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High voltage Engineering

Module-1:- Conduction and Breakdown in gases.
Breakdown in liquid dielectrics.
Breakdown in solid dielectrics.

Module-2:- Generation of High voltages & currents.

Module-3:- Measurement of High voltages & currents.

Module-4:- Over voltage Phenomenon & Installation coordination in Power system.

Module-5:- Non-destructive testing of materials and electrical Apparatus.
High voltage testing of electrical apparatus.

* All insulators are not dielectrics but all dielectrics are insulators.

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→ High voltages are used for a wide variety of applications covering the power systems, industry and research laboratories.
Such applications have become essential to sustain modern civilisation.
High voltages are applied in laboratories in nuclear research, in particle accelerators and vandegraaff generators.

→ For transmission of large bulbs of power over long distances, high voltages are indispensable. Also, voltages upto 100kV are used in electrostatic precipitators, in automobile ignition coils etc.
X-Ray equipment for metal and industrial applications also use high voltages.
Modern high voltage text laboratories employee voltages upto 6MV or more.

→ The diverts condition under which high voltage apparators is used to necessitate careful design of its insulation and the electrostatic field profiles. The insulation used are gases, vaccum, solid and liquid or a combination of these.

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Dielectric strength

The dielectric strength of an insulated material can be defined as the maximum dielectric stress with which the material can withstand.
It can also be defined as the voltage at which the current starts increasing to very high values unless controlled by the external impedance of the circuit.

The electric breakdown strength of its insulating depends on a variety of parameters such as pressure, temperature humidity, nature of applied voltage & imperfections in dielectric materials, material of electrodes and surface condition of electrodes, etc.

low vtg → 0 - 1000V
Medium vtg → 100V - 100kV
High vtg → 100kV - 230kV
Extra high → 230kV - 1000kV
Ultra high → 1000kV (above)

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High voltage Engineering

Branch of Electrical engineering that encompasses the study and application of the Electrical Phenomenon occuring in various medium at high voltages.

High voltage engineering provides the access to Electrical Energy for consumers far away from power generation units.

Importance of high voltage

The primary reason that power is transmitted at high voltages is to increase efficiency.

As electricity is transmitted over long distances, there are inherent energy losses along the way.

High voltage transmission minimizes the amount of power lost as electricity flows from one location to the next.

What do you mean by HV

In the context of building wiring and the general use of an Electrical apparatus, the International Electrotechnical commission defines high voltage as more than 1000 volts (V) of alternating current (AC)

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and above 1,500 V of direct current (DC)

Dielectric

Dielectric : very poor conductor of electric current.

When dielectrics are placed in an electric field, pratically no current flows in them because unlike metals, they have no loosely bound or free electrons that may drift through the material.

→ All dielectrics are insulators.

→ Supporters of electric field.

→ Examples of dielectrics :- ceramic, paper, mica.

→ Examples of insulators :- wood, plastics.

Types of dielectrics

Gas :- Air, SF_6, vaccum.

Solid :- PVC, vaccum, mica.

Liquid :- mineral oil.

Composite :- impregnated paper.

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Dielectric strength

-> Dielectric strength also known as dielectric breakdown strength (DBS).

-> The maximum electrical potential that a material can resist before the electrical current breaks through the material and the material is no longer an insulator.

-> Ceramic :- 100kV/mm.

-> Volts per meter (V/m), volts per centimeter (V/cm), megavolts per meter (MV/m).

Dielectric breakdown

-> Dielectric breakdown is the failure of an insulating material to prevent the flow of current under an applied electrical stress.

-> The breakdown voltage is the voltage at which the failure occurs, and the material is no longer electrically insulating.

-> Current flows through electrics when applied voltage exceeds breakdown voltage.

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Properties of Dielectric material.

1. High dielectric strength.
2. Thermal stability.
3. Chemical inertness.
4. Non inflammable.
5. Good heat transfer
6. Low cost.

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Module - 1

CONDUCTION

Gases as insulating media

-> The simplest and most commonly found dielectrics are gases. Most of the electrical apparatus use air as insulating medium and in a few cases other gases such as nitrogen carbondioxide, SF_6, freon are also used.

-> When the applied voltage is low small currents flow between the electrodes and the insulation retains its electrical properties.

-> When the applied voltage is large, the current flowing through the insulation increases very sharply and an electrical breakdown occurs.

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

-> The electrical discharges in gases are of two types :-
① Non-sustaining discharge.
② Self-sustaining types.

-> The breakdown in gas called spark breakdown is the transition of non-sustaining discharge into a self sustaining discharge.

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→ The build-up of high currents in a breakdown is due to the process known as ionization, in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents.

→ At present, two types of theories.
(i) Townsend theory
(ii) Streamer theory
are known which explains the mechanism for breakdown under different conditions.

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

Collision Processes

→ ~~Atomic and~~ An electrical discharge is normally created from unionized gas by collision process. These processes are mainly gas processes which occur due to the collision between the charged particles and gas atoms or molecules, or ions.

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→ Atomic and molecular collision processes are the physical interactions of atoms & molecules when they are brought into close contact with each other and with electrons, protons, neutrons or ions.

What happens during collision?

→ A collision is a short duration interaction between two bodies or more than two bodies simultaneously causing change in motion of bodies involved due to internal forces acted between them during this.

Types of collision

① Elastic collision:-

→ No changes take place in the internal energy of the particles but only their kinetic energy gets redistributed.

→ These collisions do not occur in practice.

→ When electrons collide with gas molecules, a single electrons traces a zig-zag path during its travel.

→ Electrons are very light in weight, they transfer only a part of their kinetic energy to the much heavier ions or gas molecules with which they collide.

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② In Elastic collision

→ In which internal changes in Energy take place within an atom or a molecule at the expense of the total kinetic Energy of the colliding particle.

→ The collision often results in a change in the structure of atom.

→ For example ionisation, attachment, excitation, recombination etc.

Ionisation process

A gas in its normal state is almost a perfect insulator, however, when an high voltage is applied between the two electrodes ~~immersed~~ immersed in a gases medium the gas becomes a conductor and electrical breakdown occurs.

Types of ionisation

① Ionisation by collision.
② photo - ionization.
③ Secondary - ionization.
④ Electronic - attachment process.

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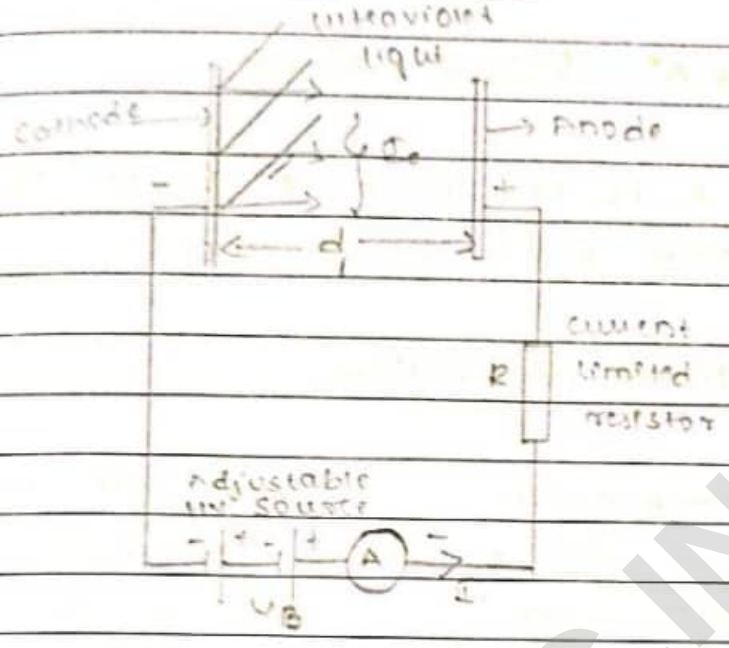
Ionization by collision



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

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

Consider the low pressure gas atom in which an electric field E is applied across a plane parallel as shown in figure. Then any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel towards the anode. If the energy e gained during this travel between collisions exceeds the ionization potential V_i which is the energy required to dis. an electron from an atomic cell then ionization takes

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place. this process can be represented as

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

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

Photo-ionization

-> The phenomenon associated with ionization by radiation or photo-ionization, involves the interaction of radiation with matter.

