac{dQ}{dt} = \frac{I}{C} \quad \text{where } I \text{ is the net charging current.}$$

7. The shape of electrodes are spherical
8. The charging of the belt is done by the lower spray points which are sharp needles and connected to a DC source of about 10 to 100 kV, so that the corona is maintained between the moving belt and the needles.
9. Belt has self charging system

2.1.2Cock croft Walton type high voltage DC set.

1. Cascaded voltage multiplier circuits (Voltage Doubler circuit) for higher voltages are cumbersome(difficult) and require too many supply and isolating transformers.
2. It is possible to generate very high DC voltages from single supply transformers by extending the simple voltage doubler circuits.
3. This is simple and compact when the load current requirement is less than one milli ampere, such as for cathode ray tubes, etc.

4. Valve type pulse generators may be used instead of conventional AC supply.
5. The circuit becomes compact



P — Pulse generator
Vb — D.C. supply to pulse generator
Vg — Bias voltage

- DI, D2, C1, C2, and the transformer T are identical as in the voltage doubler circuit.
- The condenser C4 is charged to 4Vmax and C2n to 2nVmax above the earth potential.
- But the volt across any individual condenser or rectifier is only 2Vmax.

Cascaded rectifier unit with pulse generator

D1, D3, D2n-1 conduct: positive half Cycle.
D2, D4, D2n conduct: Negative half cycle.

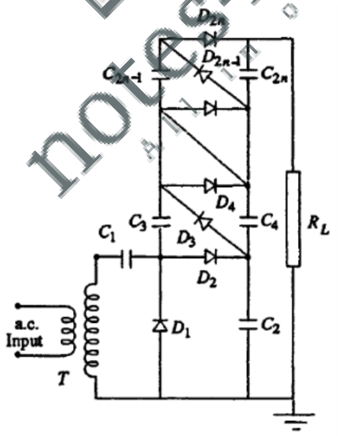


Fig 2.2 :Cockroft Walton voltage multiplier circuit

1. A DC power supply of about 500V applied to the pulse generator, is sufficient to generate a high voltage DC of 50 to 100 kV with suitable number of stages.
2. DI, D2, C1, C2, and the transformer T are identical as in the voltage doubler circuit.
3. The condenser C4 is charged to 4Vmax and C2n to 2nVmax above the earth potential.
4. But the volt across any individual condenser or rectifier is only 2Vmax.
5. D1, D3, D2n-1 conduct: Positive half Cycle. • D2, D4, D2n conduct: Negative half cycle.

1. Calculation of output voltage

- The pulses generated in the anode circuit of the valve P are rectified and the voltage is cascaded to give an output of across the load RL.

$$\text{Output} = 2nV_{\max}$$

- A trigger voltage pulse of triangular waveform (ramp) is given to make the valve switched on and off.

Ripple content & Voltage drop in cock croft- Walton type dc set

2.Calculation of ripple voltage

$$\delta V = \text{ the ripple} = \frac{I_1}{fC_2}$$

I_1 = load current from the rectifier

f = supply frequency,

In general the expression for ripple voltage is given by $\frac{nI_1}{fC}$,

n stages the total ripple will be

$$\delta V_{\text{total}} = \frac{I_1}{fC}[1+2+3\ldots+n] = \frac{I_1}{fC}\frac{n(n+1)}{2}$$

3. Calculation of % ripple

$$\%\ \text{ripple} = \frac{\delta V \times 100}{2nV_{\max}}$$

Where 2nVmax is the output voltage

4. Calculation of voltage regulation

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

$$\text{Voltage regulation} = \left(\frac{\Delta V}{2nV_{\max}}\right)$$

5. Optimum number of stages for minimum voltage drop

1. In addition to the ripple δV, there is a voltage drop Δv which is the difference between the theoretical no load and the on load voltage.

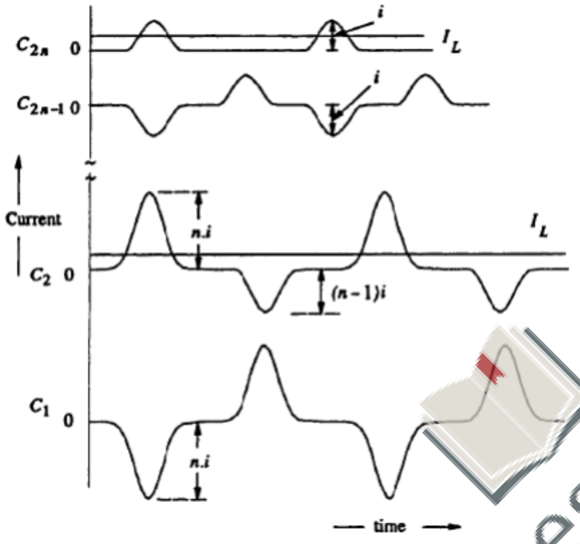
2. optimum number of stages for the minimum voltage drop may be expressed as

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

where I is the load current.

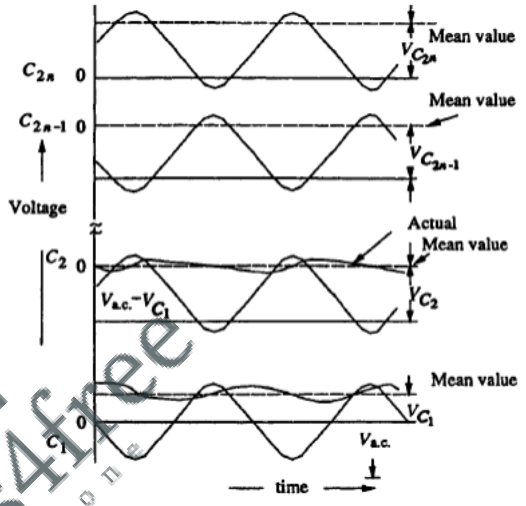
Eg Thus, for a multiplier or a cascaded circuit with
f= 50 Hz, C = 0.1 *micro Farad, Vmax = 100 kV*
and I=5 mA, the number of stages = *10.*

Current and voltage waveforms of cock croft- Walton type high voltage DC Set

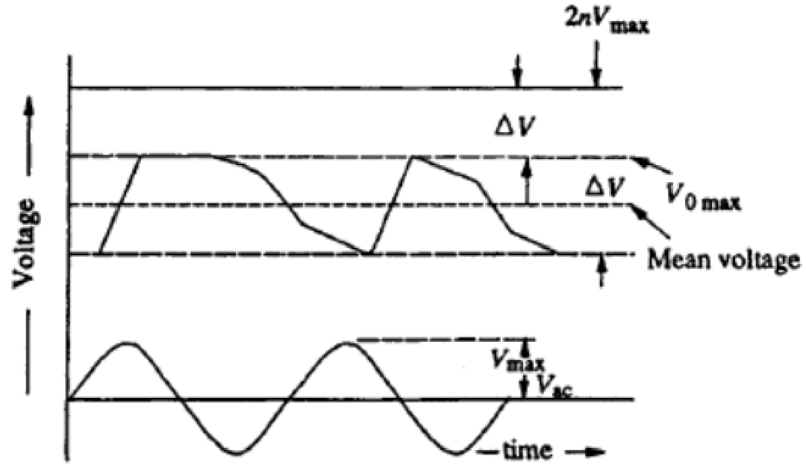


Schematic current waveforms across the first and the last capacitors of the cascaded voltage multiplier circuit

Voltage waveforms across the first and the last capacitors of the cascaded voltage multiplier circuit



Ripple content & Voltage drop in cock croft- Walton type dc set



Ripple voltage δV and the voltage drop ΔV in a cascaded voltage multiplier circuit

2.1.3.Numerical on Cockroft Walton type high voltage DC set

A Cockcroft-Walton type voltage multiplier has eight stages with capacitances, all equal to 0.05 μF. The supply transformer secondary voltage is 125 kV at a frequency of 150 Hz. If the load current to be supplied is 5 mA, find (*a*) the percentage ripple, (*b*) the regulation, and (*c*) the optimum number of stages for minimum regulation or voltage drop.

Solution: (*a*) *Calculation of Percentage Ripple*

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

$$I = 5\text{ mA},\ f = 150\text{ Hz},\ C = 0.05\ \mu\text{F, and } n = 8,$$

$$\therefore \qquad \delta V = \frac{5\times 10^{-3}}{150\times 0.05\times 10^{-6}}\times\frac{8\times 9}{2}$$

$$= 24\text{ kV}$$

$$\%\text{ ripple} = \frac{\delta V\times 100}{2nV_{\max}} = \frac{24\times 100}{2\times 125\times 8}$$

(*b*) *Calculation of Regulation*

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

$$= \frac{5\times 10^{-3}}{150\times 0.05\times 10^{-6}}\left[\left(\frac{2}{3}\times 8^3\right)+\left(\frac{1}{2}\times 8^2\right)-\frac{8}{6}\right]$$

$$= 248\text{ kV}$$

$$\therefore \qquad \text{regulation}\left(\frac{V}{2nV_{\max}}\right) = \frac{248}{2\times 8\times 125} = \frac{124}{1000}$$

$$= 12.4\%$$

(*c*) *Calculation of Optimum Number of Stages* (n_{optimum})

Since $n > 5$,

$$n_{\text{optimum}} = \sqrt{V_{\max} fC/I}$$

$$= \sqrt{\frac{125\times 150\times 0.05\times 10^{-6}\times 10^{+3}}{5\times 10^{-3}}}$$

$$= \sqrt{125\times 1.5}$$

$$= 13.69$$

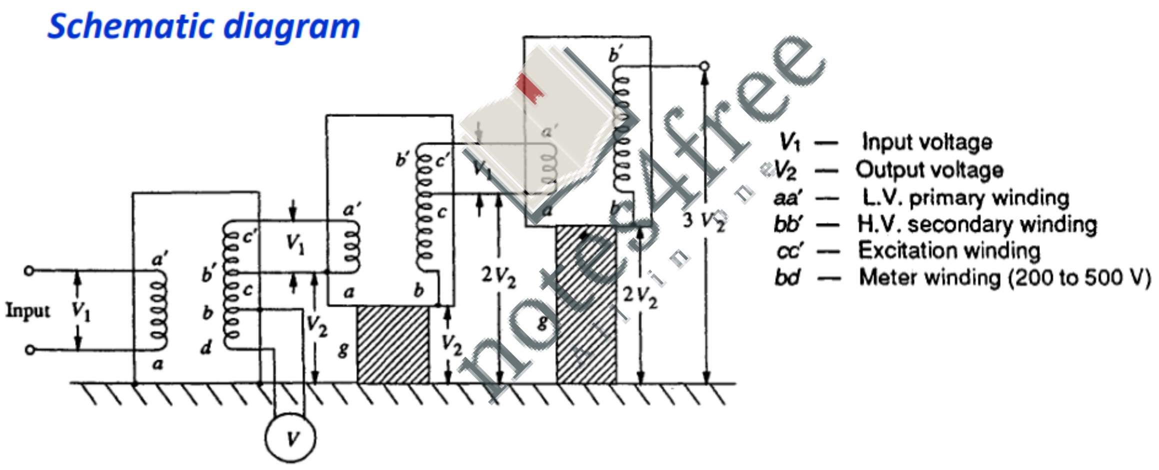
$$= 14\text{ stages}$$

2.2 Generation of HV AC Voltage

Need for Cascade transformer connection

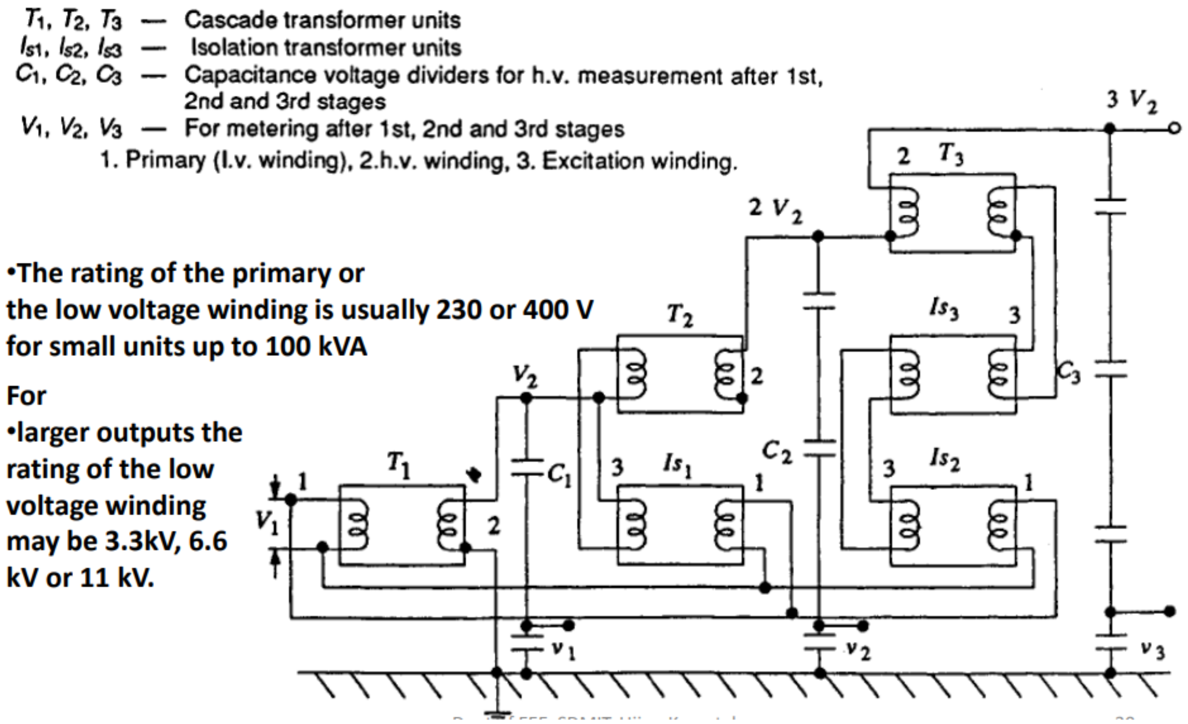
1. When test voltage requirements are less than about 300 kV, a single transformer can be used for test purposes.
2. The impedance of the transformer should be generally less than 5%
3. Transformer must be capable of giving the short circuit current for one minute or more depending on the design.
4. Third winding known as meter winding is provided to measure the output voltage.
5. For higher voltage requirements, a single unit construction becomes difficult and costly due to insulation problems.
6. Transportation and arranging of large transformers become difficult.
7. These drawbacks are overcome by series connection or cascading of the several identical units of transformers, wherein the high voltage windings of all the units effectively come in series.

Schematic diagram of cascade transformer for HVAC generation



Cascade transformer connection (schematic)

1. The first transformer is at the ground potential along with its tank.
2. The second transformer is kept on insulators and maintained at a potential of V2, the output voltage of the first unit above the ground.
3. The high voltage winding of the first unit is connected to the tank of the second unit.
4. The low voltage winding of this unit is supplied from the excitation winding of the first transformer, which is in series with the high voltage winding of the first transformer at its high voltage end.
5. The rating of the excitation winding is almost identical to that of the primary or the low voltage winding



T_1, T_2, T_3 — Cascade transformer units
I_{s1}, I_{s2}, I_{s3} — Isolation transformer units
C_1, C_2, C_3 — Capacitance voltage dividers for h.v. measurement after 1st, 2nd and 3rd stages
V_1, V_2, V_3 — For metering after 1st, 2nd and 3rd stages
1. Primary (l.v. winding), 2.h.v. winding, 3. Excitation winding.

- The rating of the primary or the low voltage winding is usually 230 or 400 V for small units up to 100 kVA

For

- larger outputs the rating of the low voltage winding may be 3.3kV, 6.6 kV or 11 kV.

6. Supply to the units can be obtained from a motor-generator set or through an induction regulator for variation of the output voltage.
7. Isolating transformers IS1,IS2 and IS3 & are 1:1 ratio transformers
8. They are insulated to their respective tank potentials and are meant for supplying the excitation for the second and the third stages at their tank potentials
9. Power supply to the isolating transformers is also fed from the same AC input.

Advantages of cascade connection

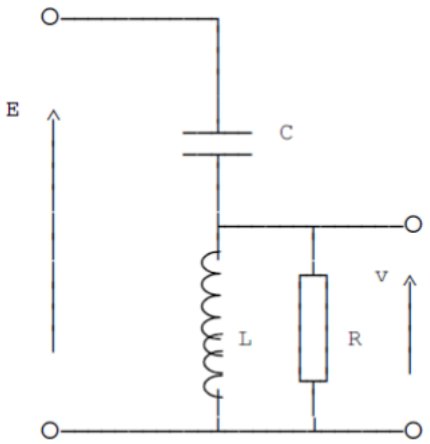
1. Natural cooling is sufficient
2. Transformers are light and compact
3. Ease of transportation & assembly
4. Construction is similar to the isolating transformer & cascaded unit
5. Either star or delta connection are possible

Draw backs

1. More space requirement and expensive

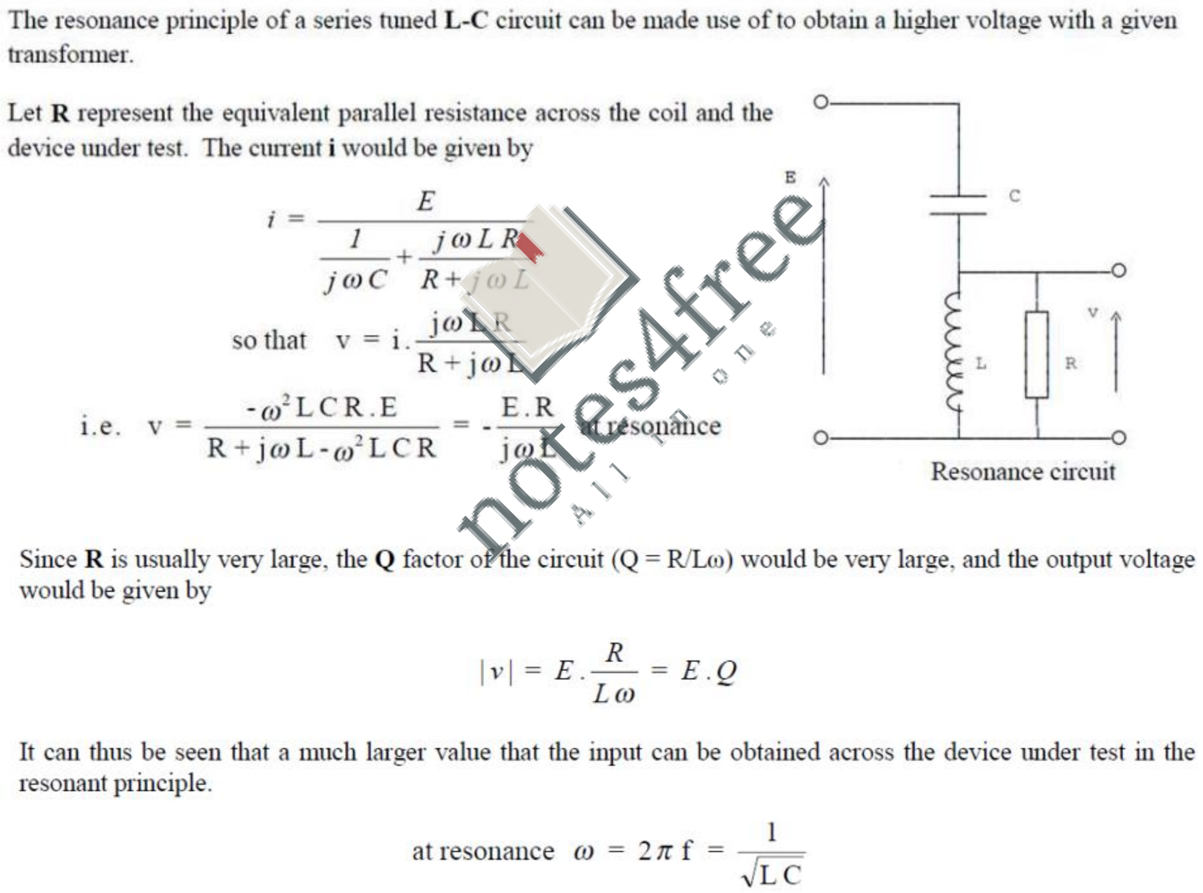
2.2.1 Resonant Circuit

The resonance principle of a series tuned L-C circuit can be made use of to obtain a higher voltage with a given transformer.



Resonance circuit

Basic principle of Resonant circuit



The resonance principle of a series tuned **L-C** circuit can be made use of to obtain a higher voltage with a given transformer.

Let **R** represent the equivalent parallel resistance across the coil and the device under test. The current **i** would be given by

$$i = \frac{E}{\frac{1}{j\omega C} + \frac{j\omega L R}{R + j\omega L}}$$

$$\text{so that} \quad v = i \,.\, \frac{j\omega L R}{R + j\omega L}$$

$$\text{i.e.} \quad v = \frac{-\omega^2 L C R . E}{R + j\omega L - \omega^2 L C R} = -\frac{E . R}{j\omega L} \quad \text{at resonance}$$

Resonance circuit

Since **R** is usually very large, the **Q** factor of the circuit (Q = R/Lω) would be very large, and the output voltage would be given by

$$|v| = E \,.\, \frac{R}{L\omega} = E \,.\, Q$$

It can thus be seen that a much larger value that the input can be obtained across the device under test in the resonant principle.

$$\text{at resonance} \quad \omega = 2\pi f = \frac{1}{\sqrt{LC}}$$

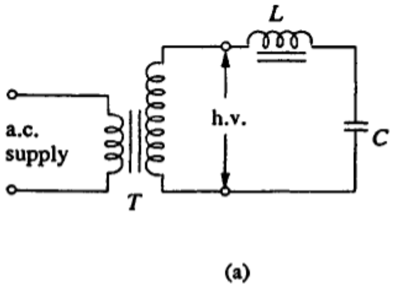
2.2.2 Resonant Transformers

1. resonant transformer, an electrical component which consists of two high Q coils wound on the same core with capacitors connected across the windings to make two coupled LC circuits.
2. Resonant transformer is one of the best choice for high voltage generation which operates on resonance phenomenon (XL = Xc).
3. In resonance condition, the current through test object is very large and that is limited only by the resistance of the circuit.
4. The waveform of the voltage across the test object will be purely sinusoidal.

Applications of Resonant Transformer:

1. This principle is utilized in testing at very high voltages and on occasions requiring large current outputs such as cable testing , dielectric loss measurements, partial discharge measurements, etc.

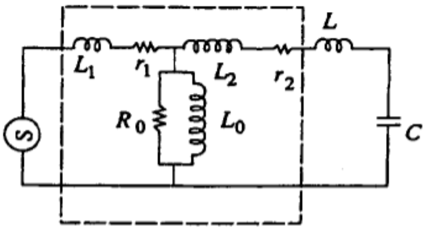
Series Resonant Transformers



(a)

Fig. 6.12a Transformer

T — Testing transformer
L — Choke
C — Capacitance of h.v. terminal and test object
L_0 — Magnetizing inductance



(b)

Fig. 6.12b Equivalent circuit

L_1, L_2 — Leakage inductances of the transformer
r_1, r_2 — Resistances of the windings
R_0 — Resistance due to core loss

1. The equivalent circuit of HV testing circuit consists of a)leakage reactance of the winding, b)winding resistance, c)magnetizing reactance, d)shunt capacitance across the output
2. It is possible to have a series resonance at power frequency w, if

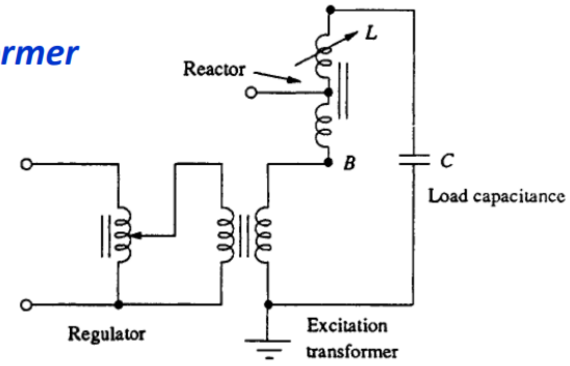
$$\boxed{(L_1+L_2)=1/\omega C}$$

3. During the resonance condition current in the test object is very large and is limited only by the resistance of the circuit.
4. The magnitude of the voltage across the capacitance C of the test object will be

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

5. Q factor of the circuit and gives the magnitude of the voltage multiplication across the test object under resonance conditions.
6. The input voltage required for excitation is reduced by a factor 1/2, and the output kVA required is also reduced by a factor 1/Q.
7. The secondary power factor of the circuit is unity.

Series Resonant transformer



Series resonant a.c. test system

Ratings: Regulator : 10 – 100 kVA
Excitation transformer : 10 – 100 kVA with an output voltage of about 10 kV.
Reactor voltage – each unit up to 300 kV.

1. A voltage regulator of either the auto-transformer type or the induction regulator type is connected to the supply mains.
2. The secondary winding of the exciter transformer is connected across the H.V reactor, L, and the capacitive load C.
3. The inductance of the reactor L is varied by varying its air gap and operating range is set in the ratio 10 : 1.
4. Capacitance C comprises of the capacitance of the test object, capacitance of the measuring voltage divider, capacitance of the high voltage bushing etc.
5. The Q-factor obtained in these circuits will be typically of the order of 50.

Advantages of series resonant circuit

1. It gives an output of pure sine wave.
2. Power requirements are less (5 to 10% of total kVA required).
3. No high-power arcing and heavy current surges occur if the test object fails, as resonance ceases at the failure of the test object.
4. Cascading is also possible for very high voltages.
5. Simple and compact test arrangement.
6. No repeated flashovers occur in case of partial failures of the test object and insulation recovery

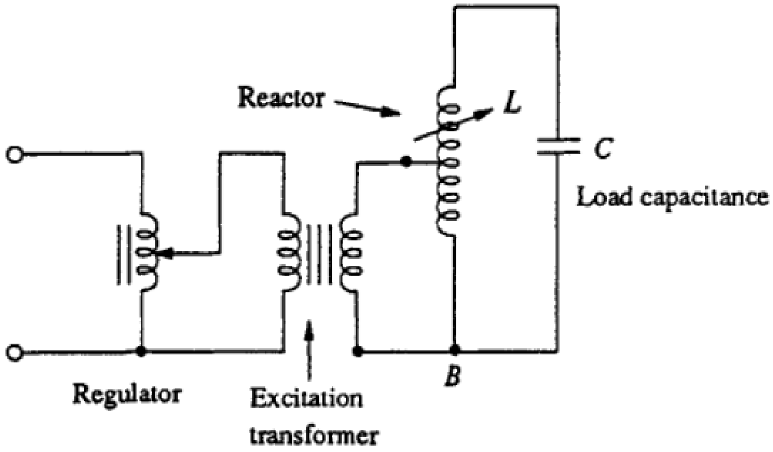
Disadvantages of series resonant circuit

1. Requirements of additional variable chokes capable of withstanding the full test voltage and the full current rating

2.2.3 Parallel Resonant Transformer

1. In the parallel resonant mode the high voltage reactor is connected as an auto-transformer and the circuit is connected as a parallel resonant circuit.
2. The advantage of the parallel resonant circuit is that more stable output voltage can be obtained along with a high rate of rise of test voltage.
3. Independent of the degree of tuning and the Q-factor.

4. Single unit resonant test systems are built for output voltages up to 500 kV, while cascaded units for outputs up to 3000 kV, 50/60 Hz are available.



Parallel resonant a.c. test system

Numerical on Parallel Resonant circuit

Example : A 100 kVA, 400 V/250 kV testing transformer has 8% leakage reactance and 2% resistance on 100 kVA base. A cable has to be tested at 500 kV using the above transformer as a resonant transformer at 50 Hz. If the charging current of the cable at 500 kV is 0.4 A, find the series inductance required. Assume 2% resistance for the inductor to be used and the connecting leads. Neglect dielectric loss of the cable. What will be the input voltage to the transformer ?

Solution

The maximum current that can be supplied by the testing transformer is

$$\frac{100\times 10^3}{250\times 10^3}\,0.4\ \text{A}$$

$X_C =$ Reactance of the cable is

$$\frac{V_C}{I} = \frac{500\times 10^3}{0.4} = 1250\ \text{k}\Omega$$

$X_L =$ Leakage reactance of the transformer is

$$\frac{\%X}{100}\times\frac{V}{I} = \frac{8}{100}\times\frac{250\times 10^3}{0.4} = 50\ \text{k}\Omega$$

At resonance, $X_C = X_L$.

Hence, additional reactance needed

$$= 1250 - 50 = 1200\ \text{k}\Omega$$

Inductance of additional reactance (at 50 Hz frequency)

$$\frac{1200 \times 10^3}{2\pi \times 50} = 3820\ \text{H}$$

R = Total resistance in the circuit on 100 kVA base is 2% + 2% = 4%.

Hence, the ohmic value of the resistance

$$= \frac{4}{100} \times \frac{250 \times 10^3}{0.4} = 25\ \text{k}\Omega$$

Therefore, the excitation voltage E_2 on the secondary of the transformer

$$\begin{aligned} &= I \times R \\ &= 0.4 \times 25 \times 10^3 \\ &= 10 \times 10^3\ \text{V or } 10\ \text{kV} \end{aligned}$$

The primary voltage or the supply voltage, E_1

$$\begin{aligned} &= \frac{10 \times 10^3 \times 400}{250 \times 10^3} \\ &= 16\ \text{V} \end{aligned}$$

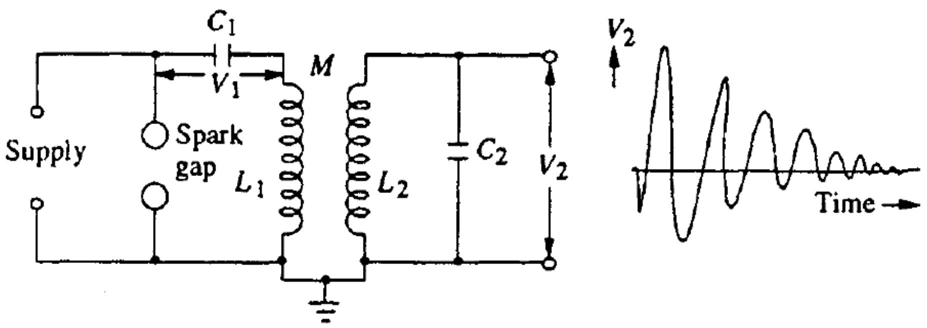
$$\text{Input kW} = \frac{16}{400} \times 100 = 4.0\ \text{kW}$$

2.2.4 Tesla coil

1. Tesla coil is an electrical resonant transformer circuit designed by inventor Nikola Tesla.
2. It is Used to generate or produce high voltage, low current & high frequency AC electricity.
3. High frequency transformer is required.
4. The commonly used high frequency resonant transformer is the Tesla coil.
5. Tesla coil is a doubly tuned resonant circuit.
6. The primary voltage rating is 10 kV and the secondary may be rated to as high as 500 to 1000 kV.
7. Output frequency range: 50kHz to 1 MHz.
8. Damped oscillations can be obtained by using Tesla Coil.

Applications:

1. X-ray generation, experiment in electrical Lighting etc



(a) Equivalent circuit (b) Output waveform

1. The primary is fed from an AC supply through the condenser C1.
2. A spark gap G connected across the primary is triggered at the desired voltage V, which induces high self excitation in the secondary.
3. Spark gap G act as a switch of the circuit.
4. 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.
5. The output voltage V is a function of the parameters LI, L2, C1, C2 and the mutual inductance M.
6. Usually, the winding resistances will be small and contribute only for damping of the oscillations.

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

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

Where

$$\sigma^2 = 1 - \frac{M^2}{L_1 L_2} = 1 - K^2$$ K = coefficient of coupling between the windings L1 and L2

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

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

The *peak amplitude* of the secondary voltage V2 can be expressed as

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

Where ,

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

$$a = \frac{L_2C_2}{L_1C_1} = \frac{W_1^2}{W_2^2}$$

1. 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.
2. 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

$$W_1 = \frac{1}{2}\eta\, C_1V_1^2 = (\tfrac{1}{2}C_2V_2^2)$$

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

Advantages of Tesla coil

1. The absence of iron core in transformers and hence saving in cost and size.
2. pure sine wave output (Less wave form distortion).
3. Slow build-up of voltage over a few cycles and hence no damage due to switching surges
4. Uniform distribution of voltage across the winding coils due to subdivision of coil stack into a number of units.

2.3 Generation of Impulse Voltages

What is Impulse Voltage

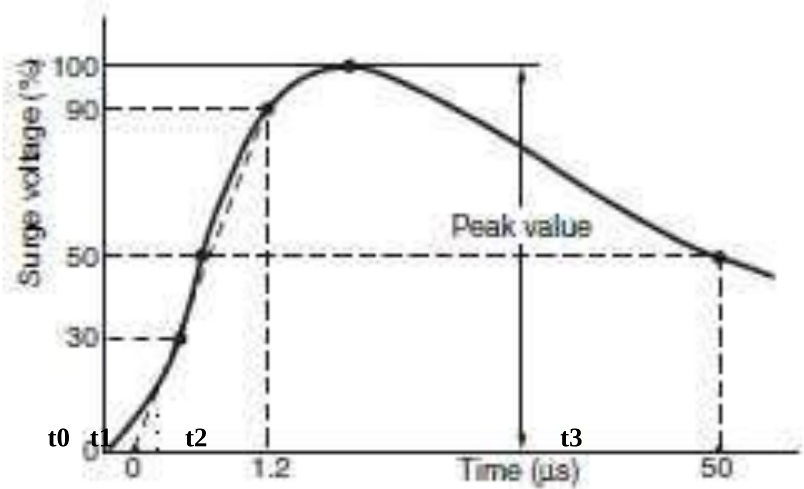
"Impulse voltage is a unidirectional voltage with no appreciable oscillation. It rises rapidly to a maximum value and falls more or less rapidly to zero."

A unidirectional voltage that rapidly rises to a peak value and then drops to zero more or less rapidly. Also known as ***pulse voltage.***

Why Impulse Voltage?

To *study the effect of transient over voltages* generated by lightning or switching operations on the system.

Representation of Impulse Wave



Wave front = 1.5*(t2-t1)

Wave tail = t3-t0

t2 is the time taken to reach 90% of peak value

t1 is the time taken to reach 10% of peak value

a) Impulse Voltage

1. Maximum value is called *peak value* of impulse voltage.
2. If an impulse voltage develops without causing flashover or puncture is called ***full impulse voltage.***
3. Due to flash over or puncture sudden collapse of impulse voltage will occur and it is called as ***chopped impulse voltage.***

b) Wave front & Wave tail

A full impulse voltage consists of both *wave front* and *wave tail.*

1. ***Wave front-*** Time taken by the wave to reach its maximum value starting from zero value.
    - ***Since it is*** difficult to identify the *wave front* ,Wave front is considered as *1.5 times (t2-t1)*
    - Where *t2* is the *time taken to reach 90% of peak value*
    - *t1* is the *time taken to reach 10% of peak value*
    - *(t2-t1)* is about 80% of wave front time

2. ***Wave tail-*** Time measured between the *nominal starting point t0* and the point on the wave tail where the voltage is 50% of peak value.
    - wave tail time (t3-t0)
    - Part of a signal-wave envelope (in time or distance) between the steady-state value (or crest) and the end of the envelope.

c) Standards for impulse voltage

Three standards

1. **BSS & ISS standard**
2. **American Standard Association**
3. **IEC standard**

1. ***BSS and ISS standard***

- *Standard wave shape* specified *(1/50) microseconds* wave.

  i.e a *wave front of 1 micro second* and *wave tail of 50 micro seconds.*

- Tolerance is not more than +50% or -50% on the duration of the wave front.
- 20% on the time to half value on the wave tail is allowed.
- *Complete specification* of the wave is *100kV, (1/50) microseconds* , where *100kV* is the *peak value of the wave*

2. *American Standard Association*

- *Wave shape* recommended by American standard is *1.5/40 microseconds.*
- Permissible variation *0.5 microseconds on the wave front* and *+10 or -10 microseconds for wave tail.*
- The wave front time is taken as 1.67 times the time taken by the wave to rise from 30% to 90% of its peak value.
- Wave tail time is computed same as that of BSS and ISS standard

3. *IEC (International Electro technical Commission)*

- The standard impulse wave shape belonging to 1.2/50µs.
- Should withstand higher voltage (above 220kV).

d) Important Definitions Related to Impulse Voltage (Types of impulse Voltage)

1. Chopped wave

- If an impulse voltage is applied to a piece of insulation a flash over or puncture occurs and sudden collapse of impulse voltage is called *chopped wave.*
- If the chopping takes place front part of the wave is called front chopped wave

2. Impulse puncture voltage

- Peak value of impulse voltage which cause the puncture of the material.

3. Impulse flash over voltage

- When impulse voltage applied to the insulating material flash over may or may not occur.
- If the *flashover occurs* more than *50% of number of applications,* then it is called as *impulse flash over voltage.*
- *Impulse flash over voltage* depends *polarity, duration of wave front & wave tail and nature of material.*

IMPULSE GENERATOR

2.3.1 Analysis of single stage impulse generator-expression for Output impulse voltage

"An **impulse generator** is an electrical apparatus which produces very short high-voltage or high-current surges"

It can be classified into two types

a) Impulse voltage generators

b) Impulse current generators.

Basic impulse generator

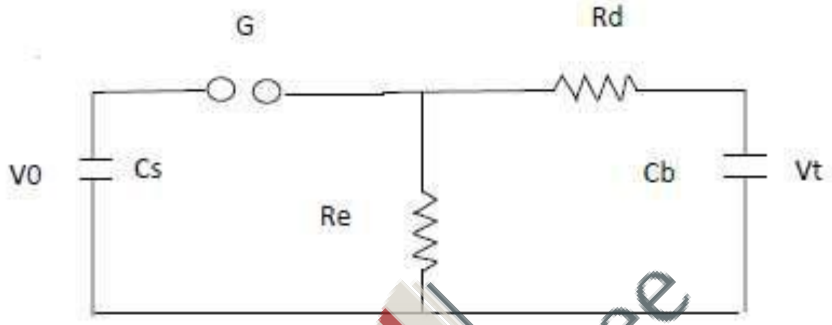


Fig. 2. Basic circuit of single stage impulse generator

a) Why impulse Generator

1. *Impulse generator* produces *high impulse voltage.*
2. High impulse voltages are used to test the *strength of electric power equipment* against lightning and switching surges.
3. *Steep-front impulse* voltages are sometimes used in *nuclear physics experiments.*
4. High impulse currents are needed for *tests* on equipment such as *lightning arresters.*
5. Fuse testing
6. Technical applications such as lasers, thermonuclear fusion, and plasma devices.

b) Basic Impulse Generator

1. An impulse generator essentially consists of a *capacitor* which is *charged to the required voltage* and *discharged through a circuit.*
2. The circuit parameters can be adjusted to give an impulse voltage of the desired shape.
3. *Cs* is charged from a dc source *until the spark gap G breaks down.*
4. The voltage is then impressed upon the object under test of capacitance Cb.
5. The *wave shaping resistors Rd and Re control the front and tail* of the impulse voltage available across Cb respectively.
6. *c)Overall the wave shape* is determined by the *values of the generator capacitance (Cs)* and the load capacitance (Cb), and the wave control resistances Rd and Re.
7. The output voltage waveform can be defined by

$$v(t) = \frac{V_0}{C_b R_d(\alpha - \beta)}(e^{-\alpha t} - e^{-\beta t}).$$

Where, v(t) instantaneous output voltage, Vo DC charging voltage, , roots of the characteristics equation, which depends on the parameters of the generator. Where

$$\alpha = \frac{1}{R_d C_b}, \quad \beta = \frac{1}{R_e C_z}$$

c) Classification of Impulse Voltage Generator

1. Single Stage Impulse Generator

2. Multi Stage Impulse Generator

d) (Marx generator)

Single stage Impulse Generator

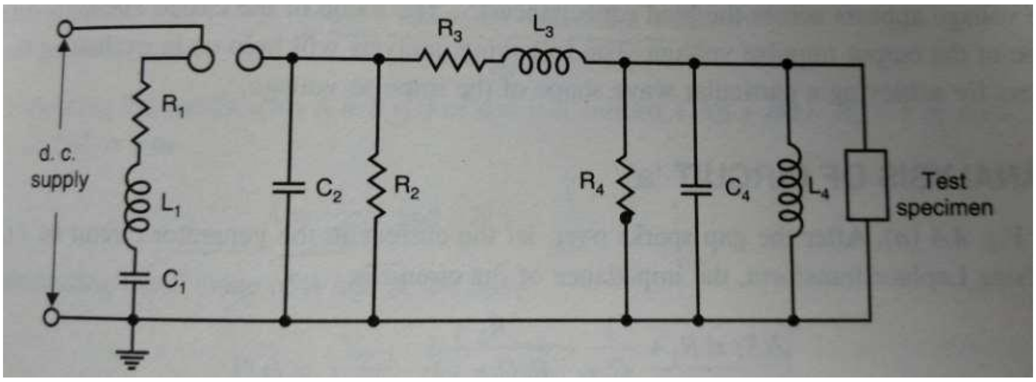


Fig: Single stage Impulse Generator Circuit

1. *The spark gap* act as voltage limiting & voltage sensing switch.
2. The apparatus which produces the *required voltages* is the **impulse generator.**

3. In high voltage engineering, an impulse voltage is normally a *unidirectional voltage* which rises quickly without appreciable oscillations, to a peak value and then falls less rapidly to zero.

Importance of each elements in impulse generator circuit

1. Capacitor (C1)-

- C1 is the capacitance of generator *charged from a dc source* to a suitable voltage.
- It will *discharge through the* ***space gap.***
- If the generator is single stage C1 is enough.

In the case of *multistage impulse generator* group of capacitor connected in **parallel** and **discharged in series.**

2. Inductor (L1)

- It is used for the inductance of the generator.
- The leads of inductor is connecting to the generator.
- It consists of Small value.

3. Resistor (R1)

- Used for **Damping purpose**
- For **Output voltage / Output waveform control.**

4. L3 and R3

- These are external elements
- connected to the generator for the waveform control/shape

5. R2 and R4

- To Control the waveform duration -R4 serve as a potential divider .

6. C2 and C4

- Capacitance to the earth of high voltage components and leads.

7. C4

- Includes the capacitance of the test object -load capacitance
- Hold the voltage to produce required value of wave shape.

8. L4

- Inductance of test object
- Influence the waveform

9. Grounding

- One terminal of impulse generator is solidly grounded.
- The polarity of output voltage can be changed by changing the polarity of dc charging voltage.

Performance parameters of single stage impulse generator

1. Efficiency $\eta = \frac{1}{1 + C2/C1}$

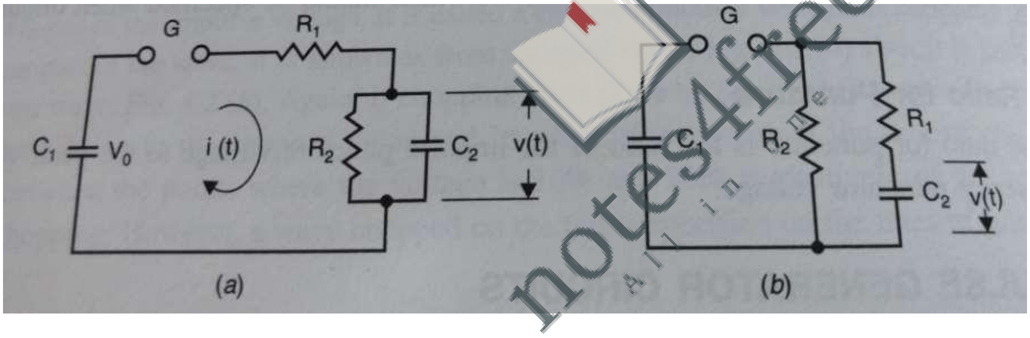
2. Impulse energy transformed during a discharge is given by

$$W = \frac{1}{2} C1 * V_0^2$$

3. The minimum value of generator capacitance is given by

$$C_1 = \frac{MVA * 10^8}{Z * V^2}$$

Equivalent circuits of single stage Impulse Generator



- Evaluation & analysis is easy as compared to main circuit.

Note: Do refer text book of M S Naidu & V Kamaraju – page no 172 for more information

e) Drawbacks of single stage impulse generator

1. *Physical size* of the circuit elements are *very large.*
2. *Large size of sphere.*
3. *High dc charging voltage* is required.
4. *Suppression* of *corona is difficult.*
5. Switching of very high voltage with the spark gap is difficult.

Multistage Impulse Generator

2.3.2 Multistage impulse generator working of Marx impulse

Introduction

- To obtain ***higher*** and ***higher impulse voltage.***

- In 1923 *E. Marx* suggested a ***multiplier circuit*** which is ***commonly used to obtain impulse voltage*** with as ***high a peak*** value as possible for a given charging dc voltage.

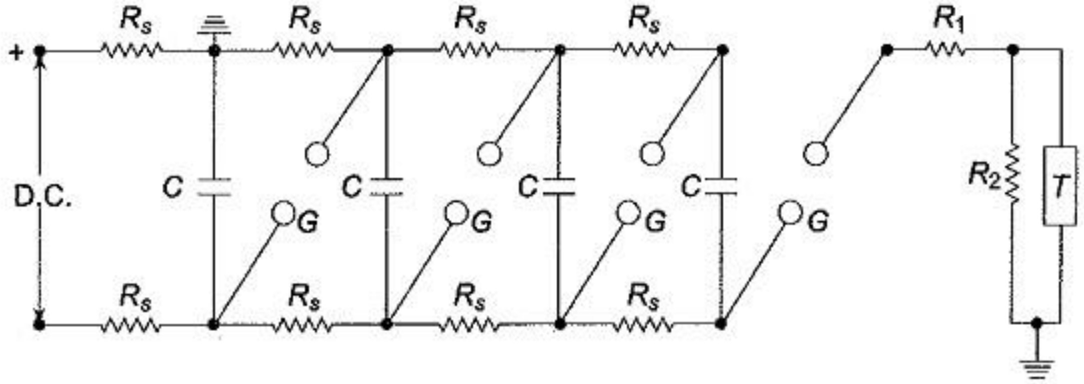
- Depending upon the charging voltage available and output voltage required "***the number of identical impulse capacitors are charged in parallel and then discharged in series***".

- Obtain total charging voltage multiplied with number of stages.

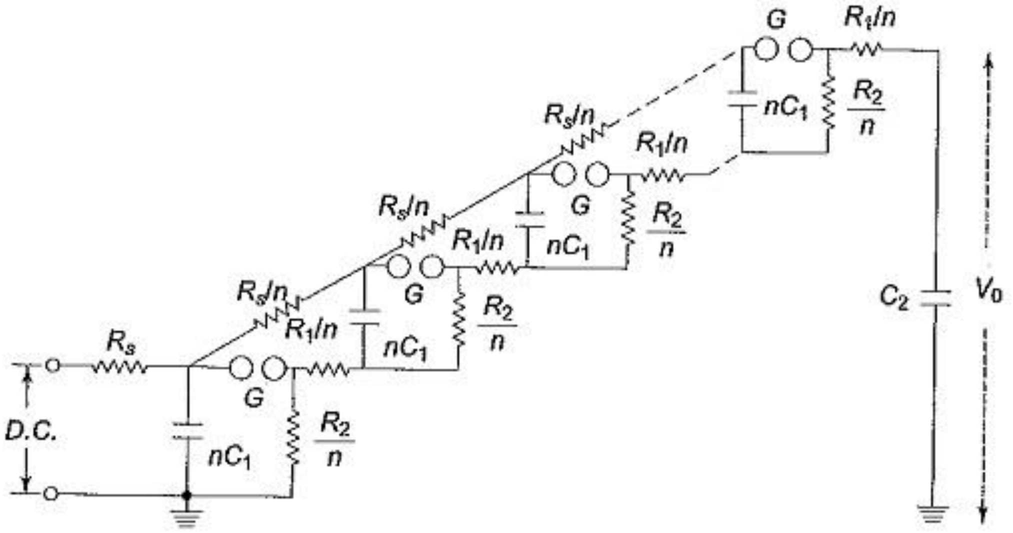
Why Multistage Impulse Generator?

A single capacitor C1 is may be used for voltages up to **200 kV.** Beyond this voltage, a single capacitor & charging unit may be too costly & the size becomes very large

Schematic Diagram of Multistage Impulse Generator



Schematic Diagram of Multistage Impulse Generator (Modified)



Rs is a charging resistance to limit the charging current.

1. The *generator capacitance C* is chosen such that the product of *CRs is about 10s to 1 min.*
2. The *gap spacing* is chosen such that the breakdown voltage of the gap G is greater than the charging voltage V.
3. All the capacitance are charged to the voltage V in about ***1 minute*.**
4. Charging time constant=CRs (in seconds)
5. Discharging time constant = **CR1/n** (in micro seconds) , where n is the number of stages.