-> photo ionization occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionization potential, they are.

1. Excitation of the atom to a higher energy state.
2. Continous absorption by direct excitation of the atom.

-> Just as an excited atom emits radiation when the electron returns to the lower state or to the ground state, the reverse process takes place when an atom absorbs radiation. this reverse process can be expressed as

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

Ionisation occurs when

$$\lambda \leq c \cdot \frac{h}{\nu_i}$$

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where h is planck's constant, c is the velocity of light, λ is the wavelength of the incident radiation and V_i is the ionization energy of the atom. substituting for h and c,

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

where V_i → is an electron volts (ev).

Secondary ionization processes

Secondary ionization processes, by which secondary electrons are produced are the one which sustain a discharge after it is established due to ionization by collision & photo ionization

① Electron Emission due to positive ion impact

Positive ions are formed due to ionization by collision or by photo-ionization, and being positively charged, they travel towards the cathode.

A positive ion approaching a metallic cathode can cause emission of electrons from the cathode by giving up its kinetic energy on impact.

If the total energy of a positive ion namely the sum of it's kinetic energy & the ionization energy is greater than twice the

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work function of the metal.

(work function :- The minimum energy required to extract electron from the metal), then one electron will be ejected and the second electron will neutralise the ion.

→ The probability of this process is measured by γ_i, which is called townsend secondary ionization coefficient, due to positive ions, and is defined as the net yield of electrons per incident positive ion.

② Electron emission due to photons

To cause an electron to escape from a metal, it should be given enough energy to overcome the surface potential barrier. The energy can also be supplied in the form of a photon of ultraviolet light of suitable frequency. Electron emission from a metal surface occurs at the critical condition.

$$h\nu < \varphi$$

$\varphi \rightarrow$ work function of the metallic electrode.

$$\nu = \frac{\varphi}{h}$$

$\nu \rightarrow$ threshold frequency.

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(3) Electron emission due to metastable and Neutral Atoms

A metastable atom or molecule is an excited particle whose lifetime is very large (10^{-3} s) compared to the lifetime of an ordinary particle (10^{-8} s).

Electrons can be ejected from the metal surface by the impact of excited (metastable) atoms, provided that these total energy is sufficient to overcome work function.

This process is most easily absorbed with metastable atoms, because the lifetime of other excited states is too short for them to reach the cathode and cause electron commision unless they originate very near to the cathode surface.

Electron Attachment process

The types of collisions in which electrons may become attached to atoms or molecules to form a negative ions are called attachment collisions. All electrically insulating gases such as CO_2, O_2, Cl_2, F_2, C_2F_6, C_3F_8, C_4F_{10}, CCl_2F_2 + SF_6 exhibit this property.

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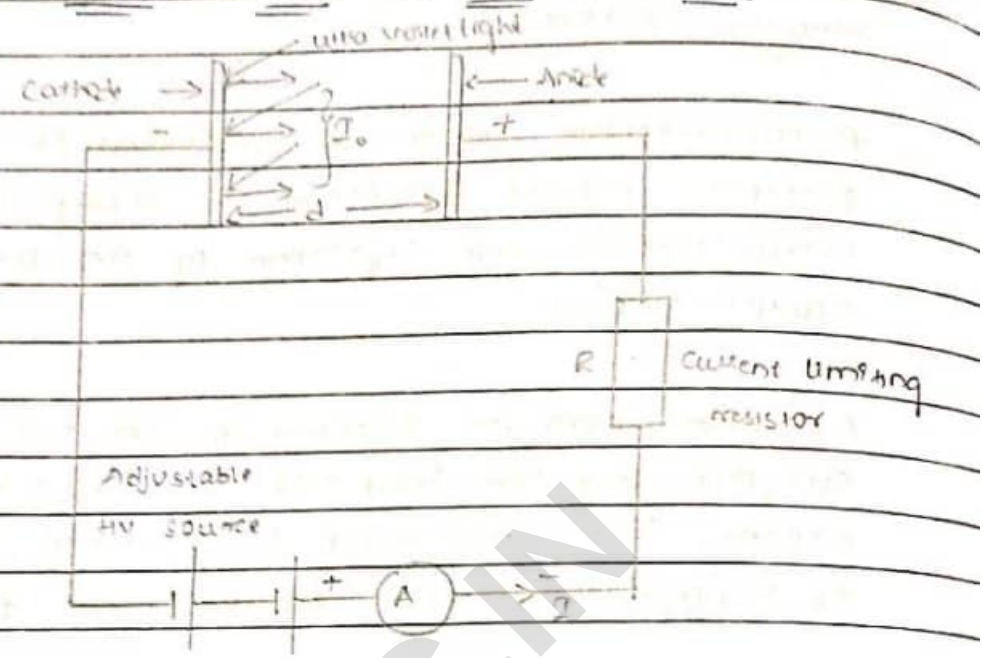
Townsend current Growth Equation



→ Refer the above figure

→ Let us assume that ~~no~~ n_0 electrons are emitted from the cathode.

→ When one electron collides with the neutral particle a positive ion and an electron are formed. This is called an ionizing collision.

→ Let α be the average number of ionising collisions.

→ α depends on gas pressure 'P' and the ratio of electric field to gas pressure

$$\alpha = \frac{E}{P}$$

→ α is called ~~as~~ townsend's first ionization coefficient.

→ At any distance 'x' from the cathode, let the no of electrons be n_x.

→ When these n_x electrons travel a further distance of dx then they give rise to

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$(\alpha n_x \cdot dx)$ Electrons

$$dn_x = \alpha n_x dx$$

$$\frac{dn_x}{n_x} = \alpha \cdot dx.$$

Integrate on both the side

$$\int \frac{dn_x}{n_x} = \int \alpha dx$$

$$\ln(n) = \alpha x + A \rightarrow (2)$$

Apply initial condition.

$$x = 0 \quad n_x = n_0$$

$$\ln(n_0) = A \rightarrow (3)$$

substitute in eq (2)

$$\ln(n) = \alpha x + \ln(n_0)$$

$$\ln(n) - \ln(n_0) = \alpha x$$

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

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

$$\frac{n}{n_0} = e^{\alpha x}$$

$$n = n_0 e^{\alpha x}$$

$$\boxed{I = I_0 \exp(\alpha x)}$$

$n \rightarrow$ no of electrons or current flows.

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Problem

① In an experiment in a certain gas it was found the steady state current is 5.5×10^{-8} A at 8 kV at a certain distance of 0.4 cm between the plane electrodes keeping the field constant and reducing the distance 0.1 cm results, a current of 5.5×10^{-9} A. Calculate the townsend primary ionization coefficient.

Soln Given

$I_1 = 5.5 \times 10^{-8}$ A at 8 kV

$d_1 = 0.4$ cm

$I_2 = 5.5 \times 10^{-9}$ A at 8 kV

$d_2 = 0.1$ cm

$I_1 = I_0 e^{\alpha d_1} \rightarrow ①$ and $I_2 = I_0 e^{\alpha d_2} \rightarrow ②$

By eq ① & ②

$$\frac{I_1}{I_2} = \frac{I_0 e^{\alpha d_1}}{I_0 e^{\alpha d_2}}$$

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

$$\frac{5.5 \times 10^{-8}}{5.5 \times 10^{-9}} = e^{\alpha(0.4 - 0.1)}$$

$$10 = e^{0.3\alpha}$$

take ln on b.s

$$\ln(10) = 0.3\alpha$$

$$\alpha = \frac{\ln(10)}{0.3}$$

$$\boxed{\alpha = 7.675 \text{ Tors}^{-1} \text{ cm}^{-1}}$$

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(2) A steady state current of 6000 μA flows through a phase electrodes separated by a distance of 0.5cm where a voltage of 10kV is applied. Determine α of current of 60μA flows when the distance of separation is reduced to a 0.1cm as the field kept constant at previous value.

Sol

$I_1 = 6000 \times 10^{-6}$ A at $V = 10$ kV

$d_1 = 0.5$ cm

$I_2 = 60 \times 10^{-6}$ A

$d_2 = 0.1$ cm

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

$I_1 = I_0 e^{\alpha d_1} \rightarrow (1)$

$I_2 = I_0 e^{\alpha d_2} \rightarrow (2)$

By eq (1) & (2)

$$\frac{I_1}{I_2} = \frac{I_0 e^{\alpha d_1}}{I_0 e^{\alpha d_2}} \qquad \frac{I_1}{I_2} = e^{\alpha(d_1 - d_2)}$$

$$\frac{\cancel{60}^{10} \times \cancel{10^{-6}}}{\cancel{6} \times \cancel{10^{-6}}} = e^{\alpha(0.5 - 0.1)}$$

$$10 = e^{0.4\alpha}$$

Applying 'ln' on b.s

$$\ln(10) = 0.4\alpha$$

$$\alpha = \frac{\ln(10)}{0.4}$$

$$\boxed{\alpha = 5.7565 \ \text{Np}\,s^{-1}\,cm^{-1}}$$

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Current growth in presence of secondary process

The single avalanche process described in the previous section becomes complete when the initial set of electrons reaches the anode, since the amplification of electrons [exp (αd)] is occuring in the field, the probability of additional new electrons being liberated in the gap by other mechanisms increases, and these new electrons create further avalanches.

The other mechanism are the following

(i) The positive ions liberated may have sufficiency energy to cause liberation of electrons from the cathode when they impinge on it.

(ii) The excited atoms or molecules in avalanches may emit photons, and this will lead to the emission of electrons due to photo-emission.

(iii) The metastable particles may diffuse back causing electron emission.

The electrons produced by these processes are called secondary electrons.

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-> 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 excited particle or metastable particle and the total value of γ is the sum of individual coefficients due to three different processes

i.e $\gamma = \gamma_1 + \gamma_2 + \gamma_3$

-> γ is called the townsend's secondary ionization coefficient and is a function of the gas pressure p & E/p.

Let us assume

n_0' -> number of secondary electrons produced due to secondary process

n_0'' -> total no of electrons leaving the cathode

$$n_0'' = n_0 + n_0' \rightarrow (1)$$

Total no of electrons n reaching the anode becomes

$$n = n_0'' \exp(\alpha d) =$$

$$n = (n_0 + n_0') \exp(\alpha d) \rightarrow (5)$$

and the number of electrons releasing in the gaseous medium

$$= n - (n_0 + n_0')$$

Assuming each positive ion releasing γ effective electron from the cathode

$$n_0' = \gamma [n - (n_0 + n_0')]$$

$$n_0' = \gamma [n - n_0 - n_0']$$

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$$n_0' = \gamma n - \gamma n_0 - \gamma n_0'$$

$$n_0'[1+\gamma] = \gamma[n - n_0]$$

$$n_0' = \frac{\gamma(n-n_0)}{1+\gamma} \rightarrow (3)$$

substitute (3) in eq (2)

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

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

$$= \left[\frac{n_0 + \cancel{n_0\gamma} + n\gamma - \cancel{n_0\gamma}}{1+\gamma}\right] \exp(\alpha d)$$

$$n = \left[\frac{n_0 + n\gamma}{1+\gamma}\right] \exp(\alpha d)$$

$$n(1+\gamma) = (n_0 + \gamma n) \exp(\alpha d)$$

$$n + n\gamma = n_0 \exp(\alpha d) + \gamma n \exp(\alpha d)$$

$$n + n\gamma - \gamma n \exp(\alpha d) = n_0 \exp(\alpha d)$$

$$n[1 + \gamma - \gamma \exp(\alpha d)] = n_0 \exp(\alpha d)$$

$$n = \frac{n_0 \exp(\alpha d)}{1 + \gamma[1 - \exp(\alpha d)]}$$

$$n = \frac{n_0 \exp(\alpha d)}{1 - \gamma(\exp(\alpha d) - 1)}$$

$n \rightarrow$ number of electrons reaching the anode.

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$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma [\exp(\alpha d) - 1]}$$

Townsend current growth equation by considering secondary processes.

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Townsends criteria for breakdown.

W.K.T $I = \frac{I_0 \exp(\alpha d)}{1 - \gamma [\exp(\alpha d) - 1]}$ → (1)

This gives the total average current in a gap before the occurance of breakdown.

→ As the distance between the electrodes 'd' is increased the denominator of equation tends to zero and at some critical distance $d = d_s$

$$1 - \gamma [\exp(\alpha d) - 1] = 0 \rightarrow (2)$$

For values $d \geq d_s$

→ Then I is approximately equal to I_0.

→ If $d = d_s$ the $I \rightarrow \infty$, & I will be heated only by the resistance of the power supply by electrical circuit.

→ This condition is called townsends breakdown criterion and written as

$$\gamma [\exp(\alpha d) - 1] = 1 \rightarrow (3)$$

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$$\gamma \exp(\alpha d) - \gamma = 1$$

Normally, $\exp(\alpha d)$ is very large when compared to γ hence γ is neglected

$$\gamma^2 \exp(\alpha d) = 1 \rightarrow (4)$$

For a given gap spacing and at a given pressure the value of the voltage V which gives the values of α & γ satisfying the breakdown criterion is called spark breakdown voltage V_s and the corresponding distance d_s is called the sparking distance.

EXPERIMENTAL DETERMINATION OF COEFFICIENTS

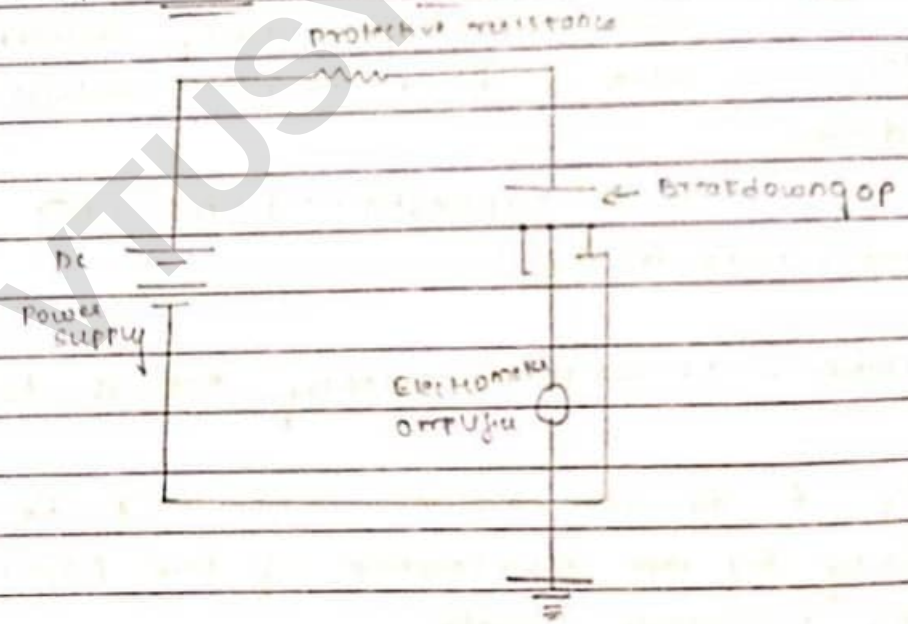

Fig: Experimental arrangement of ionisation coefficients

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→ The Electrode system consists of two uniform field electrodes.