A ***16 stage*** Multistage Impulse Generator having a stage capacitance of ***0.280μF*** And maximum charging voltage ***300kV* .**

The height of the generator will be about ***15m***.

Area = 3.25m x 3.00 m

2.3.1.1Construction of Multistage Impulse Generator

1. Require a *dc power supply* for *charging* the impulse *capacitance C1* of the generator.
2. Supply consists of *step up transformer* and *rectifier.*
3. The *value of resistor* should be *constant* & *never vary* with external factors.
4. *Non-inductive wire wound resistors* are commonly used.
5. *Resistors* which will be used for the construction for multistage impulse generator *flexible to replace.*
6. *Oil paper insulated capacitor* having high rate of discharge are normally employed and reason for *reduced size of capacitor*.
7. *The sphere gap* adjusted by a *remotely controlled motor* conjunction with indicator.
8. *Chimney* provided with *dust free and dry air.*
9. A *series protective resistance* should be included in this *earthing* device to *avoid too high discharge current.*
10. Charging resistors are fixed at sphere column.
11. Front and tail resistor fixed to the generator frame.
12. *All the leads and electrodes* should *dimensioned properly* to avoid *corona discharge.*

2.3.1.2 Components of a multistage impulse Generator

A Multistage impulse generator requires several components parts for Flexibility & production of the required wave shape.

1. DC Charging set

2. Charging Resistors

- Non inductive high value of resistance about *10 to 100k.*Ω
- Each resistance will be designed to have a maximum voltage *between 50 and 100kV.*

3. Generator Capacitors and spark gap

- Capacitor designed for several charging and discharging operations.
- Capacitors will be capable of having 10kA of current.
- Spark gaps will be usually spheres or hemispheres of 10 to 25 cm diameter.

4. Wave-shaping Resistors and Capacitors -Non inductive wound type -Capable of discharging 1000A current -50 to 100kV max. designed voltage

- Load capacitance will be 1 to 10nF

5. Triggering System

- Contains trigger spark gap to cause spark breakdown of the gaps.

6. Voltage Dividers

- Resistor type or damped capacitor type
- oscilloscope with recording arrangement are provided for measurement of voltage across test object

7. Gas insulated impulse generator

- Above 4MV impulse generator, tall & large space requirement
- 4.8MW- nearly 30m height
- N2, compressed gas and SF6 will provide proper insulation.

2.4 Triggering and Synchronization of the impulse Generator

Why triggering & synchronization?

- *Control* for *charging process* of impulse generator.
- To integrate the measuring devices.
- Chopping gap control.
- CRO is used for measuring and studying the effect of impulse wave on the performance of the insulation of the equipment.
- Impulse waves are of *shorter duration.*
- It is necessary that operation of the *generator* and the *oscillograph* should be *synchronized accurately.*
- *Time sweep circuit* is main part of *oscillograph*
- The *time sweep circuit* of the oscillograph should be initiated at the time slightly before the impulse wave reaches the deflecting plates.
- The *impulse generator drives* both *sweep and triggering circuits.*
- The *sweep circuit operating first* , triggering circuit works after 0.1 to 0.5 microseconds.

Triggering -3 Stages

1. *Fix the gap distance* between the spheres and increase the stage applied dc voltage till the flashover occurs.
2. *Set the gap distance* between the spheres large enough apply a desired voltage across them and then reduce the gap distance till flashover takes place.
3. *Fix both, the desired stage voltage* and *corresponding gap distance* within prescribed limits. Then apply the trigger pulse to the trigatron on the first stage.

Triggering and Synchronization of the impulse Generator

- ***Two methods are available***

1. **Three electrode gap arrangement**
2. **Trigatron gap**

2.4.1 Triggering of impulse generator by three electrode gap arrangement

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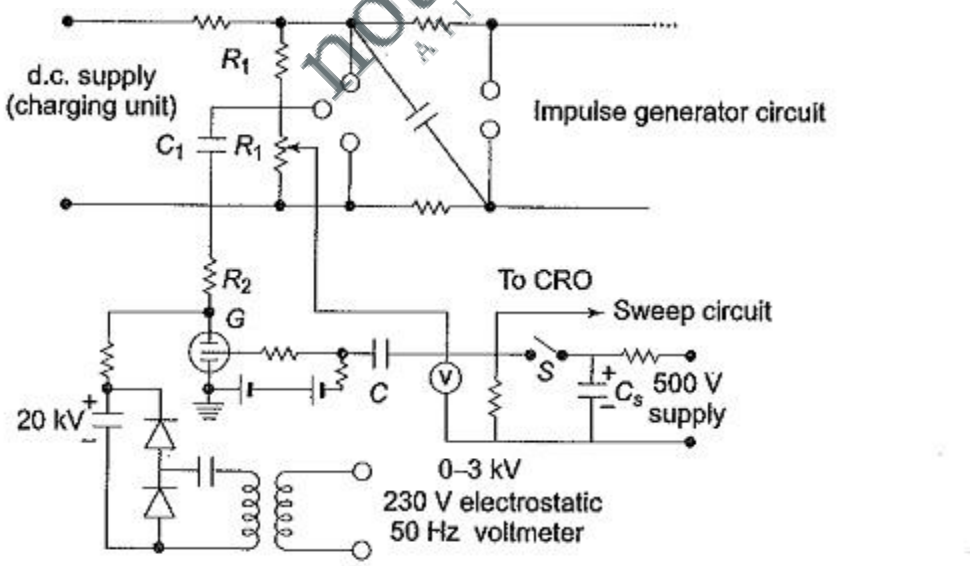
Triggering of impulse generator by

(i) Three electrode gap arrangement

1. '*Three electrode gap arrangement* ' is one of the method for triggering and synchronization of impulse generator.
2. The *spacing* between *2 spheres is adjusted* so that *two series gap are able to withstand charging voltage* of impulse generator.
3. *Central sphere* is called *control sphere.*
4. *A high resistance* is connected between the *outer sphere* and its *centre point* is connected to *control sphere.*
5. The voltage between outer sphere is equally divided between two sphere gap



To test the dielectric breakdown strength of three sphere gap arrangement

1. First *impulse generator* is to be *charged* to a voltage which is *slightly less than the breakdown voltage of the gap.*

2. *Apply an impulse wave* of either polarity & peak voltage not less than (1/5) th of charging voltage to the control sphere.
3. Check whether the dielectric breakdown has occurred or not.

Operation of three sphere gap arrangement

- **Two '*three sphere gap arrangement*' is included in the synchronization & triggering circuit**

1. Three sphere gap arrangement'

1. The switch's' is closed which initiate the sweep circuit of the oscillograph.
2. The same impulse is applied to the *thyratron tube.*
3. The inherent time delay of thyratron ensure *sweep circuit operate first* before the starting of high impulse wave.
4. We can be able to create further delay by using Capacitance-Resistance (R1C1) circuit.
5. The tripping impulse is applied through capacitor C2.
6. During charging period the voltage across thyratron is about +20kV.

2. Trigatron gap

1. **A device, known as "*Trigatron*", is used to control the flash over at the spark gaps in order to get a desired magnitude of the output voltage repeatedly.**
2. **Function- used as 'First gap of impulse generator'**
3. **"*Trigatron*", consists essentially of three-electrodes.**
4. **Three electrodes are**

1. *High voltage electrode* is a sphere- indication of HV
2. *Earthed electrode* is also a sphere. The spherical configuration gives homogeneous field.
3. *Metal rod electrode/ Trigger electrode* be the third electrode

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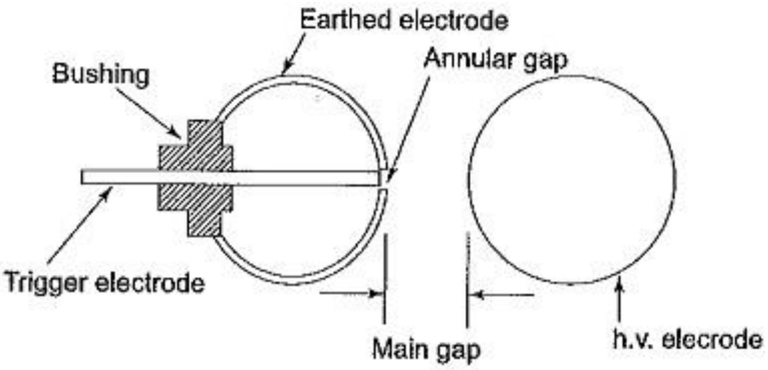
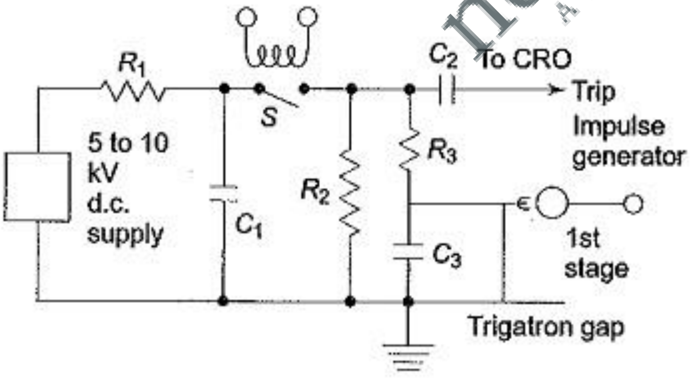
5.5 Diagram for "Trigatron spark gap"



a) Construction of “Trigatron spark gap”

1. A *small hole is drilled into earth electrode* into which metal rod projects (trigger rod).
2. The annular gap between the rod and the surrounding hemisphere is 1 mm.
3. A glass tube is fitted over rod electrode.
4. The potential of metal electrode and earth electrodes are same.
5. Both are connected through a high resistance.
6. Tripping pulse or control pulse applied between metal and earth electrodes.
7. When the tripping pulse is applied, main field is distorted.
8. Reason for dielectric breakdown.

b)Tripping circuit of trigatron



(b) Tripping circuit using a trigatron

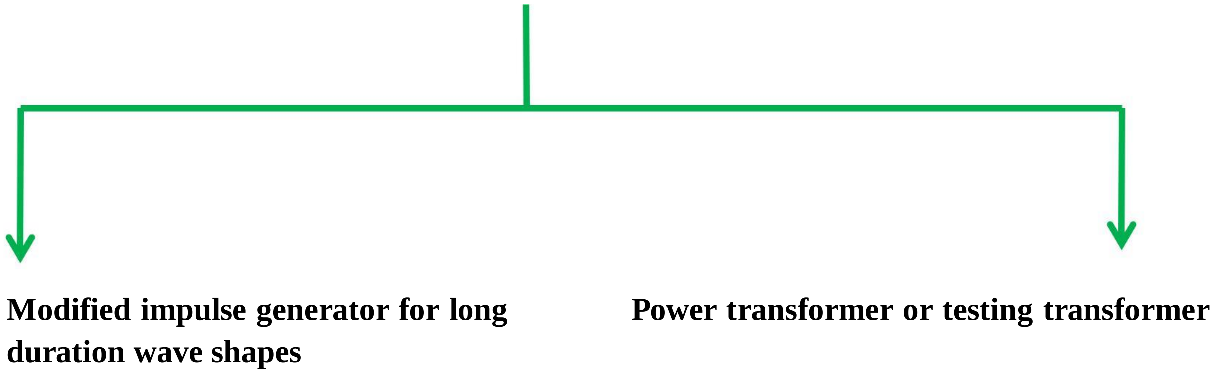
c) Operation of Tripping circuit of trigatron

- The *capacitor C1* is charged through *high resistance R1*
- Switch S is closed
- *A pulse is applied to a sweep circuit* of the oscillograph through the *capacitor C3*
- Same time capacitor *C2 is charged*
- Triggering pulse is applied through *trigger electrode* (metal rod electrode)
- The *requisite delay* in triggering the generator can be provide by *R2 and C2*
- The residual charge on the *C2* can discharged through *R2*
- Now a day's *laser is used* for *tripping the spark gap*
- The trigatron also *has a phase shifting circuit* associate with the *synchronization of initiation time* with *external Alternating voltage*.
- *Design* is to *prevent the overcharging* of capacitor
- An *indicating device* shows whether the generator is going to fire properly or not.

2.4.1 Generation of switching surges/ switching impulse voltage

- *Switching surges* has an important role in the *design of insulation* for extra high voltage transmission line (EHV) & power systems.
- *Switching surge* is a *short duration transient voltage* produced in the system due to *sudden opening or closing of switch or circuit breaker.*
- Switching surges may be produced due to *arcing at faulty power systems.*
- The *transient voltage* may be oscillatory wave or damped oscillatory wave having *frequency* of a *few hundred Hz to a few kilo Hz.*
- Wave front time= 0.1 to 10ms
- Wave tail time ~ 1ms
- Switching surges contain higher energy than lightning impulse voltage.

- ***Types of circuit*** **produced switching surges**



Modified impulse generator for long duration wave shapes

Power transformer or testing transformer

2.5 Impulse Current Generation

A *high impulse current generator* consists of *large number of capacitor* connected in *parallel* to a common discharge path. i.e by using ‘*capacitor bank*’.

- The generation of impulse current waveforms of high magnitude (nearly 100 KA) find *applications* like

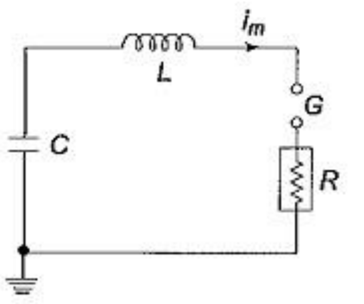
  1. test work
  2. basic research on non-linear resistors -electric arc studies
  3. electric plasma state

a) Definition of impulse current waveforms

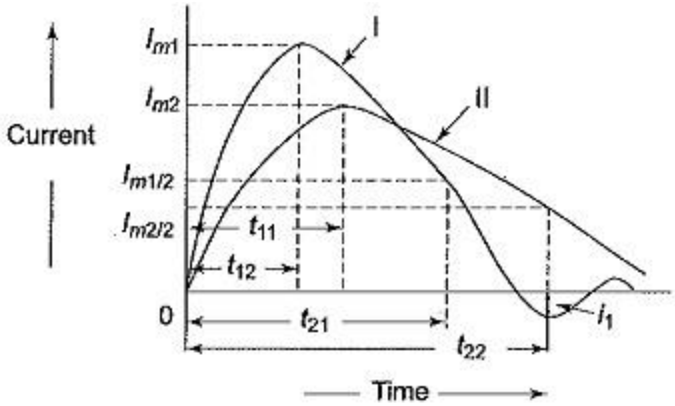
- The wave shapes used in testing surge diverters are (4/10 micro seconds-wave front) and (8/20 micro seconds –wave tail).

- Tolerance allowed in between +10% and -10%.

- Wave shapes are normally rectangular shape.



(a) Basic circuit of an impulse current generator

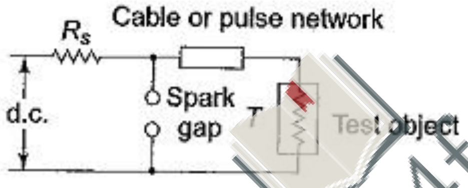


t_1 and t_{12} = time-to-front of waves I and II
t_{21} and t_{22} = time-to-tail of waves I and II

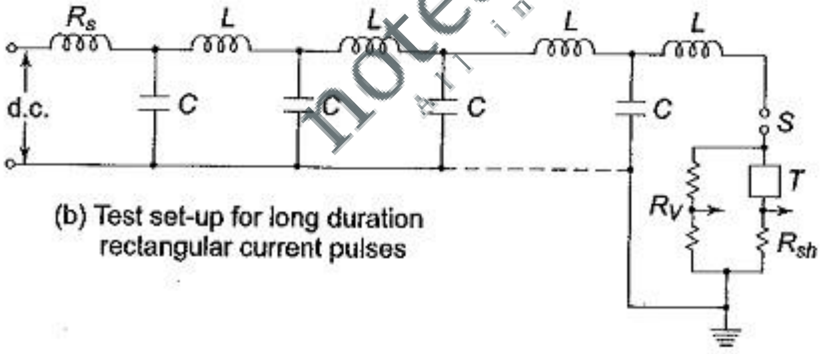
I — damped oscillatory wave
II — overdamped wave
i_1 — overshoot

(b) Types of impulse current waveforms

b) Circuit producing impulse current wave



(a) Basic circuit



(b) Test set-up for long duration rectangular current pulses

- *Number of capacitors* connected in parallel & discharged in parallel in the circuit.
- In order to minimize the value of inductance capacitance are subdivided into smaller units.

c) Components

1. *DC charging* unit giving variable voltage to capacitor bank.
2. Additional *air core inductor* having high current value.
3. Oscillograph- measurement purpose.
4. Triggering units & spark gap.

d) Generation of Rectangular Current Pulses

1. The generation of rectangular current pulse can be done by '*discharging a pulse network or cable previously charged*'
2. To produce a rectangular pulse a coaxial cable of surge impedance Z0 is used.

Course Outcomes

Explain generation of high voltages and currents and Discuss measurement techniques for high voltages and currents.

MODULE-3: MEASUREMENT OF HIGH VOLTAGE AND CURRENT

Syllabus

3.1 Measurement of High Direct Current Voltages
3.2 Measurement of High AC and Impulse Voltages
3.3 Measurement of High Currents – Direct, Alternating and Impulse ,Cathode Ray Oscillographs for Impulse Voltage and Current Measurements

Course Objectives

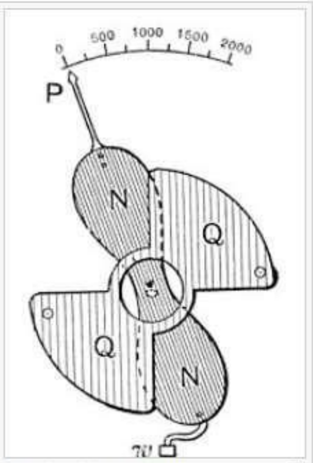
To discuss generation of high voltages and currents and their measurement

3.1 Measurement of High Direct Current and A.C Voltages

3.1.1 Electrostatic voltmeter

Principle of Operation

1. **Electrostatic voltmeter** can be referred to an ***electrostatic charge meter.***
2. Electrostatic Voltmeter to measure large electrical potential. (*Direct method of measuring HV*)
3. It can accurately measure *surface potential (voltage)* on materials without making physical contact.
4. Electrostatic voltmeter utilizes the *attraction force* between *two charged surfaces.*
5. Attraction between 2 charged surface create a *deflection of a pointer* directly calibrated in *volts.*
6. *Attraction Force* is proportional to the *square of the applied voltage.*
7. The measurement can be made for *AC or DC voltages*.
8. 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.*
9. Electrostatic voltmeter is designed to measure high potential differences; typically from a few hundred to many thousands volts.



Electrostatic voltmeter operation

10. Electrostatic voltmeter utilizes the attraction force between two charged surfaces to create a deflection of a pointer directly calibrated in volts.
11. The pivoted sector NN is attracted to the fixed sector QQ
12. The moving sector indicating the voltage by the pointer P and is counterbalanced by the small weight w.
13. Damping technique is Air friction damping.

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

$$F = \frac{1}{2}\varepsilon_0 A\left(\frac{V}{s}\right)^2$$

$V =$ applied voltage between plates,
$C =$ capacitance between the plates,
$A =$ area of cross-section of the plates,
$s =$ separation between the plates,
$\varepsilon_0 =$ permittivity of the medium (air or free space)
$W_s =$ work done in displacing a plate

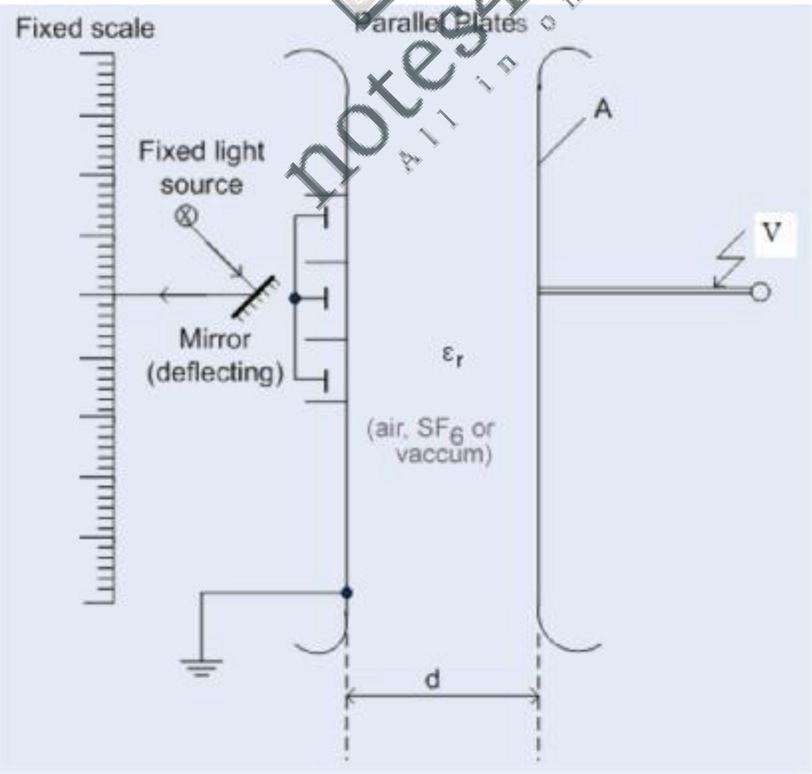


Fig: Schematic Diagram

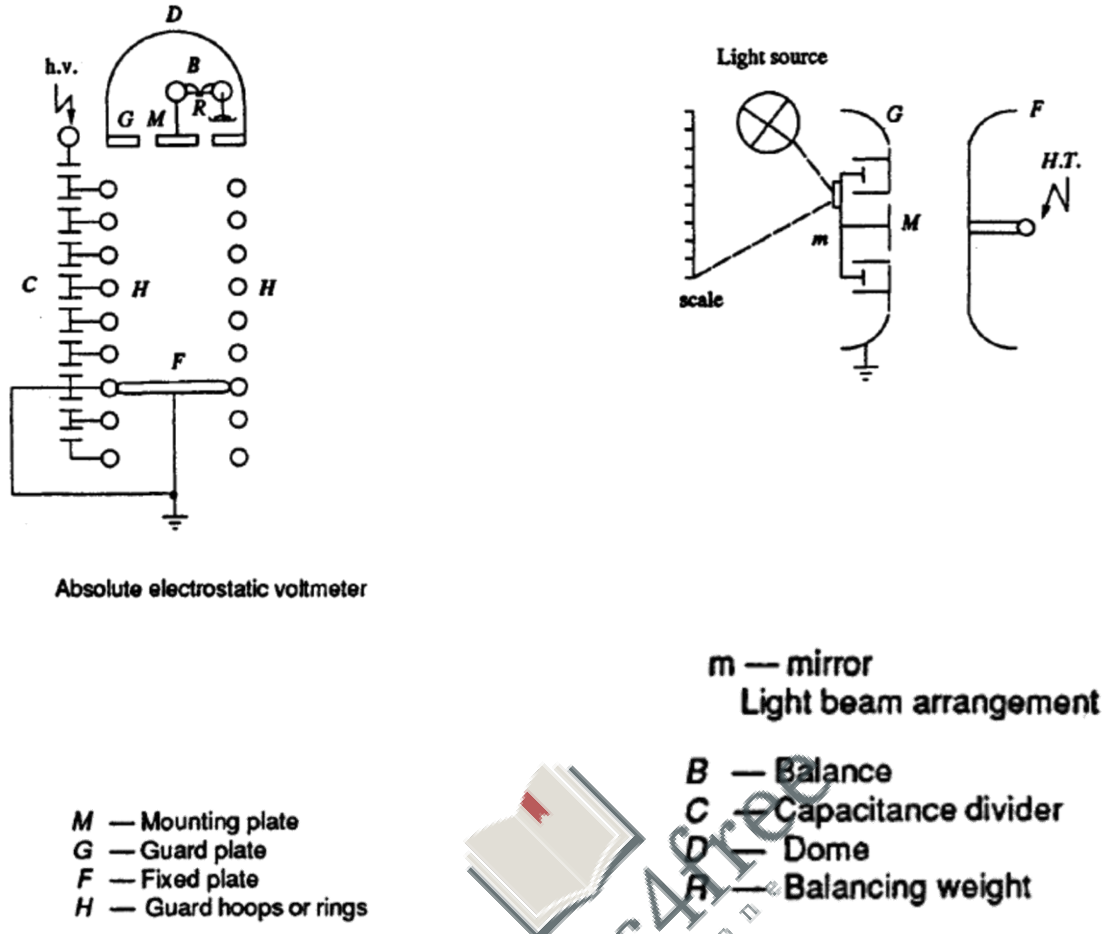
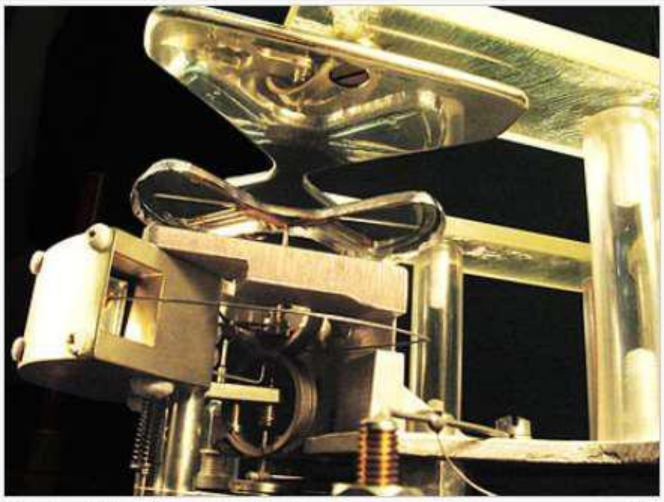


Fig: Constructional Details

Construction

1. Electrostatic voltmeters are made with *parallel plate configuration* using *guard rings* to avoid corona and maintain constant potential.
2. An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight.
3. The electrostatic voltmeters have *a small capacitance (5 to 50 pF)*
4. High insulation resistance (above 1000 ohm).
5. They are considered as devices with *high input impedance.*
6. An upper frequency limit of about *one MHz* is achieved in careful designs.
7. The *accuracy* for AC voltage measurements is better than DC voltage measurements.
8. It consists of parallel plane disc type electrodes separated by a small distance.
9. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region.
10. 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*
11. The *balancing weight* gives controlling torque.
12. Electrostatic voltmeters are constructed in an enclosed structure containing compressed air or SF6 or carbon dioxide or nitrogen.
13. The *gas pressure* may be in the order of *15atm and* Working stress= 100kV/cm



Electrostatic voltmeter mechanism

Advantages

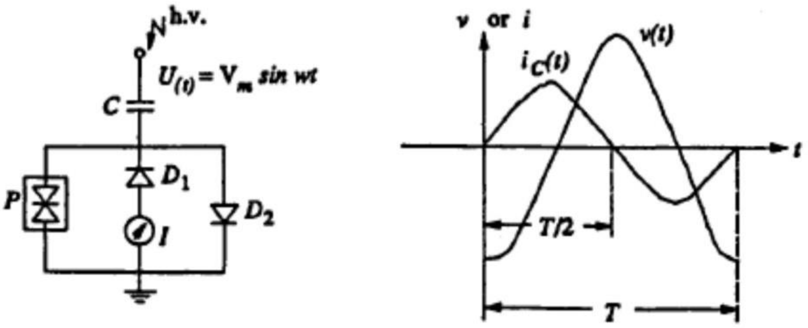
1. Active power loss is negligibly small
2. Low loading effect
3. Voltage up to 600kV can be measured

Limitations

1. The measurement of *voltage lower than 50V* is not possible because force become too small.
2. For constant distance 's', **F α V^2**, the sensitivity is small. This can be overcome by varying the gap distance d in appropriate steps.