→ The high-voltage electrode is connected to a variable high-voltage dc source (0 to 10 kV rating).

→ The low voltage electrode consists of a central electrode and a guard electrode. The central electrode is connected to the ground through the high resistance of an electrometer amplifier having an input resistance of 10^9 to 10^{13} ohms.

→ The guard electrode is directly earthed. The electrometer amplifier measures currents in the range of 10^{-14} to 10^{-8} A.

→ The electrode system is placed in an ionization chamber which is either a metal chamber made of chromium plated mild steel or stainless steel, or a glass chamber.

→ The electrodes are usually made of brass or stainless steel. The chamber is evacuated of vacuum.

→ Then it is filled with the desired gas and flushed several times till ~~the~~ all the residual gases and air are removed.

→ The pressure inside the chamber is adjusted to a few torr depending on the gap separation & left for about half an hour for the gas to fill the chamber uniformely.

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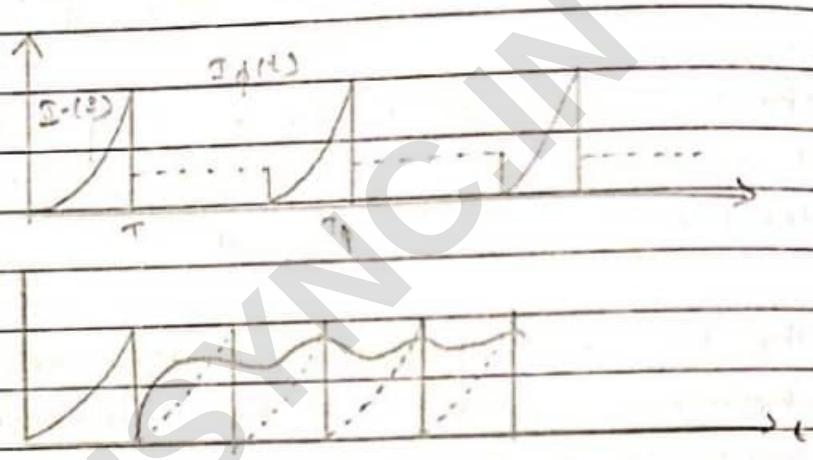
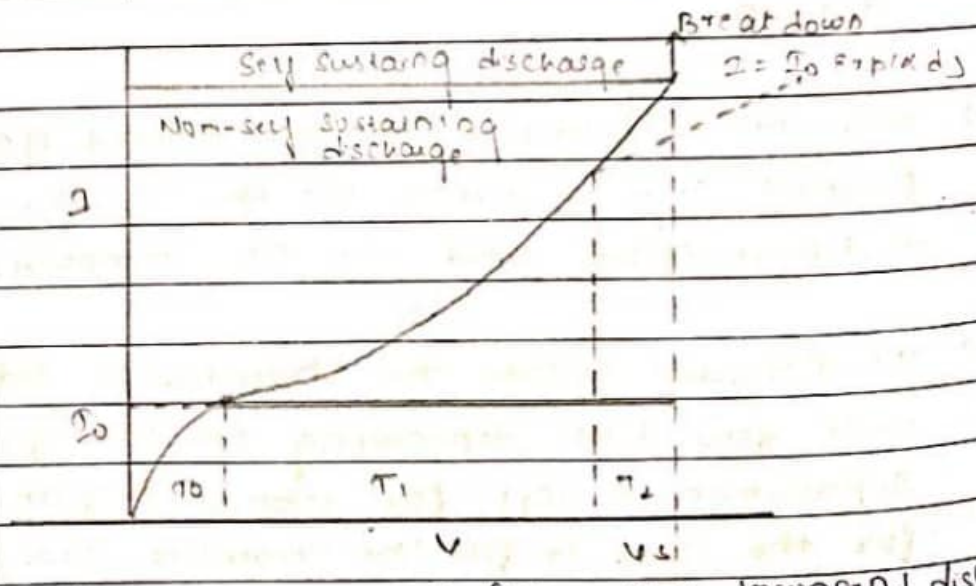
→ The cathode is irradiated using an ultra-violet (UV) lamp kept outside the chamber. The UV radiation produces the electrons by photo emission.

→ Case 1 :- When the dc voltage is low, the current pulses start appearing due to electrons and positive ions as shown, it is recorded using CRO.



→ Case 2 :- When the applied DC voltage is increased, the pulses disappear and an average dc current is obtained as shown.



Typical current growth curve in a townsend discharge

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On the initial portion (T_0), the current increases slowly an but unsteadily with the voltage applied. In the regions T_1 & T_2, the current increases steadily due to the townsend mechanism. Beyond T_2 current rises very sharply, and a spark occurs.

For determining the α & γ coefficients, the voltage - current characteristics for different gap settings are obtained. Plot is obtained under constant field (E) conditions as shown.

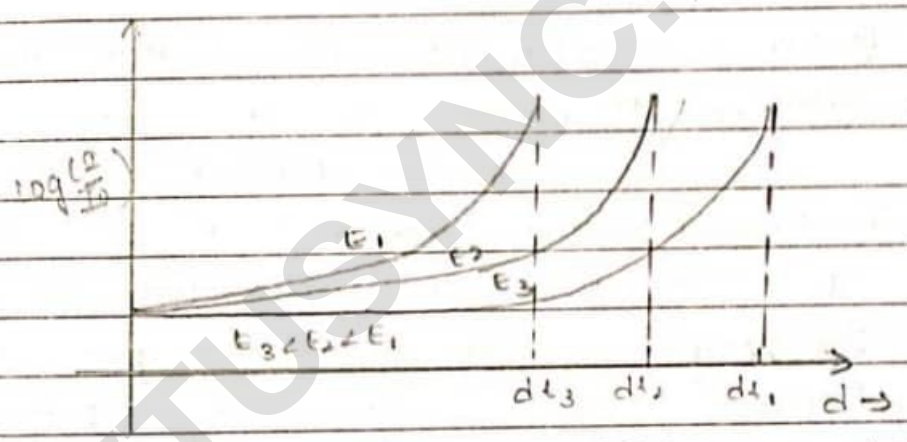

Fig:- Townsend type log (I/I0) vs d plot.

The slope of the initial portion of the curve gives the value of α knowing α, γ can be found from the equation below i.e

$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]}$$

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Breakdown in Electronegative gases

* One process that gives high breakdown strength to a gas is the electron attachment in which free electron get attached to neutral atoms or molecules to form negative ions.

* The gases in which attachment plays an active role are called electronegative gases.

* The most common attachment processes encountered in gases are

(a) Direct attachment :- An electron directly attaches to form a negative ion.

$$AB + e \rightarrow AB^- + h\nu$$

(b) Dissociative attachment :- The gas molecules split into their constituent atoms and the electronegative atom forms a negative ion. These processes may be symbolically represented as

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

* A simple gas of this type is oxygen. Other gases are sulphur hexafluoride, freon, carbon dioxide and fluorocarbons.

* In these gases 'A' is usually sulphur or carbon atom and 'B' is oxygen atom or one of the halogen atoms or molecules.

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

$$I = \frac{I_0 \left[\{\alpha/(\alpha-\eta)\} \exp(\alpha-\eta) d \right] - \left[\eta/(\alpha-\eta) \right]}{1 - \left\{ \gamma \frac{\alpha}{(\alpha-\eta)} \{\exp(\alpha-\eta) d\} - 1 \right\}} \rightarrow (1)$$

* The Townsend breakdown criterion for attaching gases can also be deduced by equating the denominator in Eq (1) to zero i.e

$$\gamma \frac{\alpha}{(\alpha-\eta)} \left[\exp(\alpha-\eta) d - 1 \right] = 1 \rightarrow (2)$$

* This shows that for $\alpha > \eta$, breakdown is always possible irrespective of the values of α, η and γ. If on the other hand $\eta > \alpha$ Eq (2) approaches an assymptotic form with increasing value.

$$\gamma \frac{\alpha}{\alpha-\eta} = 1 \; ; \text{ or } \; \alpha = \frac{\eta}{1-\gamma} \rightarrow (3)$$

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Time Lags for Breakdown:-

* In the previous section, the mechanism of spark breakdown is considered as a function of ionization processes under uniform field conditions. But in practical engineering designs, the breakdown due to rapidly changing voltages or impulse voltages is of great importance.

* Actually there is a time difference between the application of a voltage sufficient to cause breakdown and the occurance of breakdown itself. This time difference is called the time lag.

* The Townsend criterion for breakdown is satisfied only if atleast one electron is present in the gap between the electrodes

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

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* In the case of applied dc or slowly varying (50Hz ac) voltages there is so difficulty in satisfying this condition.

* With rapidly varying voltages of short duration ($\approx 10^6 s$) the initiatory electron may not be present in the gap, and in the absence of such an electron breakdown cannot occur.

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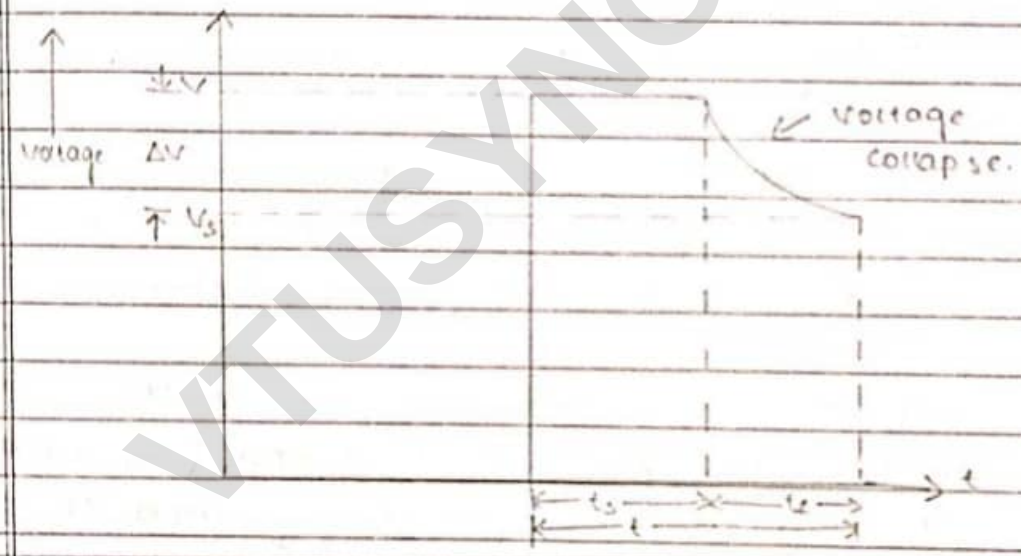
* The time t which lapses between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag (t_s) of the gap.

* After the appearance of the electron, a time t is required for the ionization processes to develop fully to cause the breakdown of the gap, and this is called the formative time lag (t_f).

* The total time $t = t_s + t_f$ is called the total time lag.



Statistical time lag:-

Statistical time lag depends upon:-

1. The amount of preionization present in the gap. This in turn depends on the size of gap : and

2. The quantity of radiation that produces the primary electrons.

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Formative time lag:-

* The formative time lag is usually much shorter than the statistical time lag and therefore the statistical time lag can be determined by measuring the total time lag

* Formative time lag depends mostly on the mechanism of the avalanche growth in the gap. In cases where the secondary electrons are produced only due to bombardment of the cathode by positive ions.

Voltage time characteristics

When an impulse voltage of a value or higher is applied as a gap, breakdown will occur on each voltage application.

The time lag will then depend on the rate of rise of the applied voltage and field uniformity. Therefore for each gap configuration it is possible to construct a voltage-time characteristics by applying a number of impulses of increasing magnitude and recording the time lag using an oscilloscope.

In uniform and fairly non-uniform field gaps, the characteristic is sharply defined in rises steeply with increasing rate of rise of the applied voltage.

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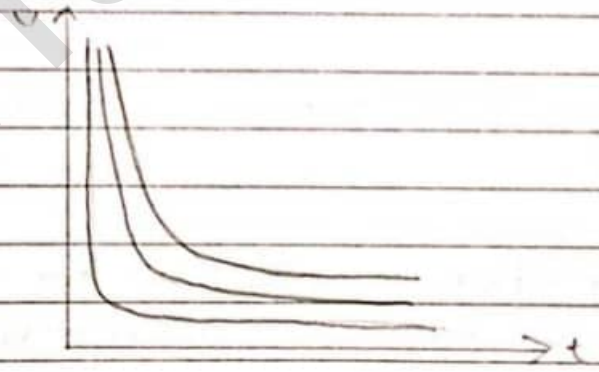
In non-uniform field gaps there will be a large scatter in results, and the time to breakdown will be less sensitive to the rate of rise of applied voltage. Hence fairly uniform field gaps such as sphere gaps are often used as protective devices against overvoltages in electric power systems.

The voltage time characteristic is an important property of any insulating structure or equipment. It provides a basis for establishing the impulse strength of the insulation as well as for the design of the protective levels against over voltage in power systems.

For breakdown to occur the applied voltage v should be greater than the static breakdown voltage V_s as shown in fig.



The difference in voltage $\Delta v = v - V_s$ is called the overvoltage, and the ratio v/V_s is called the impulse ratio.