3.2 Measurement of HVAC Voltages : Chubb and Fortescue method for HV AC measurement

1. It is a simple and accurate method for the **peak measurement of AC voltage.**
2. It can be defined as peak voltmeter method.
3. Suggested by Chubb and Fortescue in 1913.
4. *Peak value* of instrument is required for HV measurement.
5. Peak value of an *AC waveform* is more important.
6. When the waveform is not sinusoidal, **rms value of the voltage multiplied by square root of 2 is not correct.**
7. Hence a *separate peak value* instrument is desirable in high voltage applications.



Peak voltmeter with a series capacitor

C — Capacitor
D_1, D_2 — Diodes
P — Protective device
I — Indicating meter
(rectified current indicated)

v(t) — Voltage waveform
$I_c(t)$ — Capacitor current waveform
T — Period

8. When a capacitor is connected to a sinusoidal voltage source, the *charging current* is generated.
9. The meter reading is proportional to the peak value of the value ***Vm***.

$$V_m = \frac{I}{2\pi f C}$$

where '*I*' is the dc current read by the meter and C is the capacitance of the capacitor.

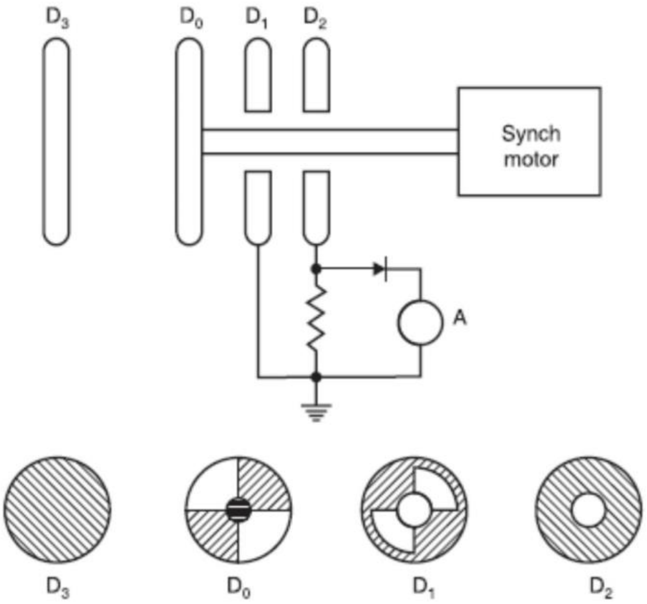
This method is known as the *Chubb-Frotscue method* for peak voltage measurement.

3.2.1 Generating voltmeter

1. **"A generating voltmeter is a *variable capacitor electrostatic voltage generator* which generates current proportional to the applied external voltage"**

2. The device is driven by an ***external synchronous or constant speed motor*** and does not absorb power or energy from the voltage measuring source. i.e *no loading effect*.
3. Generating volt meter can measure loss free AC voltage.
4. Generating voltmeters are *high impedance devices.*
5. No direct connection to the high voltage.

Construction



Schematic diagram of generating voltmeter

- **Fig. shows a schematic diagram of a generating voltmeter which employs rotating vanes for variation of capacitance.**

1. High voltage electrode is connected to a disc electrode ***D_3 which** is* kept at a fixed distance on the axis of the other low voltage electrodes ***D_2, D_1, and D_0.***

2. The **rotor *D_0*** *is* driven at a suitable constant speed by a synchronous motor.

3. Rotor vanes of D_0 cause periodic change in capacitance between the insulated disc D_2 and the high voltage electrode D_3.

4. Number and shape of vanes are so designed that a suitable variation of capacitance (sinusoidal or linear) is achieved.

5. The AC current is rectified and is measured using moving coil meters. If the current is small an amplifier may be used before the current is measured.

6. Generating voltmeters are linear scale instruments and applicable over a wide range of voltages.

7. The sensitivity can be increased by increasing the area of the pick up electrode and by using amplifier circuits

Principle of operation

1. We have charge stored in the capacitor

$$q = CV.$$

2. If the capacitance of the capacitor varies with time when connected to the source of voltage *V, the current through the capacitor*

$$i = \frac{dq}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt}$$

For d.c. voltages $dV/dt = 0$. Hence,

$$i = \frac{dq}{dt} = V\frac{dC}{dt}$$

If the capacitance C varies between the limits C_0 and $(C_0 + C_m)$ sinusoidally as

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

the current i is

$$i = i_m \cos \omega t$$

where

$$i_m = V C_m \omega$$

(i_m is the peak value of the current). The rms value of the current is given by:

$$i_{rms} = \frac{VC_m\omega}{\sqrt{2}}$$

3. For a constant angular frequency, the ***current* is proportional to the *applied voltage V.***
4. More often, the generated current is rectified and measured by a *moving coil meter*.
5. Generating voltmeter can be used for **AC *voltage measurements*** also provided the *angular frequency* is the same or equal to half that of the supply frequency.

Advantages of Generating Voltmeters

1. No source loading by the meter
2. No direct connection to high voltage electrode
3. scale is linear and extension of range is easy
4. A very convenient instrument for electrostatic devices such as **Van de Graff generator** and particle accelerators.

Limitations of Generating Voltmeters

1. They require calibration
2. Careful construction is needed and is a cumbersome instrument requiring an auxiliary drive
3. Disturbance in position and mounting of the electrodes make the calibration invalid.

Numerical

Example : 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:

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,

$$2\times 10^{-6} = \frac{20\times 10^3\times C_m}{\sqrt{2}}\times\frac{1500}{60}\times 2\,\pi$$

$$\therefore \quad C_m = 0.9\ \text{p.F}$$

$$\text{At}\quad 200\ \text{kV}, I_{rms} = \frac{200\times 10^3\times 0.9\times 10^{-12}\times 1500}{\sqrt{2}\times 60}2\pi$$

$$= 20.0\ \mu\text{A}$$

3.2.2 Series resistance micro ammeter

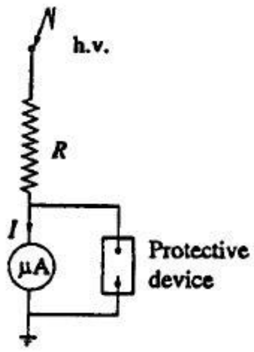
1. **A large value of resistance (few hundreds of mega ohms) is connected in series with uA.**
2. **Protective device (Zener diode) connected across the uA.**

Need for protective device:

1. If R fails, heavy current will flow through µA
2. To divert protective device is used

Operation of series resistance micro ammeter

1. **“R ”should be high**
2. **High DC voltage is applied**
3. **Voltage drop across the resistance**
4. **The current flowing through the resistance ‘R’ is measured in µA.**



Series resistance micrometer

5. *The resistance is constructed from a large no. of wire wound resistors in series.*
6. Voltage V=IR
7. Drop in Ammeter is negligible
8. R should be chosen such that 1 to 10 uA is allowed for full scale deflection **500 kV** can be measured
9. **Accuracy : 20%**

Drawbacks

1. More power dissipation
2. Temperature effects
3. Source loading.

Functions of series resistance

i) Limit the breakdown current

ii) To suppress unwanted oscillations

3.2.3 Standard Sphere Gap Measurement

---

a) Importance of sphere gap measurement

1. Peak value of voltage causes dielectric breakdown.
2. ***A sphere gap* can be used for measurement of the *peak value* of the voltage if the *gap distance* is known.**
3. Sphere gap measurement is one of the standard method of measuring *peak value of high voltage* ***DC, AC and impulse voltage.***
4. It is used for checking voltmeters and other voltage measuring devices used in HV testing circuits.
5. Two types of sphere gap arrangement
    a. **Horizontal sphere gap arrangement**
    b. **Vertical sphere gap arrangement**

b) Construction

Standard diameter of the spheres are *2, 5, 6.25, 10, 12.5, 15, 25, 50, 75,100, 150 and 200cm.*

a. Horizontal arrangement is usually is preferred for sphere diameter **d<50cm** and it is suitable for **low voltage range.**
b. One of the sphere is static and other is movable (adjustable).
c. Impulse voltage which has wave front time at least 1µs & wave tail time of 5µs can be measured using sphere gap measurement.

a. Horizontal arrangement of sphere gap

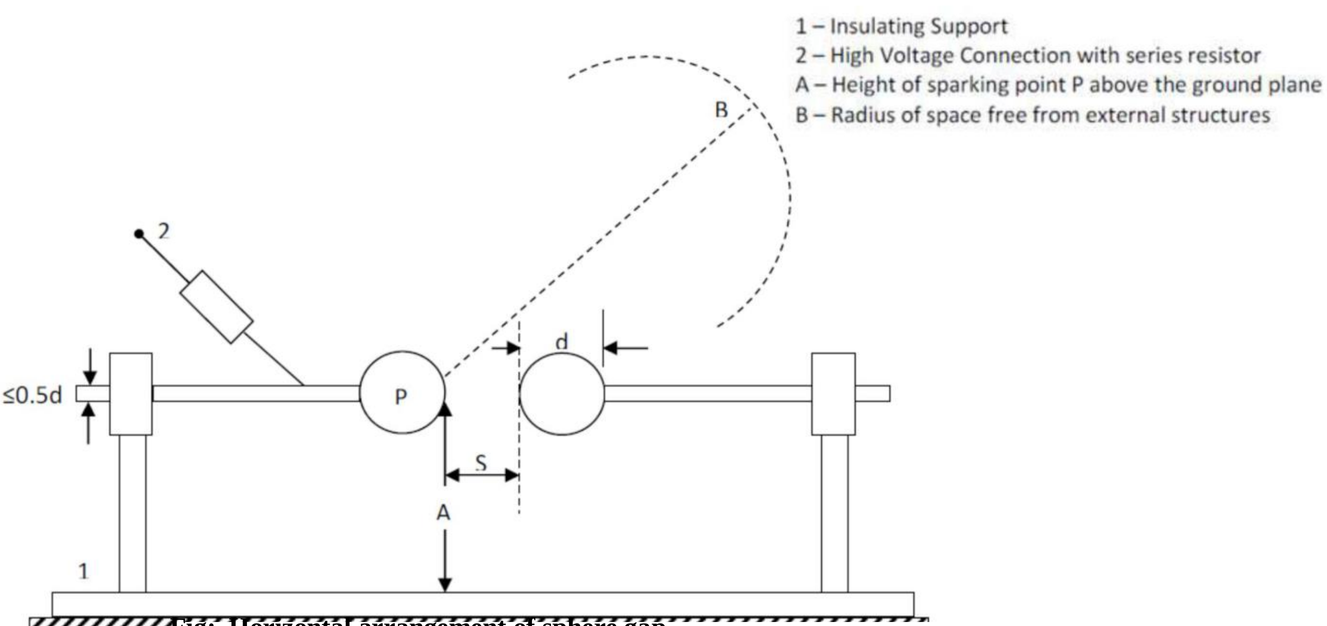
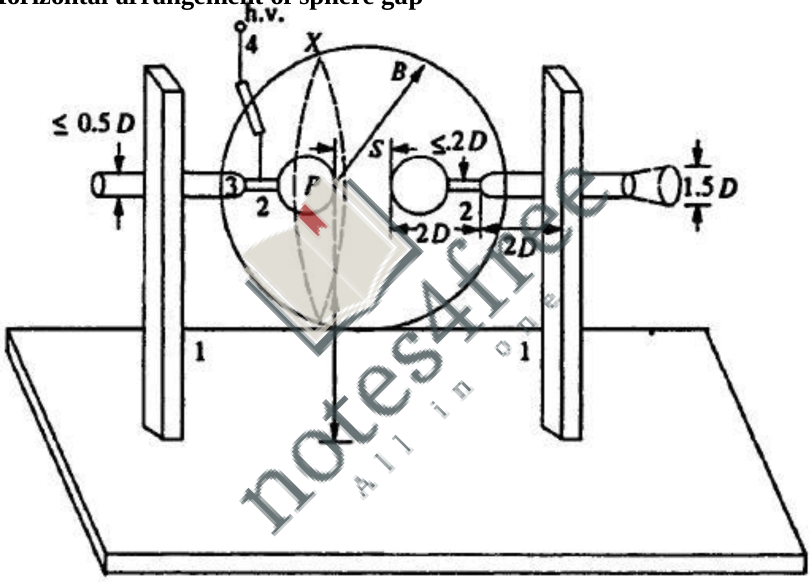
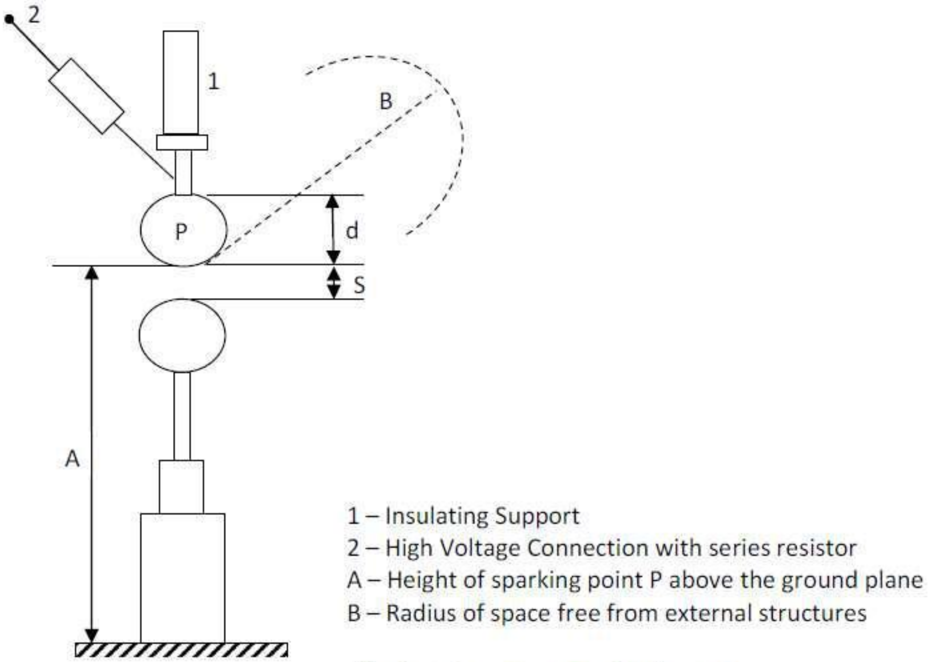


Fig: Horizontal arrangement of sphere gap



Horizontal arrangement of sphere gap

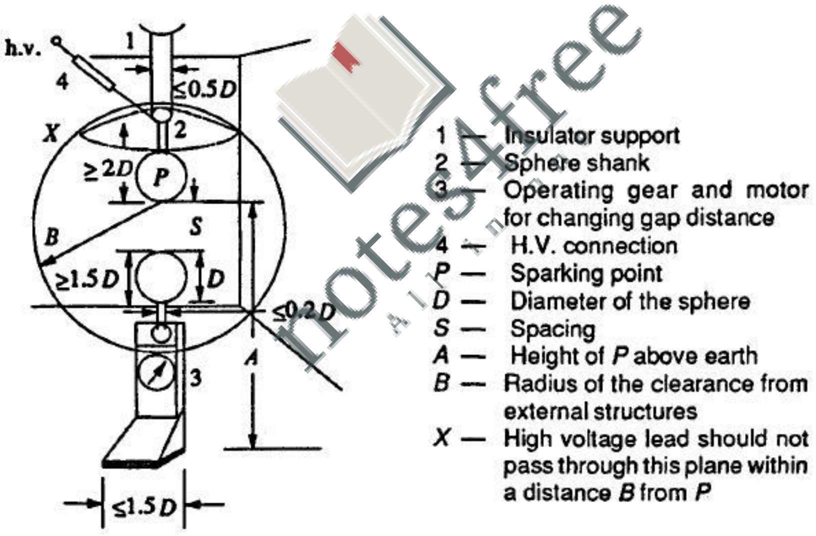
b. Vertical arrangement of sphere gap



1 – Insulating Support
2 – High Voltage Connection with series resistor
A – Height of sparking point P above the ground plane
B – Radius of space free from external structures

Vertical Arrangement of Sphere gap

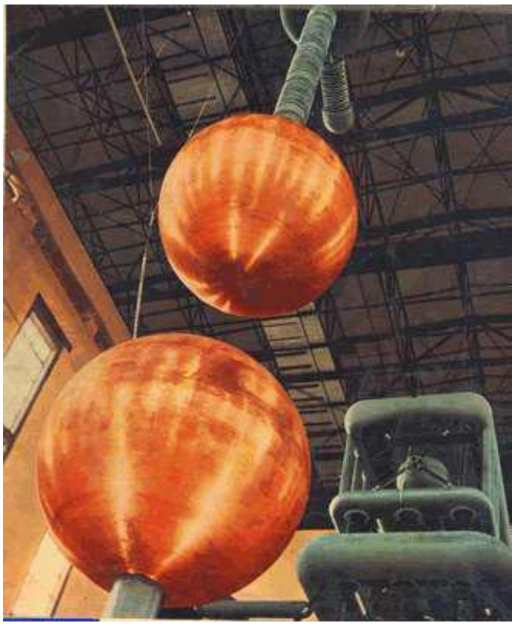
Construction



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

Vertical arrangement of sphere gap

Sphere gap for voltage measurement



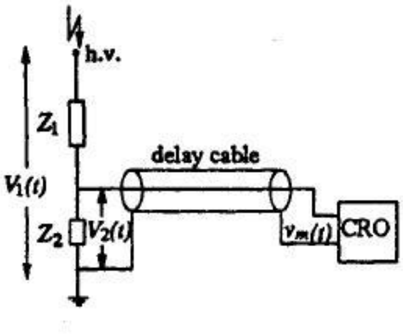
1. When the electric field across the gap exceeds static breakdown strength of gap, it results complete **breakdown of gaseous gap.**
2. Spheres having equal diameters and it is made of ***Cu or Al.***
3. The distance between two spheres are less than the diameter of spheres.
4. ***Sphere gaps can be arranged*** **either**
   (i) *Vertically* with lower sphere grounded,
   (ii) Horizontally with both spheres connected to the source voltage or one sphere grounded.
5. The spheres are carefully designed and fabricated so that their surfaces are smooth and the curvature is uniform.
6. Spacing S between them gives a measure of the *spark over voltage*.
7. ***A series resistance*** is usually connected between the source and the sphere gap to
   (i) Limit the breakdown current, and
   (ii) to suppress unwanted oscillations in the source voltage when breakdown occurs (in case of impulse voltages).
8. The value of the series resistance may vary from ***100 to 1000 kilo ohms*** for AC or AC voltages and not more than ***500 ohm*** in the case of impulse voltages.

Factors affecting the measurements

1. ***Nearby earthed objects*** *:* Changes in breakdown strength
2. ***Atmospheric conditions and humidity*** *:* Breakdown voltage of a spark gap depends on density.
3. ***Irradiation***
4. ***Polarity and rise time of voltage waveforms****:* Breakdown voltage for positive & negative polarity impulses are different.
5. ***Influence of dust particle****:* Presence of dust Particle cause erratic breakdown.

3.2.4 Potential dividers

1. Potential or voltage dividers useful for ***high voltage DC and AC measurement.***
2. Potential dividers are usually either *resistive* or *capacitive or mixed element type.*
3. The *low voltage arm* of the divider is usually *connected* to a *fast recording oscillograph* or a peak reading instrument through a *delay cable or a coaxial cable* .



Schematic diagram of a potential divider with a delay cable and oscilloscope

a. *Z1 is usually a resistor or a series of resistors in case* of a *resistance potential divider*.

b. *Z1 is usually* a single or a number of capacitors in case of a *capacitance divider*.

c. *Z1* can able to use the combination of *resistance & Capacitor in case of a mixed RC potential divider.*

d. *Z2* will be a resistor or a capacitor or an *R-C impedance depending upon the type of the* divider.

1. Resistance potential divider

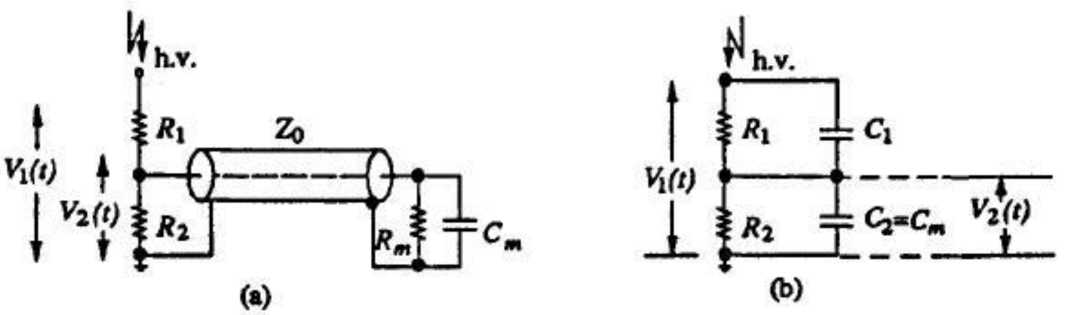
a. A simple resistance potential divider consists of two resistances *R1 and R2 in series. (R1>>R2)*

b. *Voltage ratio or attenuation factor is given by*

$$a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{R_1}{R_2}$$

c. The *divider element R2*, in practice, is connected through the *coaxial cable* to the oscilloscope.