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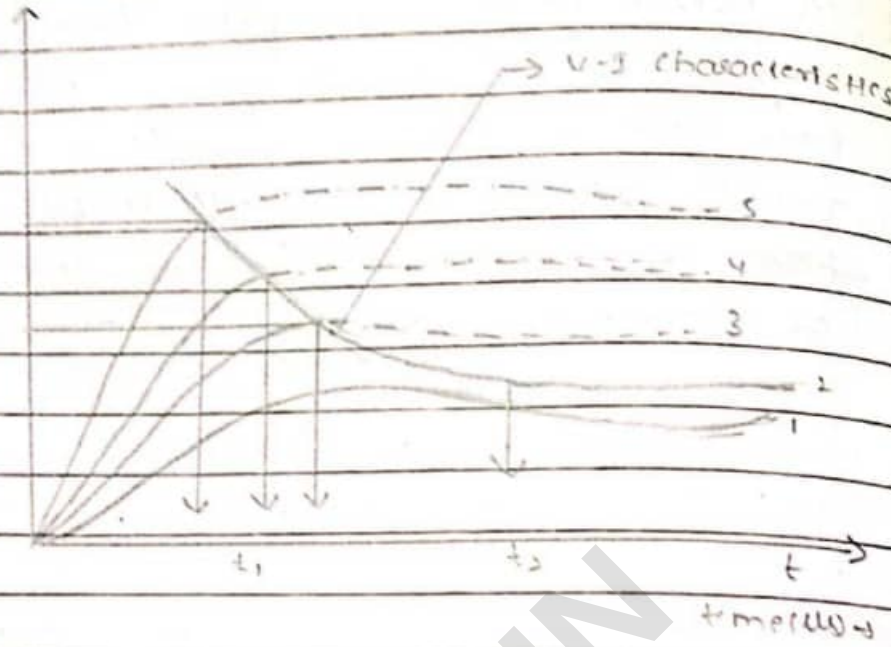

Limitations of townsend theory

Townsend mechanism when applied to breakdown at atmosphere pressure was found to have certain draw backs.

① Current growth occurs as a result of ionization processes only. But in practice, breakdown voltages were found to depend on the gas pressure and geometry of the gap.

② The mechanism predicts time lags of the order of 10^{-5} s, while in actual practice breakdown was observed to occur to very short time of order of 10^{-8} s.

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The townsend mechanism predicts a very diffused form of discharge, in actual practice, discharge were found to be filam-entary and irregular.

The townsend mechanism failed to explain all these observed phenomenon and as a result around 1940, Raether & Meek & Loeb independently proposed the streamer theory.

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Streamer theory and Breakdown in gases

The growth of charge carriers in an avalan-che in a uniform field is described by $e^{\alpha d}$.

This is valid only as long as the influence of the space charge due to ions is very small compared to applied field.

In his studies on the Effect of space charge on avalanche growth, Raether observed that when charge concentration was between 10^6 and 10^8, the growth of avalanche became weak.

When the charge concentration was higher than 10^8, the avalanche current was followed by a steep rise in the current between the electrodes leading to the breakdown of the gap.

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Both the slow growth at low charge concentrations and fast growth at high charge concentrations have been attributed to the modification of the originally applied uniform field (E) by space charge P.

Fig. shows the electric field around the avalanche as it progresses along the gap and the resulting modification to the applied field.

For simplicity, the space charge at the head of the avalanche is assumed to have a spherical volume containing negative charge at its top because of the high electron mobility.

Under these conditions, the field gets enhanced at the top of the avalanche with field lines from the anode terminating on its head.

Further the bottom of the avalanche, the field between electrons and ions reduces the applied field (E).

Still further down, the field between cathode and the positive ions gets enhanced. Thus the field distortion occurs and it becomes noticeable with a charge carrier number $n > 10^6$.

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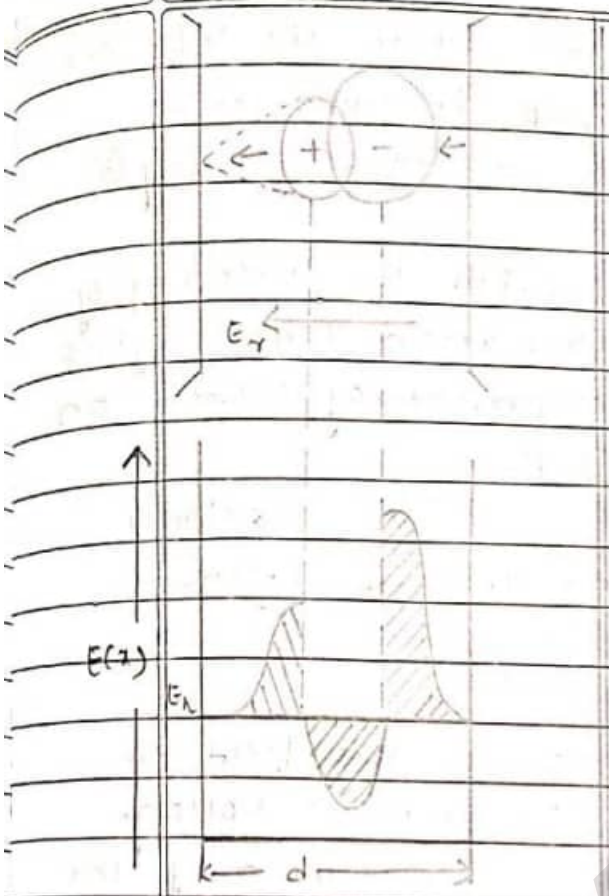

Fig: Field distortion in a gap due to space charge

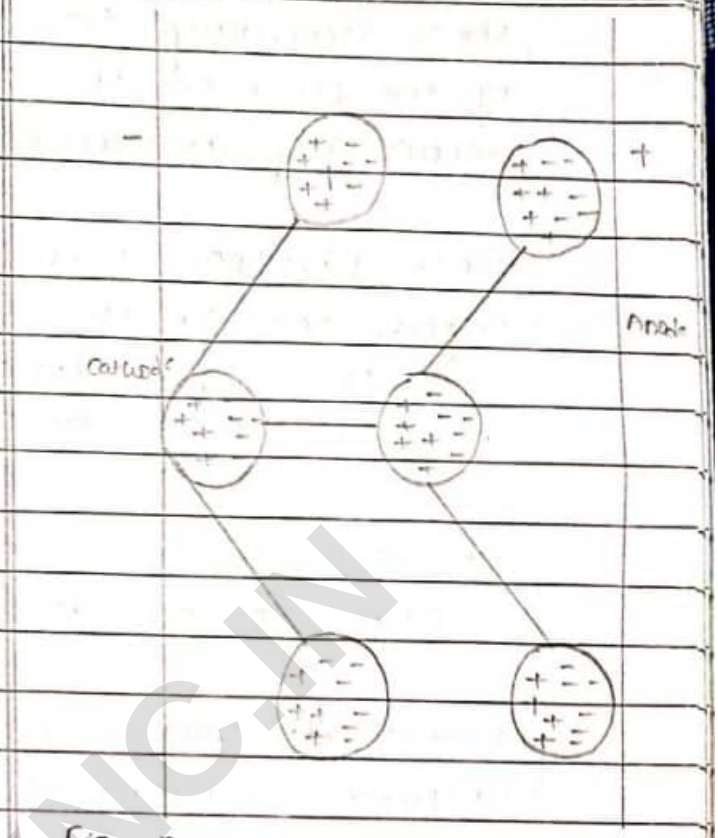

Fig: Formation of Secondary Avalanches due to Photo-ionization

In the theories proposed by Raether, and Meek it has been shown that

* When the avalanche in the gap reaches a critical size, the combined applied field and the space charge field cause intense ionization and excitation of the gas particles in front of the avalanche.

* Instantaneous recombination between positive ions and electrons releases photons which in turn produce secondary electrons by photo-ionization.

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These secondary electrons under the influence of the field in the gap develop, into secondary avalanches as shown in fig (b)

Since photons travel with the velocity of light, the photo-ionization process gives rise to rapid development of conduction channels across the gap.

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Breakdown in Non-uniform Fields and corona discharges

-> corona discharges If the electric field is uniform, a gradual increase in voltage across a gap produces a breakdown of the gap in the form of a spark without any preliminary discharges.

-> If the field is non-uniform, an increase in voltage will first cause a discharge in the gas to appear at points with highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission lines.

-> This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone.

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→ corona is responsible for considerable loss of power from high-voltage transmission lines, and it leads to the deterioration of insulation due to combined action of the bombardment of ions and of chemical compounds formed during discharges. corona also gives rise to radio interference.