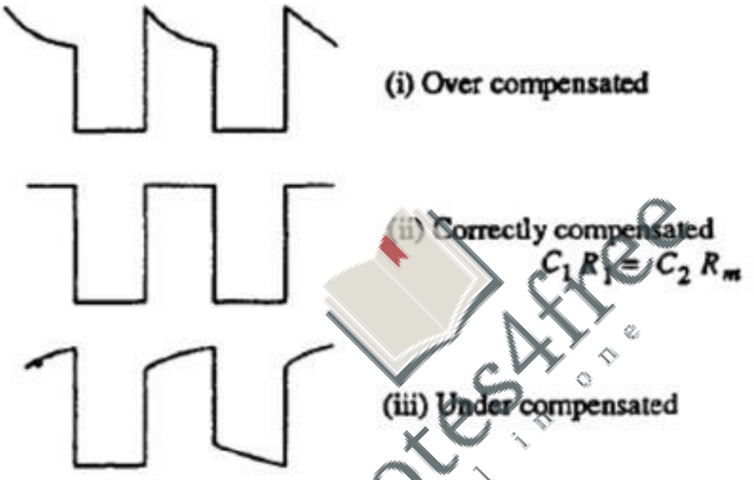
d. Sudden switching action causes Flash over voltage and that causes damage to divider circuit. In order to protect the dividers from flash over voltage, voltage controlled capacitors are used



Resistance potential divider with surge cable and oscilloscope terminations

Comepensated resistance potential divider

Resistance potential dividers



Output of compensated resistance voltage divider for different degrees of compensation

e. The cable will generally have a *surge impedance Z0*

f. Surge impedance will come in parallel with the oscilloscope input impedance *(Rm , Cm).*

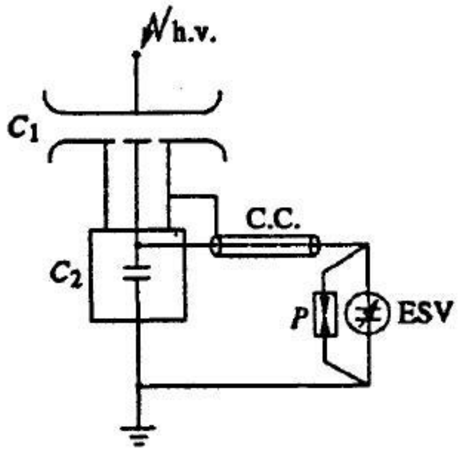
g. *Rm will generally be greater than one Mega ohm* and *Cm may be* ***10 to 50 picofarads.***

h. For high frequency and impulse voltages, the ratio in the frequency domain will be given by

$$a = \frac{V_1}{V_2} = 1 + \frac{R_1}{(R_2/1 + j\omega R_2 C_m)}$$

2. Capacitive potential divider

Impulse voltage can be measured by using capacitive potential dividers



C_1 - Standard Compressed Gas H.V. Condenser

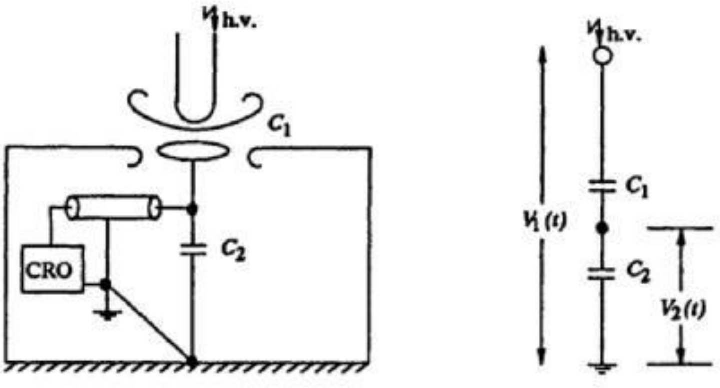
C_2 - Standard Low Voltage Condenser

ESV- Electrostatic Voltmeter P -Protective Gap C.C - Connecting Cable

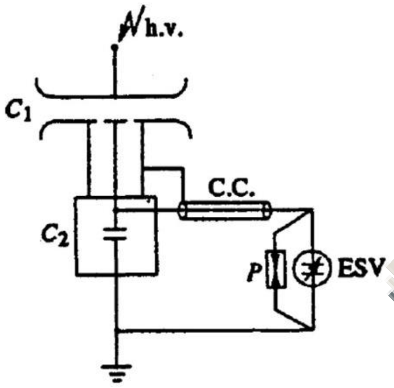
1. Harmonic Effects can be eliminated by use of Capacitive Potential Dividers (CPD) with Electro Static Voltmeter (ESV).
2. Gas filled condensers C_1 and C_2 are used as shown in figure.
3. C_1 is a three terminal capacitor, connected to C_2 by shielded cable.
4. C_2 is shielded to avoid stray capacitance
5. Capacitive potential divider can measure ***fast rising voltage & pulse and impulse voltage.***
6. Capacitance ratio *is* ***independent of frequency*.**
7. Ratio of the divider (Attenuation factor) is given by

$$a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{C_2}{C_1}$$

8. Capacitance *C1 is formed between the HV terminal of the source.*
9. **Suitable for measuring the impulse voltage up to *1 MV***
10. C1 is the *standard* ***compressed air or gas condenser- HV Capacitor.***
11. Value of *C2* is very high, C2 may be *mica capacitor, paper capacitor etc*
12. C1 is connected to C2 by using a **shield cable**
13. C2 is completely covered by using a box, for *avoiding stray capacitance.*
14. *Voltage can measure by using* ***VTVM*** **(Vacuum Tube Volt Meter) or ESV**- testing purpose for impulse voltage



Capacitance voltage divider for very high voltages and its electrical equivalent circuit



C_1 — Standard compressed gas h.v. condenser
C_2 — Standard low voltage condenser
ESV — Electrostatic voltmeter
P — Protective gap
C.C. — Connecting cable

Impulse voltage measurement by using capacitive

$$V_1 = V_2\left(\frac{C_1 + C_2 + C_m}{C_1}\right)$$

V1- Voltage to be measured

V2-Meter reading

C1-Standard compressed gas HV condenser

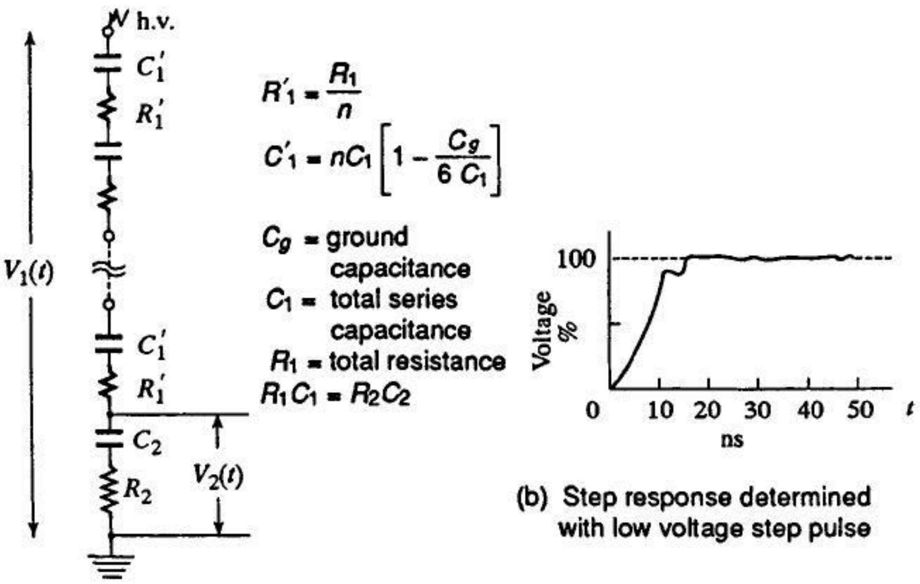
C2-Standard low voltage condenser Cm-Capacitance of the meter

Advantages

1. Loading on the source is negligible
2. Capacitance ratio independent of frequency

3. Mixed RC potential divider

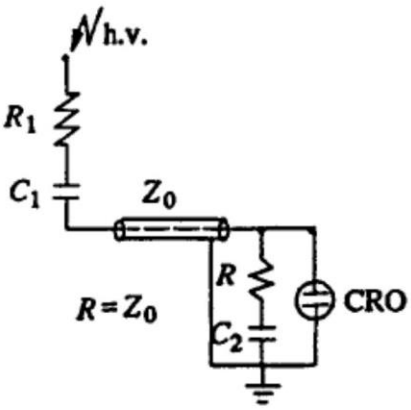
1. Mixed potential dividers use ***R-C elements in series or in parallel.***
2. *Improved step response*



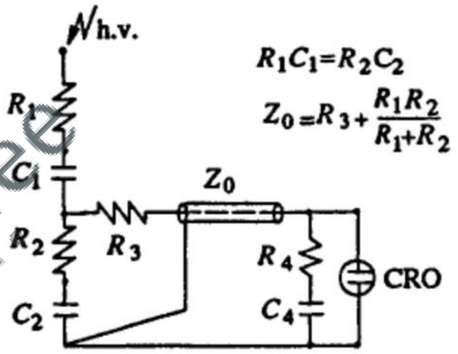
(b) Step response determined with low voltage step pulse

(a) Equivalent circuit

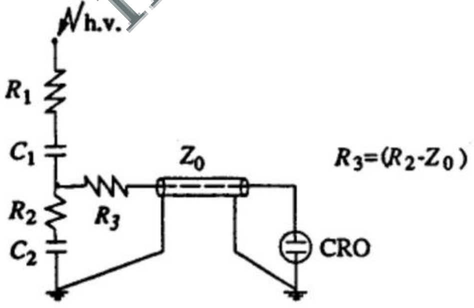
Equivalent circuit of a series R-C voltage divider and its step response



R-C series divider



Modified connection of R-C divider



Impedance matching with R-C divider

The following elements mainly constitute the different errors in the measurement:

1. *Residual inductance* in the elements
2. *Stray capacitance* occurring
   - **A.** ***between the elements,***
   - **B.** ***from sections and terminals of the elements to ground, and* (c) from the high voltage lead to the elements or sections**
3. The *impedance errors* due to *(a) connecting leads between the divider and the test objects, and (b) ground return leads and extraneous current in ground leads*

4. Parasitic oscillations due to lead and cable inductances and capacitance of high voltage terminal to ground.

Additional Information

Note1 -surge impedance

- The characteristic impedance or surge impedance of a *uniform transmission* line, usually written Z_0, is the *ratio of the amplitudes of voltage and current of a single wave propagating along the line.*
- That is, a wave travelling in one direction in the absence of reflections in the other direction.
- Characteristic impedance is determined by the *geometry and materials of the transmission line* and, for a uniform line, is *not dependent on its length*. The SI unit of characteristic impedance is the ohm.

Note 2-Parasitic capacitance

- In electrical circuits, parasitic capacitance, stray capacitance or, when relevant, self-capacitance, is an unavoidable and usually unwanted capacitance that exists between the parts of an electronic component or circuit simply because of their proximity to each other.
- All actual circuit elements such as inductors, diodes, and transistors have internal capacitance, which can cause their behavior to depart from that of 'ideal' circuit elements.
- Additionally, there is always non-zero capacitance between any two conductors; this can be significant at higher frequencies with closely spaced conductors, such as wires or printed circuit board traces.

3.3 Measurement of Impulse current

1. **In power system applications as well as in other scientific and technical fields, it is often necessary to determine the *amplitude and waveforms* of rapidly *varying high currents*.**
2. **High impulse currents occur in *lightning discharges, electrical arcs and post arc* phenomenon studies with *circuit breakers, and with electric discharge studies in plasma physics.***

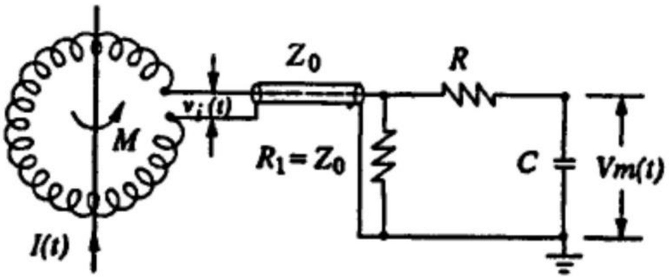
Rogowski Coils

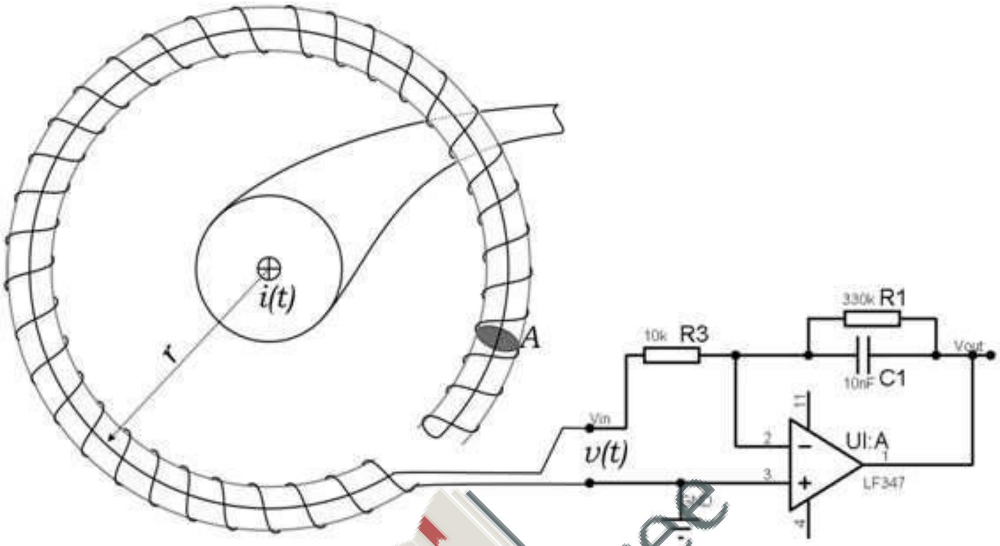
Measurement of *high impulse current*

1. A Rogowski coil, named by Walte Rogowski, is **an electrical device for measuring Alternating Current(AC) or high speed current pulses.**
2. It consists of a helical coil of wire with the lead from one end returning through the centre of the coil to the other end, so that both terminals are at the same end of the coil.
3. The whole assembly is then wrapped around the straight conductor whose current is to be measured.
4. Since the voltage that is induced in the coil is proportional to the rate of change of current in the straight conductor.
5. There is no metal (iron) core.

“A Rogowski coil is a toroid of wire used to *measure an alternating current i(t)* through a cable encircled by the *toroid*”

1. **Connected to an electrical (or electronic) The output of the Rogowski coil is usually integrator circuit to provide an output signal that is proportional to the current**





Integrator circuit

2. Usually an integrating circuit RC is employed as shown in Fig to obtain the output voltage proportional to the current to be measured.
3. If a coil is placed surrounding a current carrying conductor, the voltage signal induced in the coil is

$$v_i(t) = M dI(t)/dt$$

M is the mutual inductance between the conductor & coil.

I(t) is the current flowing in the conductor.

4. ***The coil is wound on a nonmagnetic former of toroidal shape and is coaxially placed surrounding the current carrying conductor.***
5. **The number of turns on the coil is chosen to be large, to get enough signal induced.**
6. **The output voltage is given by**

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

7. **Rogowski coils with electronic or active integrator circuits have large bandwidths (about 100 MHz).**
8. **At frequencies greater than 100 MHz the response is affected by the skin effect.**

Advantages

1. Lower construction costs.
2. Temperature compensation is simple.
3. No iron core to saturate

Disadvantages

1. **Maintenance of integrators circuit**

3.3.1 Magnetic Link

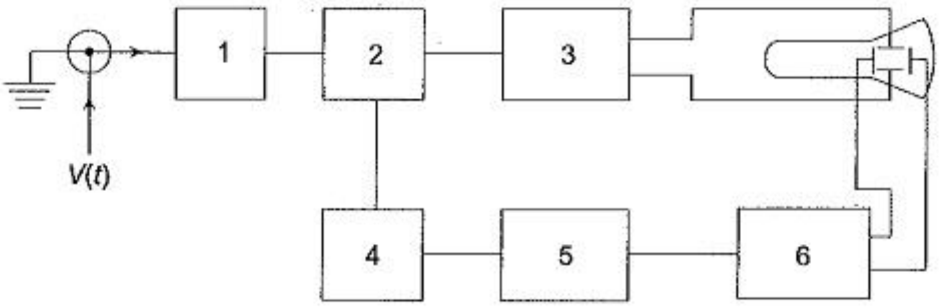
1. These can be used for measurement of peak value of impulse currents.
2. Magnetic links are high retentively steel strips arranged on a circular wheel or drum.
3. These strips have the property that the remanent magnetism (residual magnetism) for a current pulse of **0.5/5 μs** is same as that caused by a d.c. current of the same value.
4. Remenent magnetism or Residual magnetism is the magnetization left behind in a feromagnetic material after an external magnetic field is removed
5. The strips will be kept at a known distance from the current carrying conductor and parallel to it.
6. The Remanent magnetism (Residual magnetism) is then measured in the laboratory from which the peak value of the current can be estimated.
7. These are useful for field measurements, mainly for estimating the lightning currents on the transmission lines and towers.
8. By using a number of links, accurate measurement of the peak value, polarity, and the percentage oscillations in lightning currents can be made.

3.3.2 Cathode Ray Oscillograph for Impulse Measurements:

Modern Cathode Ray Oscillograph for Impulse Measurements 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 ns and bandwidth as high as 500 MHz may be necessary.

Sometimes high voltage surges test oscilloscopes do not have vertical amplifier and directly require an input voltage of 10 V. They can take a maximum signal of about 100 V (peak to peak) but require suitable attenuators for large signals.

Oscilloscopes are fitted with good cameras for recording purposes. Tektronix model 7094 is fitted with a lens of 1 : 1.2 polaroid camera which uses 10.000 ASA film which possesses a writing speed of 9 cm/ns.



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

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 μs.

The delay is obtained by:

1. A long interconnecting coaxial cable 20 to 50 in long. The required triggering is obtained from an antenna whose induced voltage is applied to the external trigger terminal.

2.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. 7.55.

3.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.

Course Outcome

At the end of the course,students will be able to:

Discuss measurement techniques for high voltages and currents.

MODULE-4: Overvoltage Phenomenon and Insulation Coordination in Electric Power Systems

Syllabus

4.1 National Causes for Over voltages - Lightning Phenomenon, Overvoltage due to Switching Surges,
4.2 System Faults and Other Abnormal
4.3 Principles of Insulation Coordination on High Voltage and Extra High Voltage Power Systems

Course Objectives

To discuss overvoltage phenomenon and insulation coordination in electric power systems.

4.1 National Causes for Over voltages - Lightning Phenomenon, Overvoltage due to Switching Surges

a) Causes of Over voltage in Power System

Increase in voltage for the very short time in power system is called as the over voltage. it is also known as the voltage surge or voltage transients. The voltage stress caused by over voltage can damage the lines and equipment's connected to the system. There are two types of causes of over voltage in power system.

1. Over voltage due to external causes
2. Over voltage due to internal causes

Transient over voltages can be generated at high frequency (load switching and lightning), medium frequency (capacitor energizing), or low frequency.Over voltage due to external causes:

This cause of over voltage in power system is the lightning strokes in the cloud.

Now, how lightning strokes are produced. So when electric charges get accumulated in clouds due to thunder Strom caused due to some bad atmosphere process.

This type of over voltages originates from atmospheric disturbances, mainly due to lightning. This takes the form of a surge and has no direct relationship with the operating voltage of the line. It may be due to any of the following causes:

A) Direct lightning stroke

B) Electromagnetically induced over voltages due to lightning discharge taking place near the line, called 'side stroke'.

C) Voltages induced due to atmospheric changes along the length of the line.

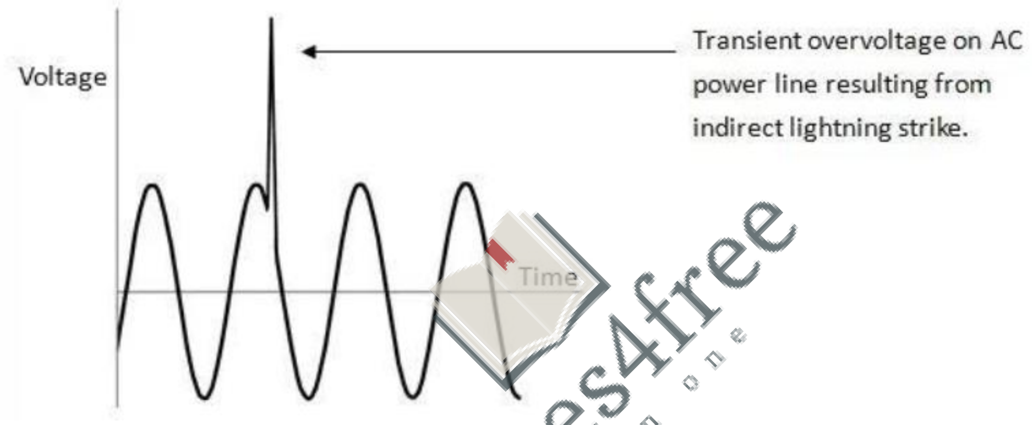
D) Electrostatically induced voltages due to presence of charged clouds nearby.

E) Electrostatically induced over voltages due to the frictional effects of small particles like dust or dry snow in the atmosphere or due to change in the altitude of the line.

The potential between the clouds and earth breaks down and lightning flash takes place between the cloud and ground when this voltage becomes 5 to 20 million volts or when the potential gradient becomes 5000V to 10000V per cm.

There are two types of lightning strokes.

1. Direct lightning strokes
2. Indirect lightning strokeS



Transient overvoltage on AC power line resulting from indirect lightning strike.

b) LIGHTNING ,SWITCHING AND TEMPORARY OVER VOLTAGE

over-voltage-spike

Over voltages are caused on power systems due to external and internal influencing factors. The voltage stress caused by over voltage can damage the lines and equipment’s connected to the system. Over voltages arising on a system can be generally classified into two main categories as below:

External Over voltages

This type of over voltages originates from atmospheric disturbances, mainly due to lightning. This takes the form of a surge and has no direct relationship with the operating voltage of the line. It may be due to any of the following causes:

a) Direct lightning stroke

b) Electromagnetically induced over voltages due to lightning discharge taking place near the line, called 'side stroke'.

c) Voltages induced due to atmospheric changes along the length of the line.

d) Electrostatically induced voltages due to presence of charged clouds nearby.

e) Electrostatically induced over voltages due to the frictional effects of small particles like dust or dry snow in the atmosphere or due to change in the altitude of the line.

Internal Over voltages

These over voltages are caused by changes in the operating conditions of the power system. These can be divided into two groups as below:

1. Switching over voltages or Transient over operation voltages of high frequency:

This is caused when switching operation is carried out under normal conditions or when fault occurs in the network. When an unloaded long line is charged, due to Ferranti Effect the receiving end voltage is increased considerably resulting in over voltage in the system. Similarly when the primary side of the transformers or reactors is switched on, over voltage of transient nature occurs.

2. Temporary over voltages:

These are caused when some major load gets disconnected from the long line under normal or steady state condition.

4.2 System Faults

Over voltage tends to stress the insulation of the electrical equipment's and likely to cause damage to them when it frequently occurs. Over voltage caused by surges can result in spark over and flash over between phase and ground at the weakest point in the network, breakdown of gaseous/solid/ liquid insulation, failure of transformers and rotating machines.

4.2.1 Overvoltage Protection

There are always a chance of suffering an electrical power system from abnormal over voltages. These abnormal over voltages may be caused due to various reason such as, sudden interruption of heavy load, lightening impulses, switching impulses etc. These over voltage stresses may damage insulation of various equipments and insulators of the power system. Although, all the over voltage stresses are not strong enough to damage insulation of system, but still these over voltages also to be avoided to ensure the smooth operation of electrical power system.

These all types of destructive and non destructive abnormal over voltages are eliminated from the system by means of overvoltage protection.

4.2.3 **Voltage Surge**

The over voltage stresses applied upon the power system, are generally transient in nature. Transient voltage or voltage surge is defined as sudden sizing of voltage to a high peak in very short duration.The voltage surges are transient in nature, that means they exist for very short duration. The main cause of these voltage surges in power system are due to lightning impulses and switching impulses of the system. But over voltage in the power system may also be caused by, insulation failure, arcing ground and resonance etc.

The voltage surges appear in the electrical power system due to switching surge, insulation failure, arcing ground and resonance are not very large in magnitude. These over voltages hardly cross the twice of the normal voltage level. Generally, proper insulation to the different equipment of power system is sufficient to prevent any damage due to these over voltages. But over voltages occur in the power system due to lightning is very high. If over voltage protection is not provided to the power system, there may be high chance of severe damage. Hence all over voltage protection devices used in power system mainly due to lightning surges.