→ The voltage gradient required to produce visual ac 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

$$E_W = 30 m d \left[1 + \frac{0.301}{\sqrt{dr}}\right]$$

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

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

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

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

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Where 'b' is the atmospheric pressure in torr and 'T' is the temperature in c, d = 1 at 760 torr and 25°c.

These expressions were found to hold good from atmospheric pressure down to a pressure of several torr.

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

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

When the voltage is negative, the corona will appear like reddish glowing spots distributed along the length of wire. Investigations with point-plane gaps in the air showed that when point is negative, corona appears as current pulses called Trichel pulses and the repetition frequency of these pulses increases as the applied voltage is increased and decreases with decrease in pressure.

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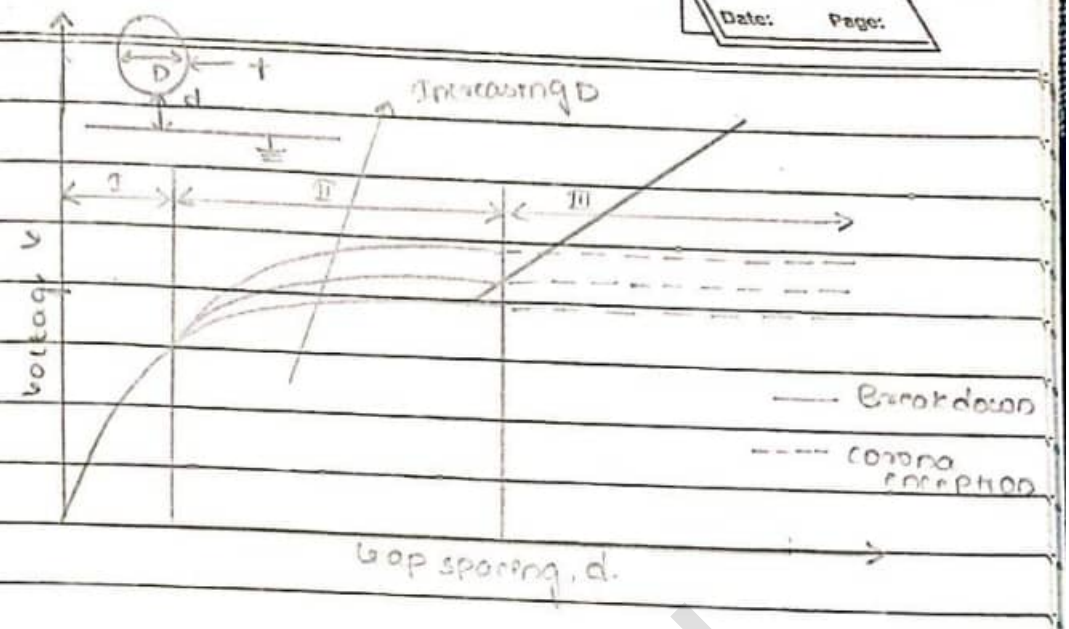

-> Breakdown and corona inception characteristics for spheres of different diameters in sphere-plane gap geometry. The corona inception and breakdown voltages of sphere-plane arrangement as shown in fig.

-> From this fig it can be seen that

(a) At small spacings (region I) the field is uniform, and breakdown voltage mainly depends on spacing.

(b) At fairly large spacings (region II) the field is non-uniform and breakdown voltage depends on both the sphere diameter and spacing.

(c) At large spacings (region III) the field is non-uniform and breakdown is preceded by corona and is controlled by spacing. The corona inception voltage mainly depends on the sphere diameter.

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Breakdown in Non-uniform fields

-> In non-uniform fields, such as coaxial cylinders, point-plane and sphere-plane gaps, the applied field varies across the gap.

-> Townsend's first ionization coefficient (α) also varies with the gap.

-> Hence αd in Townsend's criterion is rewritten by replacing αd by $\alpha \int dx$. Townsend's criterion for breakdown now becomes

$$\gamma \left\{ \exp\left[\int_0^d \alpha \, dx \right] - 1 \right\} = 1$$

-> Meek and Raether also discussed the non-uniform field breakdown process as applied to their streamer theory. Meeks equation

$$E_r = \frac{5.07 \times 10^{-7} \alpha_x \exp\left[\int_0^x \alpha \, dx \right]}{(x/p)^{1/2}} \text{ V/cm}$$

for the radial field at head of an avalanche when it has crossed distance is modified as. (refer eq)

-> where α_x is the value of α at the head of the avalanche, and p is the gas pressure. The criterion for the formation of the streamer is reached when the space charge

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field E_r approaches a value equal to the applied field at the head of the avalanche.

This equation has been successfully used for determining the corona onset voltages of many non uniform geometries.

Breakdown in liquid dielectrics

Liquids as insulators

Liquid dielectrics, because of their inherent properties, appear as though they would be more useful as insulating materials than either solids or gases.

-> This is because both liquids and solids are usually 10^3 times denser than gases and hence,

-> Also, liquids like gases, fill the complete volume to be insulated and simultaneously will dissipate heat by convection.

-> Oil is about 10 times more efficient than air or nitrogen in its heat transfer capability when used in transformers. Although liquids are expected to give very high dielectric strength of order of 10 MV/cm, in actual practice the strength's obtained are only of order of 100 kV/cm.

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-> Liquid dielectrics are used mainly as impregnants in high-voltage cables and capacitors, and for filling up of transformers, circuit breakers etc. Liquid dielectrics also act as heat transfer agents in transformers, and as arc quenching media in circuit breakers.

-> Petroleum oils (transformer oil) are the most commonly used liquid dielectrics.

-> Synthetic hydrocarbons and halogenated hydrocarbons are also used for certain appliances.

-> For very high-temperature applications, silicon oils and fluorinated hydrocarbons are employed.

-> Liquid dielectric, the choice of liquid dielectrics for a given application is made mainly on the basis of its chemical stability. Other factors such as saving of space, cost, previous usage, and susceptibility to the environmental influences are also considered.

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classification of liquid dielectrics

- transformer oil (mineral O)
- synthetic hydrocarbons.
- chlorinated hydrocarbons.
- silicon oils.
- Esters
- Latest Developments.

Characteristics :-

- A liquid dielectric should posses good dielectric properties, excellent heat transfer characteristics and must be chemically stable under the range of conditions under which the equipment operates.

- Electrical properties :- The electrical properties that are essential in determining the dielectric performance of a liquid dielectric are its
  (i) capacitance per unit volume or its relative permittivity.
  (ii) resistivity.
  (iii) loss tangent (tan δ) or its power factor
  (iv) which is an indication of the power loss under ac voltage application.
  (iv) its ability to withstand high electric stresses

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Pure liquid and commercial liquids

-> Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 10^9, and are structurally simple.
Examples of such simple pure liquids are n-hexane (C_6H_{14}), n-heptane (C_7H_{16}) and other paraffin hydrocarbons.
By using simple and pure liquids, it is easier to separate out the various factors that influence conduction and breakdown in them.

-> On the other hand, the commercial liquid oils which are not chemically pure, normally consist of mixtures of complex organic molecule which cannot be easily specified or reproduced in a series of experiments.

-> The main impurities in liquid dielectrics are dust, moisture, dissolved gases and ionic impurities. Various methods employed for purification are filtration (through mechanical filters, spray filters, and electrostatic filters), centrifuging, degassing and distillation and chemical treatment (adding ion exchange materials such as alumina, fuller's earth, etc and filtering).