4.2.3 Switching Impulse

Switching Impulse or Switching Surge

When a no load transmission line is suddenly switched on, the voltage on the line becomes twice of normal system voltage. This voltage is transient in nature. When a loaded line is suddenly switched off or interrupted, voltage across the line also becomes high enough current chopping in the system mainly during opening operation of air blast circuit breaker, causes over voltage in the system. During insulation failure, a live conductor is suddenly earthed. This may also caused sudden over voltage in the system. If emf wave produced by alternator is distorted, the trouble of resonance may occur due to 5th or higher harmonics. Actually for frequencies of 5th or higher harmonics, a critical situation in the system so appears, that inductive reactance of the system becomes just equal to capacitive reactance of the system. As these both reactance cancel each other the system becomes purely resistive. This phenomenon is called resonance and at resonance the system voltage may be increased enough.

But all these above mentioned reasons create over voltages in the system which are not very high in magnitude.

But over voltage surges appear in the system due to lightning impulses are very high in amplitude and highly destructive. The affect of lightning impulse hence must be avoided for over voltage protection of power system.

Methods of Protection Against Lightning

These are mainly three main methods generally used for protection against lightning. They are

- Earthing screen.
- Overhead earth wire.
- Lighning arrester or surge dividers.

Earthing Screen

Earthing screen is generally used over electrical substation. In this arrangement a net of GI wire is mounted over the sub-station. The GI wires, used for earthing screen are properly grounded through different sub-station structures. This network of grounded GI wire over electrical sub-station, provides very low resistance path to the ground for lightning strokes.

This method of high voltage protection is very simple and economic but the main drawback is, it can not protect the system from travelling wave which may reach to the sub-station via different feeders.

Overhead Earth Wire

This method of over voltage protection is similar as earthing screen. The only difference is, an earthing screen is placed over an electrical sub-station, whereas, overhead earth wire is placed over electrical transmission network. One or two stranded GI wires of suitable cross-section are placed over the transmission conductors. These GI wires are properly grounded at each transmission tower. These overhead ground wires or earth wire divert all the lightning strokes to the ground instead of allowing them to strike directly on the transmission conductors.

Lightning Arrester

The previously discussed two methods, i.e. earthing screen and over-head earth wire are very suitable for protecting an electrical power system from directed lightning strokes but system from directed lightning strokes but these methods can not provide any protection against high voltage travelling wave which may propagate through the line to the equipment of the sub-station.The lightning arrester is a devices which provides very low impedance path to the ground for high voltage travelling waves.

The concept of a lightning arrester is very simple. This device behaves like a nonlinear electrical resistance. The resistance decreases as voltage increases and vice-versa, after a certain level of voltage.The functions of a lightning arrester or surge dividers can be listed as below.

Under normal voltage level, these devices withstand easily the system voltage as electrical insulator and provide no conducting path to the system current.

On occurrence of voltage surge in the system, these devices provide very low impedance path for the excess charge of the surge to the ground.

After conducting the charges of surge, to the ground, the voltage becomes to its normal level. Then lightning arrester regains its insulation properly and prevents regains its insulation property and prevents further conduction of current, to the ground.

There are different types of lightning arresters used in power system, such as rod gap arrester, horn gap arrester, multi-gap arrester, expulsion type LA, value type LA. In addition to these the most commonly used lightning arrester for over voltage protection now-a-days gapless ZnO lightning arrester is also used.

4.3 Insulation Co-ordination

Insulation Coordination in Power System was introduced to arrange the electrical insulation levels of different components in the electrical power system including transmission network, in such a manner, that the failure of insulator, if occurs, confindes to the place where it would result in the least danmage of the system, easy to repair and replace, and results least disturbance to the power supply.

When any over voltage appears in the electrical power system, then there may be a chance of failure of its insulation system. Probability of failure of insulation, is high at the weakest insulation point nearest to the source of over voltage. In power system and transmission networks, insulation is provided to the all equipment and components.

Insulators in some points are easily replaceable and repairable compared to other. Insulation in some points are not so easily replaceable and repairable and the replacement and repairing may be highly expensive and require long interruption of power. Moreover failure of insulator at these points may causes bigger part of electrical network to be out of service. So, it is desirable that in situation of insulator failure, only the easily replaceable and repairable insulator fails. The overall aim of insulation coordination is to reduce to an economically and operationally acceptable level the cost and disturbance caused by insulation failure. In insulation coordination method, the insulation of the various parts of the system must be so graded that flash over if occurs it must be at intended points.

For proper understanding the insulation coordination we have to understand first, some basic terminologies of the electrical power system. Let us have a discussion.

Nominal System Voltage

Nominal System Voltage is the phase to phase voltage of the system for which the system is normally designed. Such as 11 KV, 33 KV, 132 KV, 220 KV, 400 KV systems.

Maximum System Voltage

Maximum System Voltage is the maximum allowable power frequency voltage which can occurs may be for long time during no load or low load condition of the power system. It is also measured in phase to phase manner.

List of different nominal system voltage and their corresponding maximum system voltage is given below for reference,

Nominal System Voltage in KV 11 33 66 132 220 400

Maximum System Voltage in KV 12 36 72.5 145 245 420

NB - It is observed from above table that generally maximum system voltage is 110 % of corresponding nominal system voltage up to voltage level of 220 KV, and for 400 KV and above it is 105 %.

Factor of Earthing

This is the ratio of the highest rms phase to earth power frequency voltage on a sound phase during an earth fault to the rms phase to phase power frequency voltage which would be obtained at the selected location without the fault.

This ratio characterizes, in general terms, the earthing conditions of a system as viewed from the selected fault location.

Effectively Earthed System

A system is said to be effectively earthed if the factor of earthing does not exceed 80 % and non-effectively earthed if it does.Factor of earthing is 100 % for an isolated neutral system, while it is 57.7 % (1/√3 = 0.577) for solidly earthed system.

Insulation Level

Every electrical equipment has to undergo different abnormal transient over voltage situation in different times during its total service life period. The equipment may have to withstand lightning impulses, switching impulses and/or short duration power frequency over voltages. Depending upon the maximum level of impulse voltages and short duration power frequency over voltages that one power system component can withstand, the insulation level of high voltage power system is determined.

During determining the insulation level of the system rated less than 300 KV, the lightning impulse withstand voltage and short duration power frequency withstand voltage are considered. For equipment rated more or equal 300 KV, switching impulse withstand voltage and short duration power frequency withstand voltage are considered.

Lightning Impulse Voltage

The system disturbances occur due to natural lightning, can be represented by three different basic wave shapes. If a lightning impulse voltage travels some distance along the transmission line before it reaches to a insulator its wave shaped approaches to full wave, and this wave is referred as 1.2/50 wave. If during travelling, the lightning disturbance wave causes flash over across an insulator the shape of the wave becomes chopped wave. If a lightning stroke hits directly on the insulator then the lightning impulse voltage may rise steep until it is relieved by flash over, causing sudden, very steep collapse in voltage. These three waves are quite different in duration and in shapes.

Switching Impulse

During switching operation there may be uni-polar voltage appears in the system. The wave form of which may be periodically damped or oscillating one. Switching impulse wave form has steep front and long damped oscillating tale.

Short Duration Power Frequency Withstand Voltage

Short duration power frequency withstand voltage is the prescribed rms value of sinusoidal power frequency voltage that the electrical equipment shall withstand for a specific period of time normally 60 seconds.

Protection Level Voltage of Protective Device

Over voltage protective device like surge arrestors or lightning arrestors are designed to withstand a certain level of transient over voltage beyond which the devices drain the surge energy to the ground and therefore maintain the level of transient over voltage up to a specific level. Thus transient over voltage can not exceed that level. The protection level of over voltage protective device is the highest peak voltage value which should not be exceeded at the terminals of over voltage protective device when switching impulses and lightening impulses are applied.

As we discussed above that a component of electrical power system may suffer from different level of transient voltage stresses, switching impulse voltage and lightning impulse voltage. The maximum amplitude of transient over voltages reach the components, can be limited by using protecting device like lightning arrestors in the system. If we maintain the insulation level of all the power system component above the protection level of protective device, then ideally there will be no chance of breakdown of insulation of any component. Since the transient over voltage reaches at the insulation after crossing the surge protective devices will have amplitude equals to protection level voltage and protection level voltage impulse insulation level of the components.

Generally, the impulse insulation level is established at 15 to 25 % above the protective level voltage of protective devices.

Course Outcome

At the end of the course, student will be able to:

Discuss overvoltage phenomenon and insulation coordination in electric power systems.

MODULE 5: Non-Destructive Testing of Materials and Electrical Apparatus:

Syllabus

5.1 Introduction, Measurement of Dielectric Constant and Loss Factor, Partial Discharge Measurements.

5.2 High Voltage Testing of Electrical Apparatus: Testing of Insulators and Bushings, Testing of Isolators and Circuit Breakers

5.3 Testing of Cables, Testing of Transformers, Testing of Surge Arrestors, Radio Interference Measurements, Testing of HVDC Valves and Equipment.

5.1 Introduction

What is Non-destructive Testing?

- It is a wide group of analysis techniques used in science, industry & Engineering to evaluate the properties of Insulating material, component or system without causing damage.
- It is very difficult to test the quality of insulating material after it forms part of equipment, suitable tests must be done to ensure in the said range of operation.
- Non-Destructive Testing (NDT) is ensure that the material is not destroyed as in the case of high voltage testing.
- NDT helps to estimate the electrical properties such as resistivity, dielectric constant & loss factor , loss angle & dielectric loss over a wide frequency range.
- NDT is commonly used in , mechanical engineering, petroleum engineering, electrical engineering, civil engineering, systems engineering, aeronautical engineering, medicine, and art.

5.1.1 Dielectric loss

1. Dielectric loss measure the quantity of a dielectric material's inherent dissipation of electromagnetic energy converted into heat.
2. The dielectric loss can be expressed in terms of loss angle δ.
3. An efficient dielectric material supports a varying charge with minimal dissipation of energy in the form of heat.

Dielectric loss angle

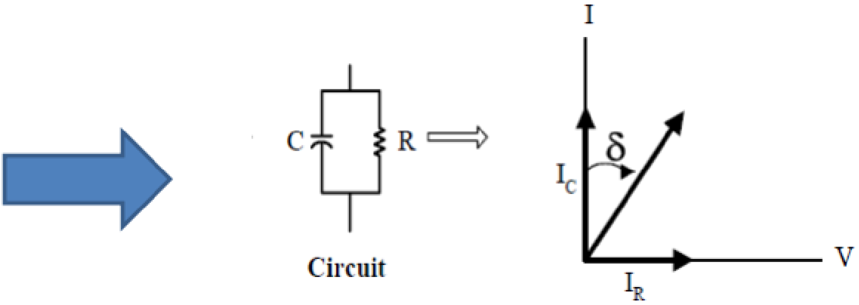
1. tan δ is called as loss angle or dissipation factor testing or loss tangent.
2. Helps to determine the quality of the cable insulation.
3. The cable and its insulation is compared to a parallel plate capacitor.
4. In a perfect capacitor, the voltage and current are phase shifted 90 degrees.
5. If there are impurities in the insulation, like water trees, electrical trees, moisture and air pockets, etc. the resistance of the insulation decreases.
6. Resulting in an increase in resistive current through the insulation.
7. It is no longer a perfect capacitor

8. The current and voltage will no longer be shifted 90 degrees. It will be something less than 90 degrees.
9. The extent to which the phase shift is less than 90 degrees is indicative of the level of insulation contamination/DIELECTRIC LOSS
10. This "Loss Angle" is measured and analyzed.

Fig represents an equivalent circuit of a cable, The tangent of the angle δ is measured

1. Perfect cable insulation δ=0
2. tan δ helps to find out the life expectancy of dielectrics

$\tan\delta = I_R / I_C$



How to measure dielectric loss and loss angle of a dielectric material?

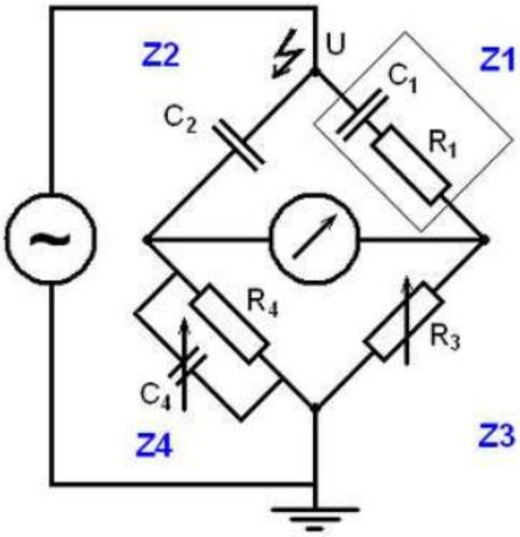
By using the following devices

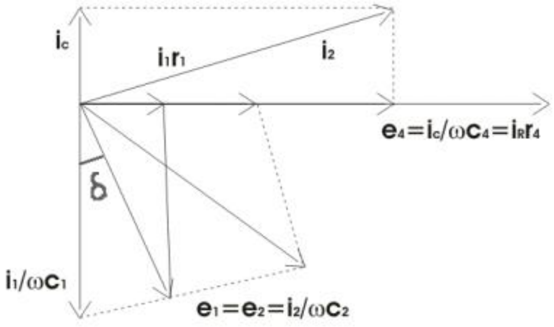
1.HIGH VOLTAGE SCHERING BRIDGE

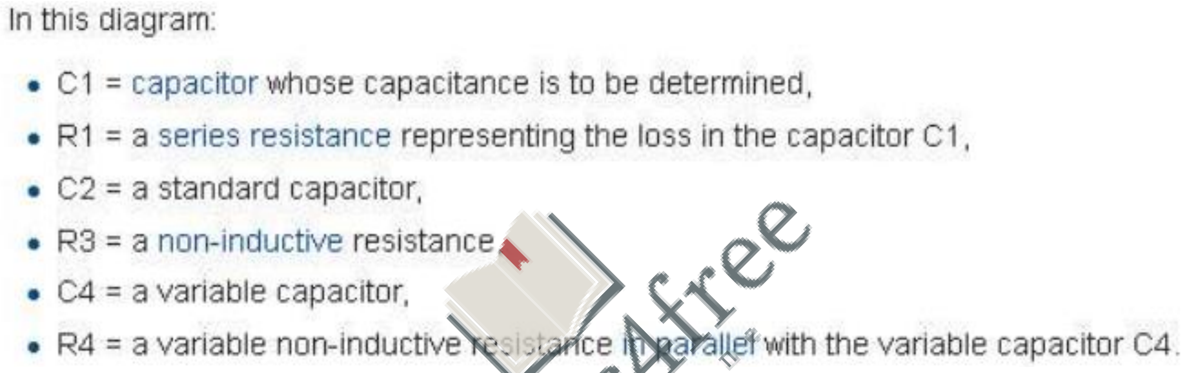
2.TRANSFORMER RATIO ARM BRIDGE

A) What is Schering bridge?

1. The Schering Bridge is an electrical circuit used for measuring the insulating properties of electrical cables and equipment.
2. Accurate value of capacitance can be measured by using Schering bridge.
3. It is used to measure insulation properties such as dielectric loss and loss angle.
4. It has the advantage that the balance equation is independent of frequency.
5. We can able to find the Unknown capacitance by using Schering bridge ,
   ie C1= C2R4/R3 R1=R3C4/C2
   Loss angle tan δ= wR1C1






In this diagram:

- C1 = capacitor whose capacitance is to be determined,
- R1 = a series resistance representing the loss in the capacitor C1,
- C2 = a standard capacitor,
- R3 = a non-inductive resistance,
- C4 = a variable capacitor,
- R4 = a variable non-inductive resistance in parallel with the variable capacitor C4.

5.1.2 Transformer Ratio Arm Bridge

Why Transformer Ratio Arm Bridge?

1. If you are proceeding with conventional bridge balancing methods, the following disadvantages will occur
2. For high frequency measurements, the arm with high resistance leads to difficulties due to their residual inductance, capacitance and skin effect.
3. If the length of arm is large, shielding difficulties.

B) What is Transformer Ratio Arm Bridge?

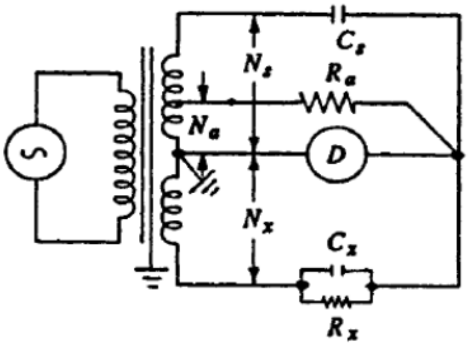
1. This bridge provide more accurate results for the small capacitance measurements.
2. Using at least two arms.
3. Two types of Transformer Ratio Arm bridges are available
   a)Voltage Ratio Arm bridge
   b)Current Ratio Arm bridge

a)Voltage Ratio Arm bridge -Suitable for high frequency low voltage application

b)Current Ratio Arm Bridge -Used for high voltage low frequency application

Circuits for Transformer Ratio Arm Bridge

A) Transformer Voltage Ratio arm bridge



Assume transformer is ideal.

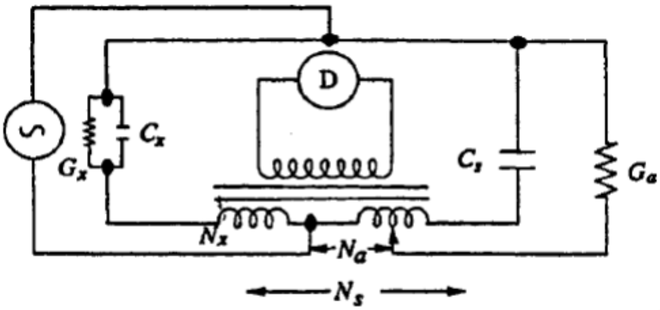
$$\frac{V_s}{V_x} = \frac{N_s}{N_x} = \frac{C_x}{C_s}; \text{ and } \frac{R_x}{R_a} = \frac{N_x}{N_a}$$

where C_x and C_s are unknown and standard capacitances respectively, R_x and R_a are unknown and standard resistances, and N_x, N_a, and N_s are the corresponding turns of the transformer ratio windings.

1. In practical situation due to the presence of magnetizing current and the load currents, the voltage ratio slightly differ from the turns ratio.
2. Those errors are ratio errors & load error.

B) Transformer Current Ratio arm bridge

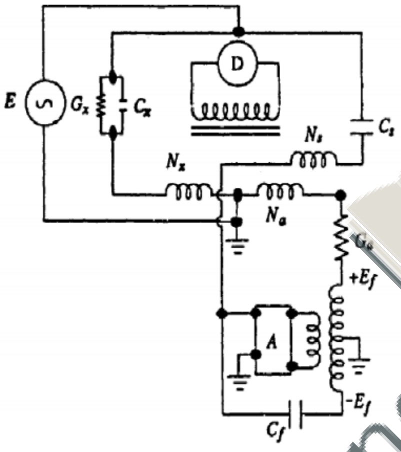
1. Suitable for high voltage low frequency applications.
2. The main component of the bridge is a three winding current transformer with very low losses & leakage (core of high permeability).
3. Transformer is carefully shielded & protected against mechanical vibrations.



Current comparator bridge

- Current ratio method
- Full voltage is applied across test capacitor
- Standard capacitor has to be built For high voltage.

$$E_f \approx \frac{C_s}{C_f} \dot{E}$$ Gain of the amplifier



Current comparator for high voltage application

Cf- Balancing capacitor
Cs- Standard capacitor

Ef – Proportional emf

At balance , there is no voltage across the current Comparator winding

Transformer Current Ratio arm bridge- Calculations

The balance equations of the bridge are

$$C_x = C_s \frac{N_s}{N_x}; \; G_x = \frac{C_s}{C_f} \frac{N_a}{N_x} G_a$$

$$\tan \delta = \frac{G_x}{\omega C_x} = \frac{1}{\omega C_f} \frac{G_a N_a}{N_x}$$

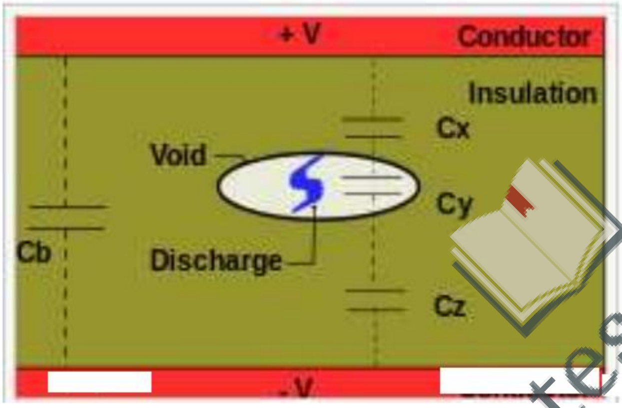
G_x and G_a are unknown and standard conductances, and C_f is the balancing condenser.

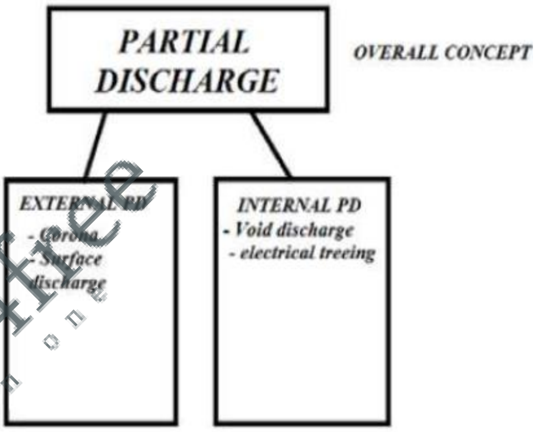
5.1.3 Partial Discharge (PD)

1. Partial discharge (PD) is a localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress.
2. The distance between two electrode is only partially bridged.
3. PD is responsible for reducing the insulation strength.

4. PD can occur in a gaseous, liquid or solid insulating medium.
5. It often starts within gas voids, such as voids in solid epoxy insulation or bubbles in transformer oil.
6. PD usually begins within voids, cracks, or inclusions within a solid dielectric , at conductor-dielectric interfaces within solid or liquid dielectrics, or in bubbles within liquid dielectrics.
7. Since PDs are limited to only a portion of the insulation
8. PD can also occur along the boundary between different insulating materials.
9. Partial discharge that only partially bridges the dielectrics or insulating between two conductors.
10. Examples of partial discharge: Internal discharge (voids in a dielectric material) , surface discharge (Discharge from the conductor into gas or liquid or solids) & corona discharge.
11. Partial discharges which in course of time reduce the strength of insulation leading to a total or partial failure or breakdown of insulation.

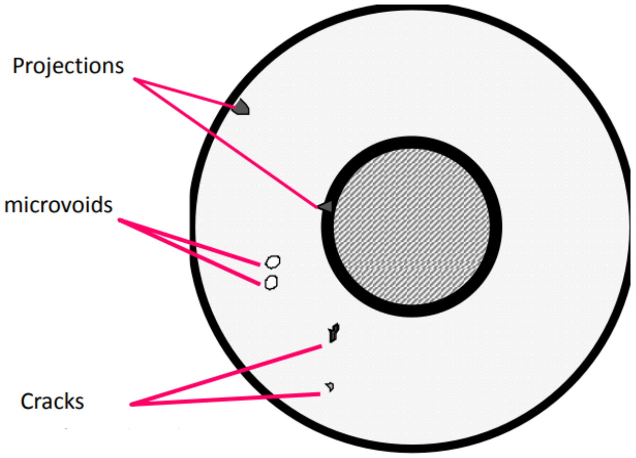
The equivalent circuit of a dielectric incorporating a cavity can be modelled as a capacitive Voltage divider in parallel with another capacitor.





Reasons for Partial Discharge

1. Poor design of insulation
2. Failure during manufacturing or assembling
3. Normal ageing
4. Degradation



Types of partial Discharge

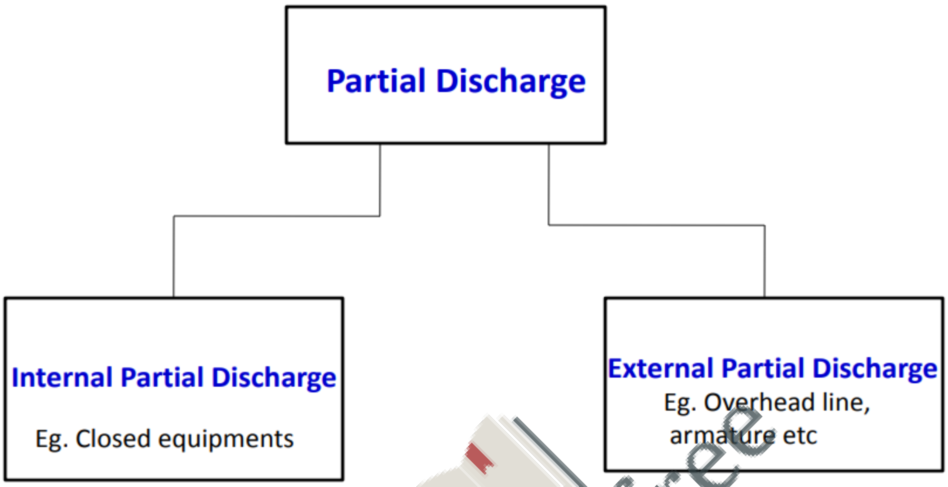
1.Corona or gas discharge- due to non uniform field, sharp edge of electrodes etc.

2.Surface discharge- interfacing of different dielectric material results over stress

3.Cavity discharge- over stress due to cavities

4.Treeing channels

Classification of Partial Discharge



5.1.3.1 Need for discharge detectors in dielectric measurement

1. Detectors are available in the wide range of frequency
2. Selection of detectors depends on bridge circuit & applications.
3. Dc measurements- dc galvanometer & dc amplifier with micro ammeter.
4. Power frequency measurements-vibration galvanometer.
5. Audio frequency range-tuned null detectors.
6. CRO or DSO can be used as a detector , if the requirement of sensitivity is very low.

a) Discharge Detection Methods

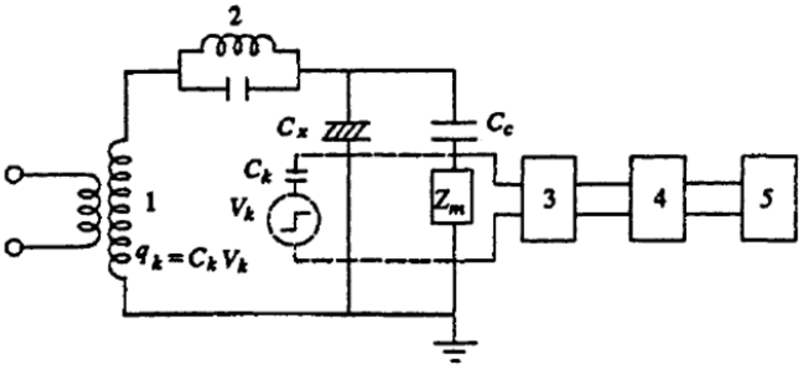
- Various methods are available for measuring discharge detection especially for analyzing Partial Discharge (PD).

1.Discharge Detection using ‘straight detectors’

2.Balanced detection methods

3.Narrow band & Wide band circuits

1.Discharge Detection using ‘straight detectors’



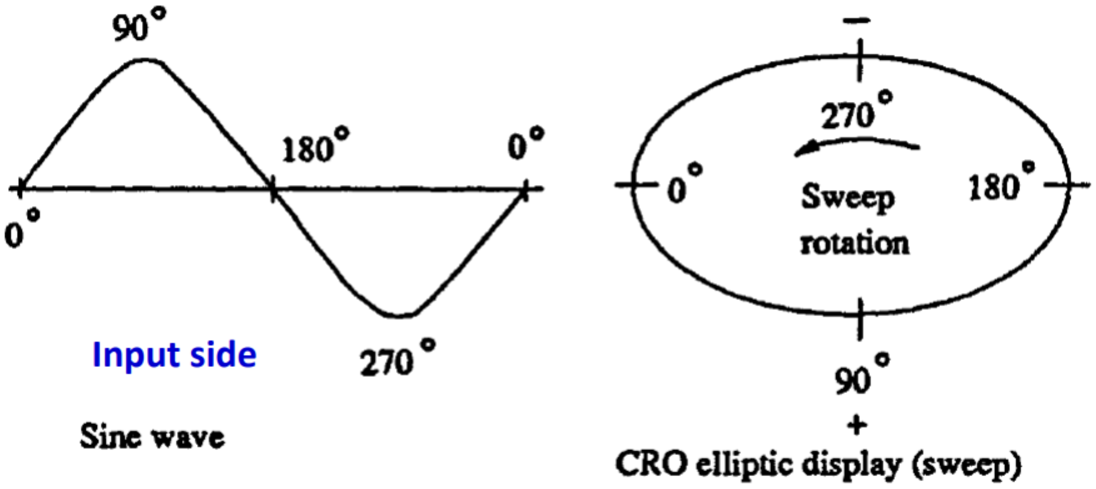
1 — H.V. testing transformer
2 — Filter
3 — Band pass filter
4 — Amplifier
5 — Display unit (CRO or pulse counter or multi-channel analvser unit)

C_x — Sample or test piece
C_c — Coupling condenser
Z_m — Detector impedance
V_k — Calibrating pulse
C_k — Calibrating capacitor
q_k — Calibrator charge

Component descriptions of ‘straight detectors’

1. HV Transformer is free from discharge
2. The resonant filter is used to prevent any pulses starting from the capacitance of the windings and bushings of the transformer
3. Cx is the test object- 100 pF to 0.1pF
4. Cc is the coupling capacitor
5. Zm is the detection impedance
6. The signal is developed across detection impedance Zm
7. Then the signal is passed through band pass filter (10kHz frequency) ,amplifier and displayed Unit (on the CRO & multi channel analyzer unit)

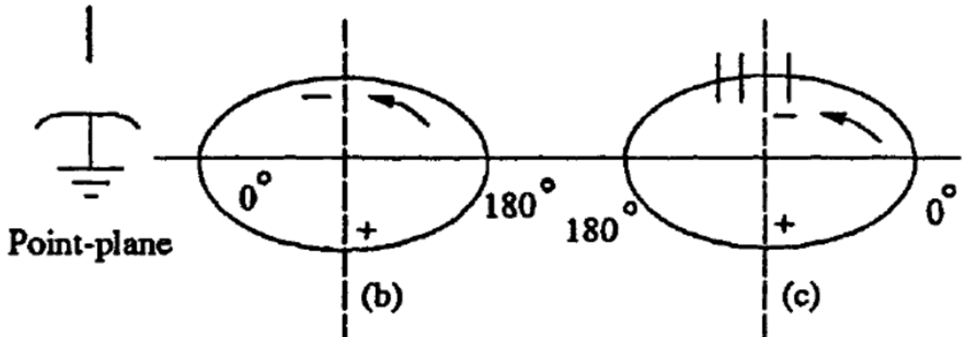
Discharge patterns



Sine wave

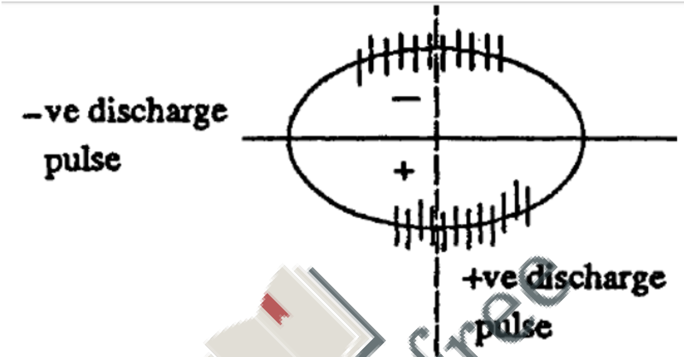
CRO elliptic display (sweep)

(a) Elliptic sweep display

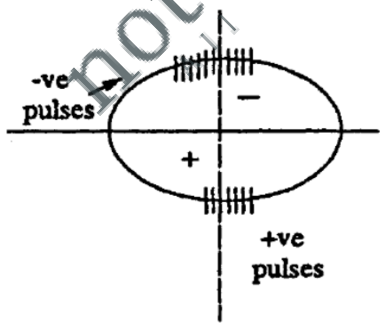


(b), (c) Corona discharges in point-plane configuration

Discharge patterns – voids in insulating materials



(d) Discharges in voids in the insulation



(e) Discharges in voids bound on one side with insulation, and on the other side by a conductor

Drawbacks of straight detectors

1. Noise problems.
2. The filter used to block the noise sources may not be effective.
3. External disturbances are not fully rejected.
4. Tuning of filters is a difficult task.

2.Discharge Detection using 'Balanced Detection Method'

Two methods

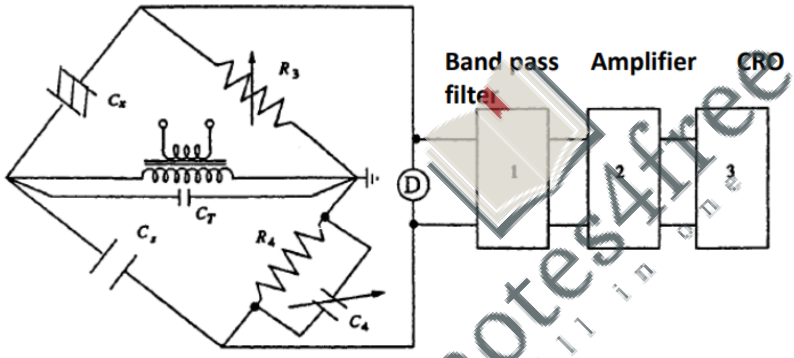
1. Balance Detector using Schering Bridge

2.Balance Discharge Detector Schemes (Differential detector)

1. Balance Detector using Schering Bridge

1. In this method test object is not grounded.
2. The bridges are tuned & balanced at 50 Hz.
3. External interferences from outside is balanced out.
4. A filter is used across the detector terminals to block 50Hz components present & pass the signals in between 5 to 50kHz (Band pass filter).
5. Only internally generated pulses (from the test object) are detected.
6. Internally generated pulse signal is amplified by using an amplifier.
7. CRO gives the display of pulse pattern.

Circuit arrangement for Balance Detector by using Schering Bridge



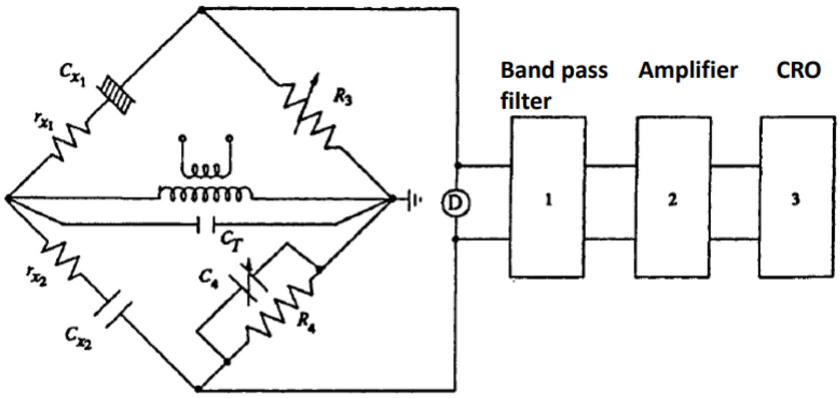
D — Power frequency detector
1 — Filter (band pass)
2 — Amplifier
3 — Display unit — CRO or counter

Balanced detector using Schering bridge

2.Balanced Discharge Detection Scheme (Differential Detector)

1. Modified scheme of balanced discharge detection using Scherings bridge.
2. Another test sample called dummy sample is used in the place of standard capacitor •
3. Capacitance and tan δ of dummy coil & test sample are made approximately equal, but not exactly equal.
4. Advantages- i)capacity for better rejection of external noises, ii) better resolution & iii)wide frequency band
5. Drawbacks – If two discharges occur in both samples simultaneously , they cancel out, but this is very rare.

Circuit for Balanced Discharge Detection Scheme (Differential Detector)



Differential detector

Balanced discharge detector schemes

Factors affecting discharge detection

1. Applied voltage
2. Different sample of material
3. Different void size

5.2 Definitions of terminologies,

1.Disruptive Discharge Voltage

- The voltage which produces the loss of dielectric strength of an insulation.
- Collapse of voltage & passage current
- Permanent loss for solid dielectrics, temporary loss for liquid and gaseous dielectrics.

2.Flashover

-when a discharge taking place in between two electrodes in a gas or liquid is called flashover.

3.Puncture

-when the discharge occur through solid insulation medium is called puncture

4.**Withstand voltage-** The voltage which has to be applied to a test object under specified condition in a withstand test is called withstand voltage. (as per IS:731 & IS:2099-1963)

5.**Fifty per cent flashover voltage** – This is the voltage which has a probability of 50% flashover when applied to a test object which results loss of insulation strength temporarily.

6.**Hundred per cent flash over voltage**-The voltage ,that causes a flash over at each of its applications under specified conditions , when applied to test objects as specified, is 100% flash over voltage

7.**Creepage Distance-** It is the shortest distance between two metal fittings on the insulator or dielectrics.

8.**AC Test Voltage-** Alternating test voltage should have power frequency in the range of 40 to 60 Hz and approximately sinusoidal. The deviation allowed for the sinusoidal wave is 7%. The deviation checked by measuring peak value, average vale & RMS value continuously. Computing average value, RMS value & Form factor continuously.

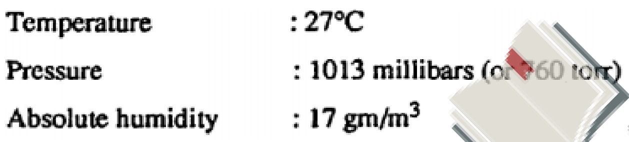
9. **Impulse Voltage-** Impulse voltages are characterized by polarity, peak value, time to front, and time to half the peak value after the peak

. • The time to front is defined as 1.5 times to time between 30% and 90% of the peak value in the rising portion of the wave.

10.**Reference Atmospheric Condition**

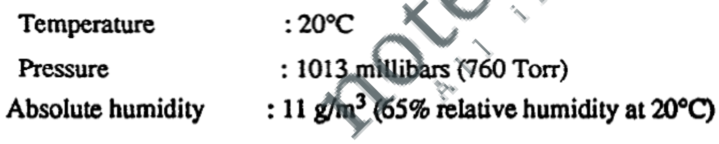
• The electrical characteristics of the insulators and other apparatus are normally referred to the reference atmospheric conditions

. • According to the Indian Standard Specifications

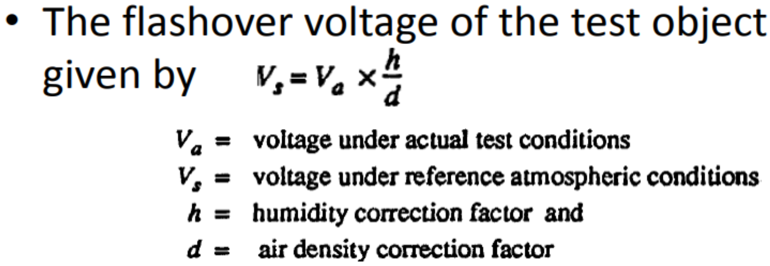


Temperature : 27°C
Pressure : 1013 millibars (or 760 torr)
Absolute humidity : 17 gm/m^3

Based on British Standard Specifications



Temperature : 20°C
Pressure : 1013 millibars (760 Torr)
Absolute humidity : 11 g/m^3 (65% relative humidity at 20°C)



- The flashover voltage of the test object is given by $V_s = V_a \times \frac{h}{d}$

V_a = voltage under actual test conditions
V_s = voltage under reference atmospheric conditions
h = humidity correction factor and
d = air density correction factor

11. Air density correction factor

- The air density correction factor is given by,

$$d = \frac{0.289b}{273+t} \text{ for } 20°C$$

$$\text{or, } \frac{0.296b}{273+t} \text{ for } 27°C$$

where

b = atmospheric pressure in millibars, and

t = atmospheric temperature, °C.

5.2.1 Test on Insulators

High voltage test includes

i)The power frequency tests &

ii) Impulse tests: All insulators are tested for both categories of test.

i)Power frequency test: Dry and wet flash over test, Wet & dry withstand tests (1 minute)

ii)Impulse Tests: Impulse withstand voltage test, Impulse flash over test and pollution testing

Why testing on insulators are required….?

1. To check the design features
2. To check the quality of test piece

i) Power frequency tests

(a) Dry and wet flashover test:

• The AC voltage of power frequency is applied across the insulators & increased at an uniform rate of about 2% of the estimated test voltage, checking the breakdown.

• If the test is conducted without any rain or precipitation it is called as dry flashover test.

• If the test is done under condition of rain called as wet flash over test.

(b)Wet & dry withstand test

• In theses 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.

ii)Impulse tests

(a)Impulse withstand voltage test

• This test is done by applying standard impulse voltage of specified value under dry condition with positive & negative polarities.

- 5 consecutive waves are passed.
- That shouldn't case flashover or puncture

(b) Impulse Flash over test

- Test is done under the specified voltage.
- Adjust the test voltage for the exact 50% flash over value.
- The insulation surface should not damaged.

(c) Pollution Testing

- Creating artificial pollution environment (salt fog test).
- Test duration – 1 hour.

Testing of Isolator & Circuit Breaker

Importance of isolator

1. Disconnector switch used for isolating the section of the circuit from any energized conductor .
2. In HV , isolators are used in conjunction with circuit breaker
3. Isolators opened after a circuit breaker has opened the circuit, and closed before the circuit breaker closes the circuit.
4. Off-load or minimum current breaking mechanical switch.
5. Isolator is operated after the circuit breaker to completely isolate the circuit.
6. Isolator is used to isolate the circuit permanently after a fault. Circuit breaker is used to disconnect the circuit temporarily. That is the main difference between an isolator and CB.

Importance of circuit breaker

1. A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit.
2. Its basic function is to detect a fault condition and interrupt current flow.
3. On load or high current breaking switch

Why do we perform the testing of Isolators & Circuit breaker?

1. To evaluate operating characteristics
2. To study the constructional features
3. To calculate electrical parameters/characteristics

4. Conventional tests are available
   1.The dielectric tests or over voltage tests
   2. Impulse test
   3.The temperature rise tests (Thermal test)

4.The mechanical tests
5. The short circuit tests

1. Dielectric tests or overvoltage tests

Objectives of Dielectric test:

1. This test consists of overvoltage withstand test of power frequency.
2. Testing of withstanding lightning & switching impulse voltage.
3. This test is done for checking internal & external insulation level. ie circuit breaker in open and closed position.
4. Apply the test voltage separately when circuit breaker is in open and closed position.

Checking the internal insulation level

1. In the open position test voltage levels are 15% higher than the test voltage used when the circuit breaker is closed. (Voltage in Open position >15% of that of closed position.)
2. Chance of line to ground flash over.
3. To avoid the flash over the circuit breaker is mounted on insulator above the ground.
4. So the insulation level of body of circuit breaker is raised.
5. We can measure the requirement of insulation level based on flashover

Wet dielectric test- To check the external insulation level

1. It is used for outdoor switch gear.
2. The external insulation is provided for 2 minutes while the rated service voltage is applied.
3. Test over voltage is maintained over 30s.
4. No flash over should be occurred.
5. The test voltage is applied for a period of 1 minutes between (i) phases with the breaker is closed (ii) phases and earth with circuit breaker open (iii) across the terminals with circuit breaker open.
6. Perfect breaker should free from flash over or puncture. • The test voltage should be a standard (1/50) micro second wave.

2. The impulse tests

To check the performance under overvoltage due to switching operation of circuit breaker.

1. To check the performance of switching operation of circuit breaker by using standard impulse wave form.
2. Ensure the successful operation of circuit breaker.

3.Temperature rise test

1. These tests are make sure that the circuit breaker are designed according to the specification.
2. Checking thermal behavior of the breaker.
3. Test can be done with the help of thermo couple.

4. At 40 degree Celsius standard current rating will be 800A.
5. By connecting a resistance parallel with fixed and moving contact, we can measure - requirement of contact resistance - Heat dissipation
6. B.S.116:1952 specification require 500 operation for circuit breaker without failure.

4. Mechanical Test

1. A Circuit breaker must open and close at the correct speed and perform such operation without mechanical failure.
2. Based on B.S. 116: 1952 requires 500 opening & closing operation without failure & with no adjustment mechanism.
3. Mechanical test gives the details on material.
4. Helps to check the life span of the circuit breaker.

5.Short Circuit Test

Importance of Short Circuit Test • Most important test.

1. Check the primary performance of the device.
2. Checking their ability to safely interrupt the fault currents.
3. Short Circuit test consists of determining making and breaking capacities of circuit breaker at various load current and rated voltage.
4. Making capacity of a circuit breaker is the maximum current which the breaker can conduct at the instant of closing.
5. Breaking capacity of the circuit breaker refers to the maximum current in rms value the circuit breaker can interrupt.
6. In the case of isolators, SC test determine their capacity to carry rated short circuit current for a given duration.

Method of conducting short circuit tests

1.Direct test

2.Synthetic Tests

1.Direct test

1. Direct test can be conducted in two ways i) By using a short circuit generator as the source.
2. Short circuit generators is driven by an Induction motor & voltage can be varied by using field excitation. • ii)By using power utility system or network as the source. Overall system includes master breaker and test breaker.

2.Synthetic test

a) Direct testing in the network or field

b) Direct testing in short circuit test laboratories

c) Synthetic testing of circuit breaker

d) Composite testing

e) Unit testing

f) Testing procedure

g) Asymmetrical tests

a) Direct testing in the network or field

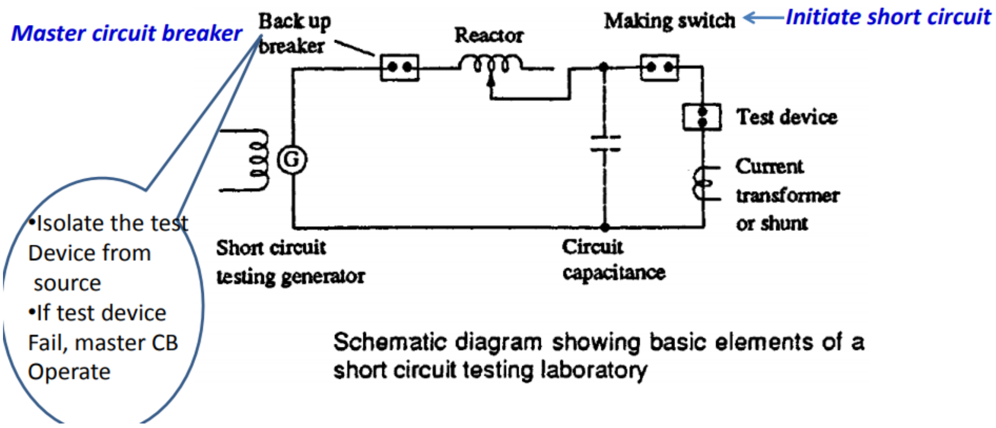
- Circuit breaker are some times tested for their ability to make or break the circuit under normal load conditions or under short circuit conditions in the network itself.
- We can do the actual test / real time test in the network.
- We can test the special occasions like very short line fault, breaking of charging current of long line etc.
- It is possible to study the thermal & dynamic effects of short circuit current

Drawbacks of direct testing in network or field

- The circuit breaker can be tested at only a given rated voltage and network capacity.

b)Direct testing in short circuit test laboratories

- In order to test the circuit breakers at different voltage and at different short circuit current short circuit laboratories are provided.
- Short circuit laboratories consists i)short-circuit generator associated with a master circuit breaker ii)resistors iii)reactors and iv)measuring devices.
- A make switch initiate short circuit.
- Master circuit breaker isolate the test device from source.
- If the test device failed to operate, tripping occurred for master breaker.



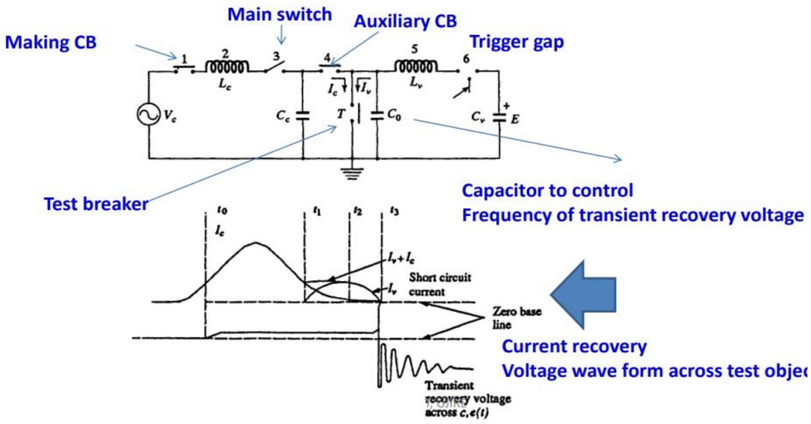
Schematic diagram showing basic elements of a short circuit testing laboratory

c)Synthetic testing of circuit breaker

- Two sources are used

- One supply provide ac current and other supply provide high voltage.

- Current and recovery voltage waveforms across the test circuit breaker can be determined using this test



d)Composite testing

1. The breaker is tested under rated voltage level.
2. The breaker is tested under reduced voltage level for checking breaking capacity.

- **Drawback:**

This method doesn't give the proper information about circuit breaker performance.

e)Unit testing

- Large circuit breaker testing under high voltage.

- Above 220kV system.

- More than 1 break is provided per pole.

- Checking the conditions of arc.

- Study the features of arc between fixed and moving contacts.

f)Asymmetric tests

- One test cycle is repeated for asymmetrical breaking capacity.

- Checking dc component in between fixed and moving contact.

- Test condition: dc component at the instant of contact separation is not less than 50% of AC component.

5.3Testing of Cables

- Importance of cables & its insulation- Underground cable and power transmission.

- Transmitting voltage signals.

- Necessity of cable insulation testing.

Types of cable insulation testing

1. Mechanical tests like bending test, dripping test, drainage test , fire resistance and corrosion test.
2.Thermal duty test

3.Dielectric power factor test

4.Power frequency with standing capacity

5.Impulse with stand voltage test

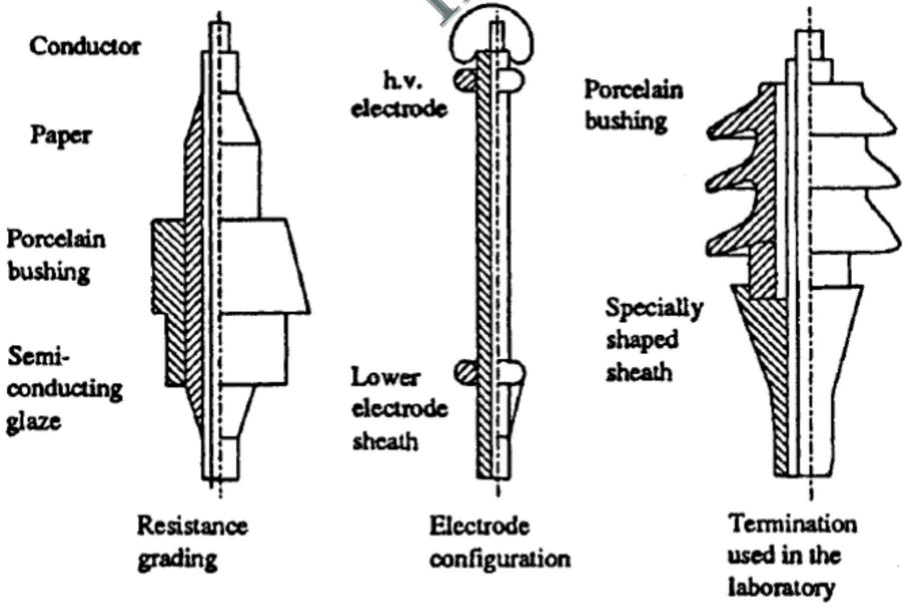
NOTE: 4 and 5 are HV Tests

6.Partial discharge test

7.Life expectancy test

Initial step –preparation of cable samples

1. In order to prepare over voltage withstand test sample have to prepare very carefully.
2. Otherwise excessive leakage or flash over occur during testing.
3. The normal length of the cable samples varies from 50cm to 10m.
4. The termination are usually made shielding of the end conductor with stress shield



Cable and terminals

1.Dielectric power factor test

1. By using the HV Schering bridge.
2. Dissipation factor tanδ is measured at 0.5,1,1.66 & 2 times of the rated voltage of the cable.
3. Schering bridge has to be given protection against overvoltage , in case breakdown occur in the cable.
4. balance equation is independent of frequency

2.HV Test on cable

a)Power frequency withstand voltage test
b) Impulse voltage with stand voltage test

Cables are tested for with stand the voltage using the power frequency AC, DC & Impulse voltage.

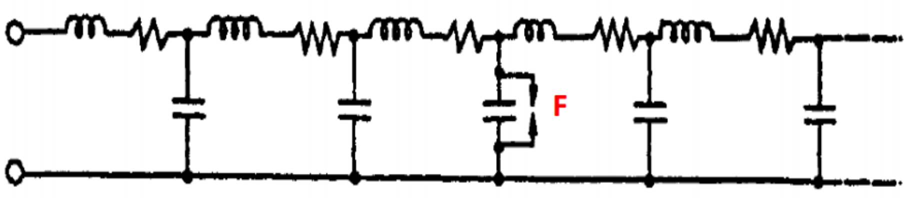
1. At a time of manufacture entire cable is tested under HV for checking continuity of the cable. procedure
2. (i) First cable is tested under AC voltage of 2.5 of rated voltage for 10 minutes & no damage should occur.
3. (ii) After cable is tested under high voltage dc voltage. DC voltage test consist of applying 1.8 times of rated voltage for 30 minutes.
4. (iii) Impulse voltage of the prescribed magnitude as per specification is applied & the cable has to withstand five applications without any damage.
5. Ensure no failure occur during insulation

3.Partial Discharge Test

1. Partial discharge depends upon internal discharge, electric stress and voltage stress. •
2. Procedure:(a) Discharge detection , (b) location of discharge & (c) Scanning methods are important steps of partial discharge test for ensuring the life of insulation.

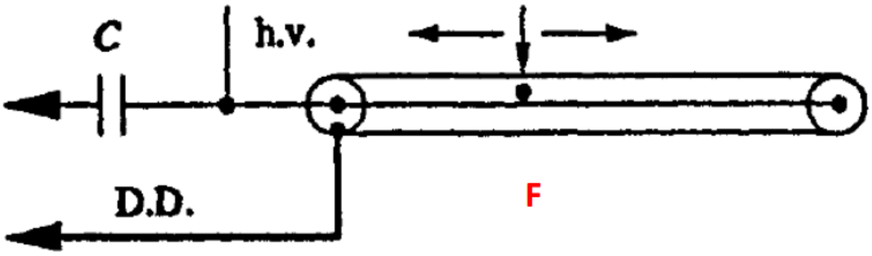
(a) Discharge detection

Equivalent circuit of a cable for discharge

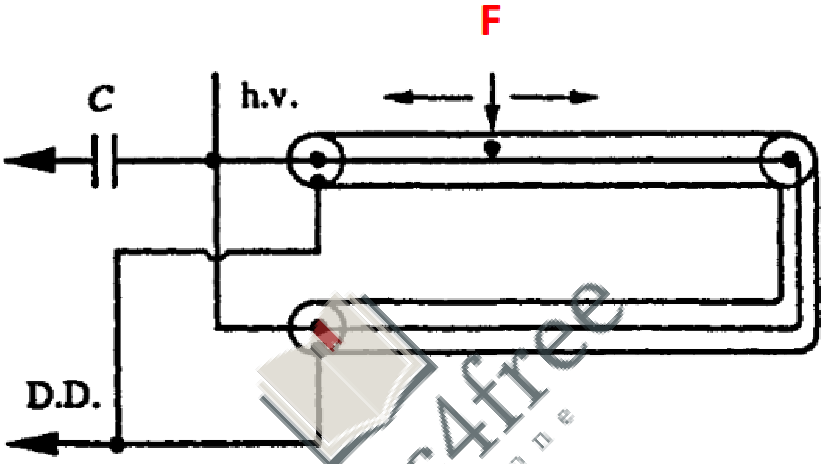


Equivalent circuit of the cable for discharges

1. The cable is connected to the discharge detector through the coupling capacitor.
2. Passage of travelling wave one or two times.
3. Check the cavity by analyze the nature of travelling wave.

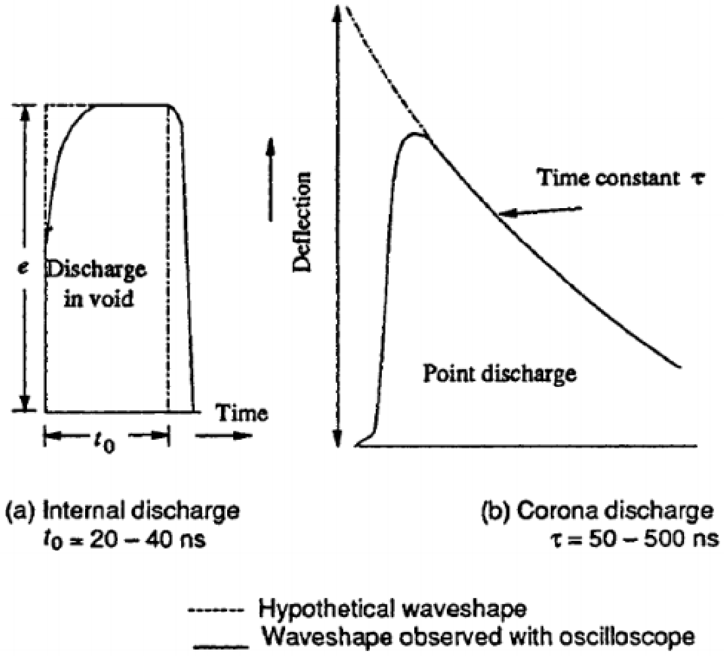


4. In order to improve transient response the given circuit is applicable Considering more number of cable & transient response
5. Serious error can detect • Error depends upon the shape of detector
6. Testing of long cable



(b) Location Discharge

1. Travelling wave is passing through the cable.
2. If any void present inside the cable ,there will be drop in travelling wave.
3. Measure the duration of wave/ pulse & the distance at which the discharge taking place from the cable can be calculated.
4. The shape of wave/pulse depends upon the nature of discharge.
5. We can observe the attenuation of the travelling wave.

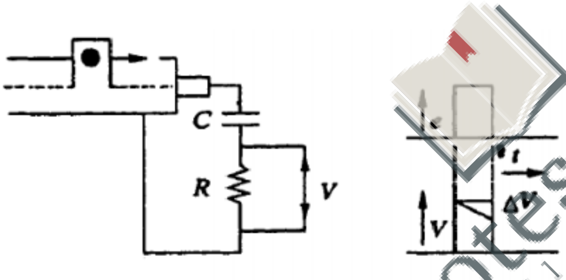


(a) Internal discharge
$t_0 = 20 - 40$ ns

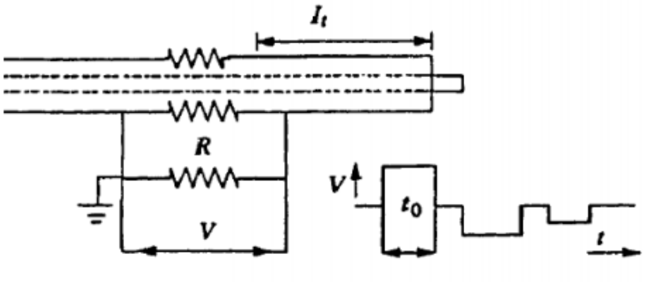
(b) Corona discharge
$\tau = 50 - 500$ ns

Typical waveshapes of pulses at the cable ends

Location Discharge- detection circuits for long cable

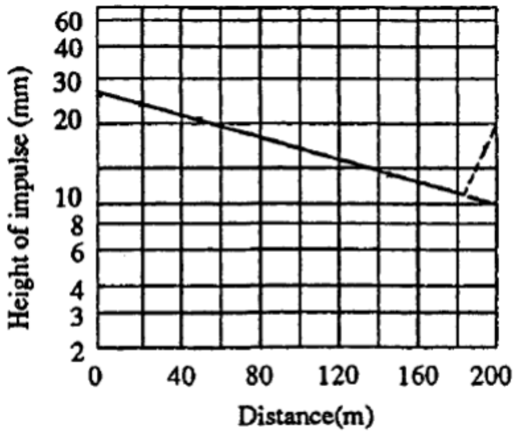


Resistor and capacitor



Without capacitor

Verification of location discharge



Attenuation of travelling waves

(c) Scanning method

1. To scan the overall cable for checking the voids or imperfections in manufacture. procedure
2. (i) Bare core cable is passed through high electric field & discharge location is done.
3. (ii) The core of the material is passed through a tube of insulating material filled with distilled water.
4. 4 electrodes in the form of rings are arranged
5. They should have electrical contact with water
6. We can check where exactly the occurrence of discharge
7. Discharge can locate at the length of the cable
8. The defective part can be easily isolate by using this method.
9. Can increase the perfection of insulation production.
10. Can isolate the defective insulation at factory site.

(d) Life tests

1. Reliability studies.
2. Able to determine the expected life of insulation.
3. Cables are performed under normal stress and maximum stress.
4. It is established that the relation between the maximum electrical stress Em and the life of the cable insulation in hours ‘t’ approximately follows the relationship
5. The duration of life tests is about 1 hr to 1000 hrs

$$E_m = Kt^{-(1/n)}$$

$K =$ constant which depends on the field conditions and the material, and

$n =$ life index depending on the material.

5.3.1Testing of transformers

Importance of transformer testing

1. Transformer is Important & costly apparatus in power systems.
2. Great care has to be exercised to see that the transformers are not damaged due to transient overvoltage's of either lightning or power frequency.
3. overvoltage tests become very important in the testing of transformers.
4. Mainly concentrating the overvoltage test.
5. Other tests are temperature rise test, short circuit test etc.
6. Performance test- OC-SC test, sumpners test(Back to back test) etc

Types of transformer testing

1.Preliminary testing- To check core insulation level

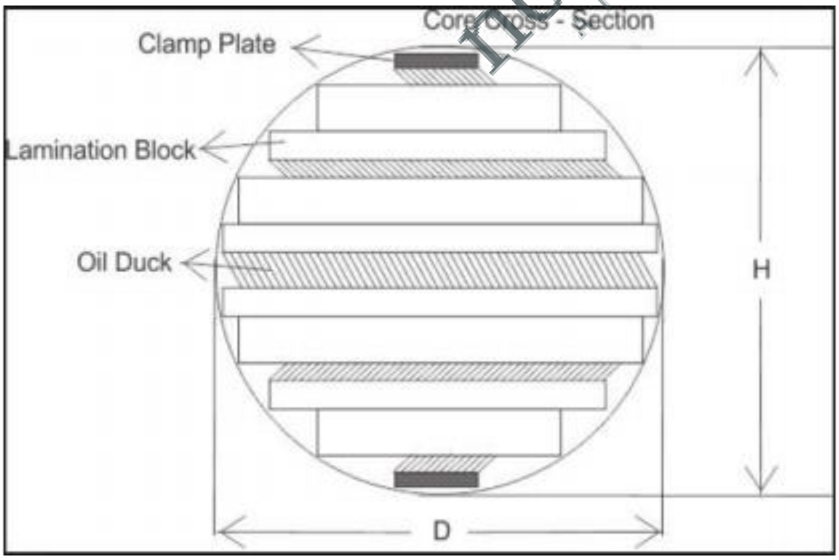
2.Routine Tests- Measurement of insulation resistance

3.Type test- Temperature rise test 4.Dielectric Test

5.Over Voltage Test- Induced over voltage test & Partial Discharge Test 6.Impulse Testing of Transformers

1. Preliminary testing

• After the core is assembled, 2kV test is done to ensure that the insulation between clamp plates, core bolts and core is adequate.



2. Routine Test

1. To measure winding insulation resistance
2. Measurement of Insulation resistance using ' Megger'.
3. The 'Megger' consists of a D.C power source (hand operated or electrically driven D.C generator or a battery source with electronic circuit) and a measuring system.
4. The insulation test reveals the condition of the insulation inside the transformer.
5. The insulation resistance values are affected by temperature, humidity and presence of dirt on insulators and bushings.

3.Type test- Temperature rise test •

1. Purpose: to confirm that under normal conditions, the temperature rise of the windings and the oil will not exceed the specified limit.
2. Temperature rises are measured above the temperature of the cooling air – Air cooled transformers
3. In water cooled transformers, the temperature rise is measured above the inlet water temperature – Water cooled type transformers
4. Hourly readings of the oil temperatures are taken.
5. Thermometer placed in a pocket in the transformer top cover.
6. Temperature at inlet and outlet of the cooler bank is also taken hourly and mean oil temperature is determined.
7. Ambient temperature is measured.
8. It should be demonstrated that the top oil temperature rise does not vary more than 1 degree Celsius per hour during four consecutive hourly readings.
9. The last reading is taken for the determination of the final oil temperature rise.

4. Dielectric Test

1. Purpose – to verify the power frequency withstand strength of the winding Insulation under test
2. The full AC test voltage shall be applied for 60s to the Windings with graded insulation. •
3. The test shall be successful if no collapse of the test voltage occurs.

5. Overvoltage tests

(i) Induced over voltage test:

1. Purpose : To verify the power frequency withstand strength along the winding under test, between its phases, and to earth and other windings. This test checks the inter turn insulation.
2. Test voltage is twice the corresponding rated voltage.
3. Supply frequency 100 to 400 Hz higher than normal is used.
4. The insulation withstand strength can be checked by using Induced Over Voltage Testing

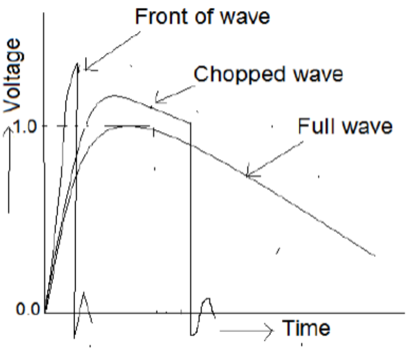
(ii) Partial Discharge test:

1. Partial discharge tests on the windings are done to calculate the discharge magnitude and the radio interference levels.
2. The winding insulation can be tested using any of the discharge detection methods..

3. The location of the fault or void is sometimes done by using the travelling wave technique similar to that for cables.
4. No method has been standardized as to where the discharge is to be measured.
5. Under the application of power frequency voltage, the discharge magnitudes greater than 10^4 pico coulomb are considered to be severe.
6. The transformer insulation should be such that the discharge magnitude will be far below this value.

6. Impulse testing of transformers

1. Lightning – common cause of flashover on overhead transmission lines.
2. Lightning stroke makes direct contact with a phase conductor and produces a voltage in excess of impulse voltage level.
3. 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.

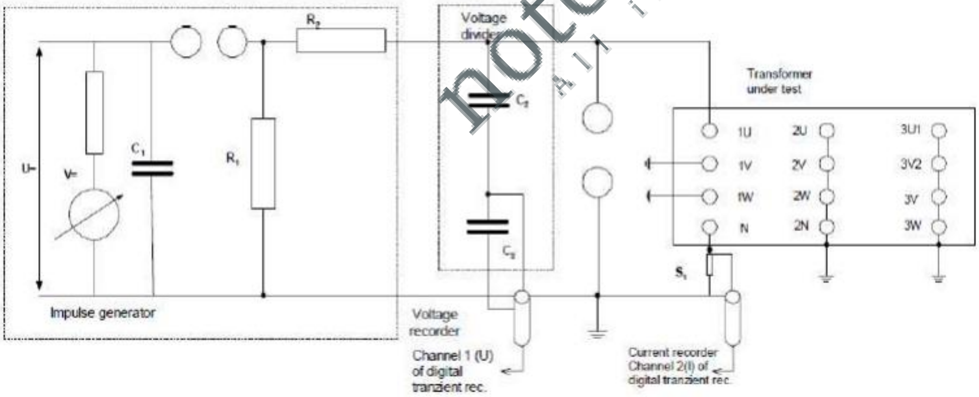


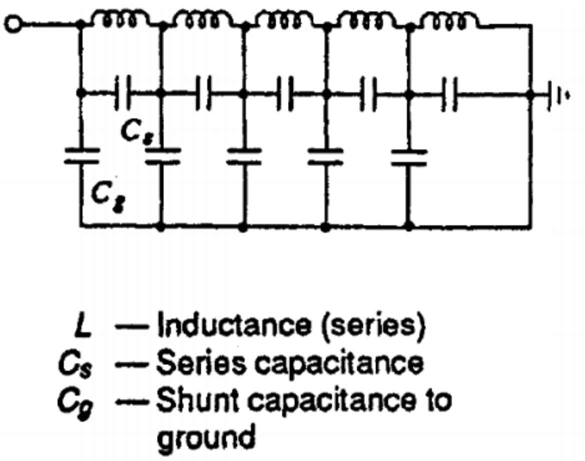
Lighning Impulse Wave Shapes

(1) Full wave 1.2/50 wave

(2) chopped wave

(3) front of waves





Equivalent circuit of transformer winding for impulses

Detection and fault location during impulse voltage testing of transformer

1. Can use any of the following methods
    1. General observations
    2. Voltage oscillogram method
    3. Neutral current method
    4. Transferred surge current method

1. General observations

• The fault can be located by general observations like noise in the tank or smoke or bubbles in breather

2. Voltage oscillogram method

• Fault or failure appears as a partial or complete collapse of the applied voltage wave.

• The sensitivity of this method is low

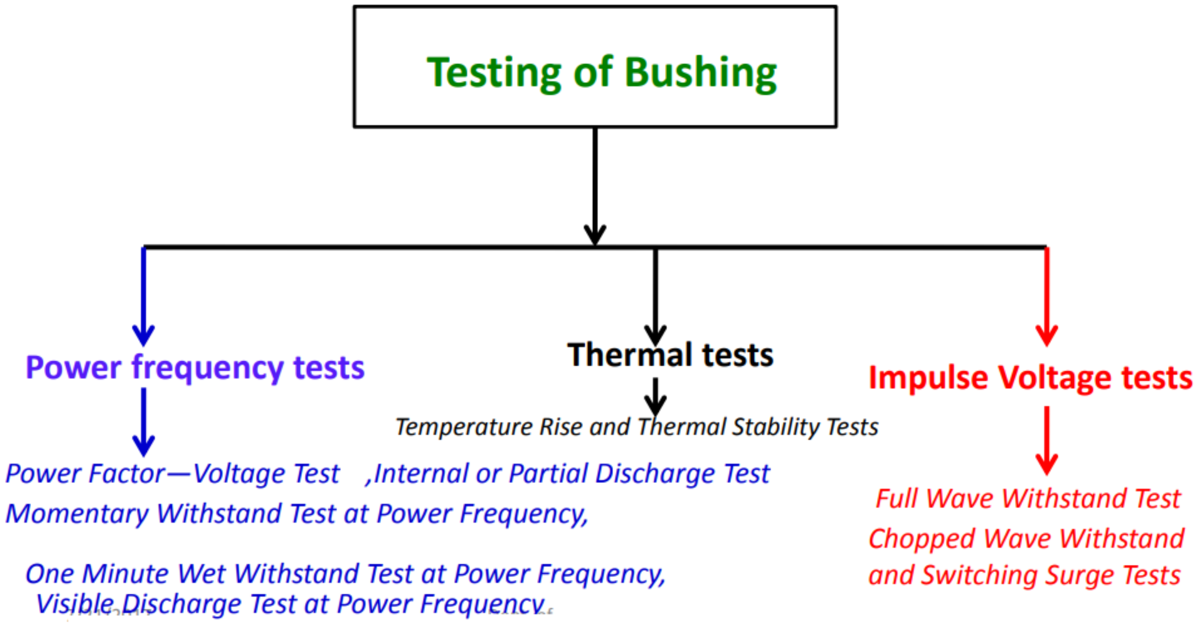
3. Neutral current method

• 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.

4. 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.

Testing of Bushings



(A) Power frequency test: Power Factor—Voltage Test – using schering bridge Internal or Partial Discharge Test – Any methods for measuring partial discharge Momentary Withstand Test at Power Frequency- Based on IS:2099 specification, Duration – 30s One Minute Wet Withstand Test at Power FrequencyDuration 1 minute, Provide rain /moisture Visible Discharge Test at Power Frequency- Dark room, Based on IS:2099 specification & observe discharge

(B) Impulse Voltage Testing: • Full Wave Withstand Test- Five consecutive full waves of standard waveform are applied, if two of them cause flashover, the bushing is said to have failed in the test. • Chopped Wave Withstand and Switching Surge Tests- HV test, procedure is same as that of Full Wave Withstand Test

(C) Thermal Tests: Temperature Rise and Thermal Stability Tests

• Temperature rise test is carried out in free air with an ambient temperature below 400 degree C at a rated power frequency (50 Hz) AC current.

• 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.

Course Outcome:

At the end of the course, students will be able to:

Discuss non-destructive testing of materials and electric apparatus and high-voltage testing of electric apparatus