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-> Dust particles. When present become charged and reduced the breakdown strength of liquid dielectrics, and they can be removed by careful filteration. Liquid will normally contain moisture and dissolve gases in small quantities.

-> Gases like oxygen and carbon dioxide significantly, affect the breakdown strength of the liquids, and hence it is necessary to control the amount of gas present.

-> This is done by distillation and degassing. Ionic impurity in liquids, like water vapour which easily dissociates, leads to very high conductivity and heating of the liquid depending on the applied electric field.

-> Water is removed using drying agents or by vaccum drying. Sometimes, liquids are shaken with concentrated sulphuric acid to remove wax and residue and washed with caustic soda and distilled water. A commonly used closed-cycle liquid purification system to prepare liquids as per the above requirements is shown in fig. This system provides for cycling the liquid.

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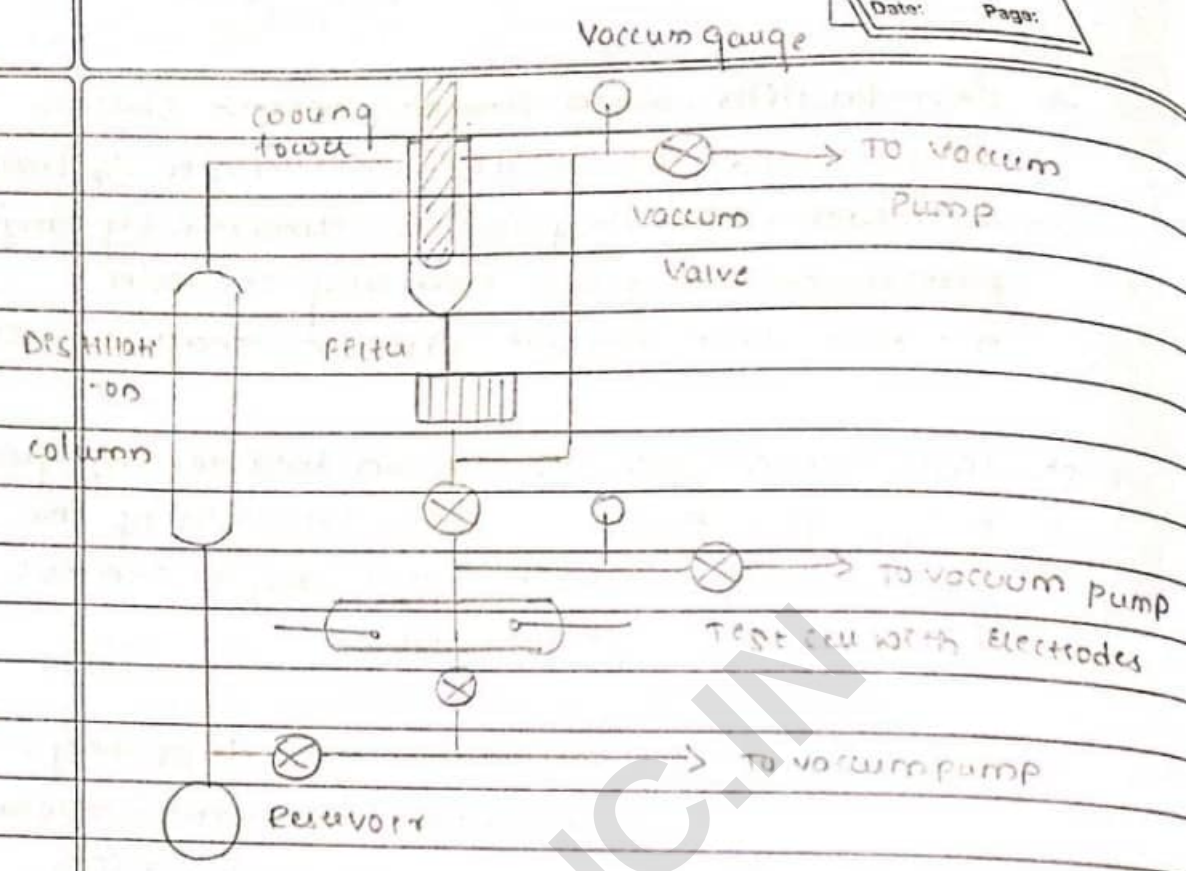

Fig:- Liquid Purification system with test cell.

→ The liquid from the reservoir flows through the distillation column where ionic impurities are removed. Water is removed by drying agents or frozen out in low-temperature bath. The gases dissolved in the liquid are removed by passing them through the cooling ~~agents~~ tower and/or pumped by the vaccum pumps.

→ The liquid then passes through the filter where dust particles are removed. The liquid thus purified is then used in test cell. The used liquid then flows back into the reservoir. The vaccum system thus helps to remove the moisture and other gaseous impurities.

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Liquid Purification system with test cell

- Breakdown test are normally conducted using test cells. For testing pure liquids, the test cells used are small so that less quantity of liquid is used during testing. Also, test cells are usually an integral part of purification system as shown in fig.

- The electrodes used for breakdown voltage measurements are usually spheres of 0.5cm to 1cm in diameter with gap spacing of about 100-200nm (i.e 0.1 mm). The gap is accurately controlled by using a micrometer. Sometimes parallel plane uniform-field electrode system are also used. Electrode separation is very critical in measurements with liquids, and also the electrode surface smoothness and the presence of oxide film have a marked influence on the breakdown strength.

- The test voltages required for these tests are usually low of the order of 50-100 kV because of small electrode spacings. The breakdown strength and dc conductivities obtained in pure liquids are very high of order of 1 MV/cm and 10^{-18} - 10^{-20} mho/cm respectively, the conductivity being measured at electric fields of order of 1 kV/cm. However, the corresponding values in commercial liquids are relatively low.

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Conduction and breakdown in pure liquids

Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 10^9.

→ And are structurally simple.

Ex:- n-hectane $[C_6H_{14}]$, n-heptane $[C_7H_{14}]$

→ this curve will have the distinct region as shown.

→ At very low fields, the current is due to the dissociation of ions.

→ With intermediate fields, the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from the cathode gets multiplied in the liquid medium by a Townsend type of mechanism.

→ The current multiplication also occurs from the electrons generated at the interfaces of liquid and impurities. The increase in current by these processes continues till breakdown occurs.

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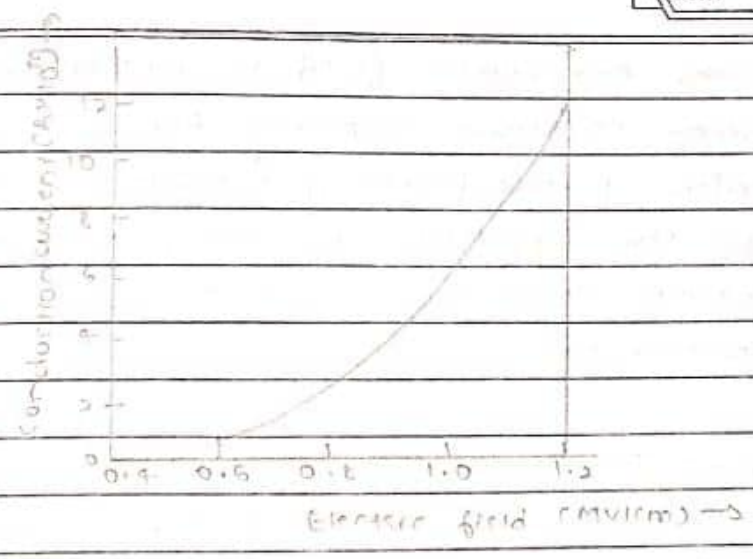

Fig: conduction current - Electric field characteristic in hexane at high fields.

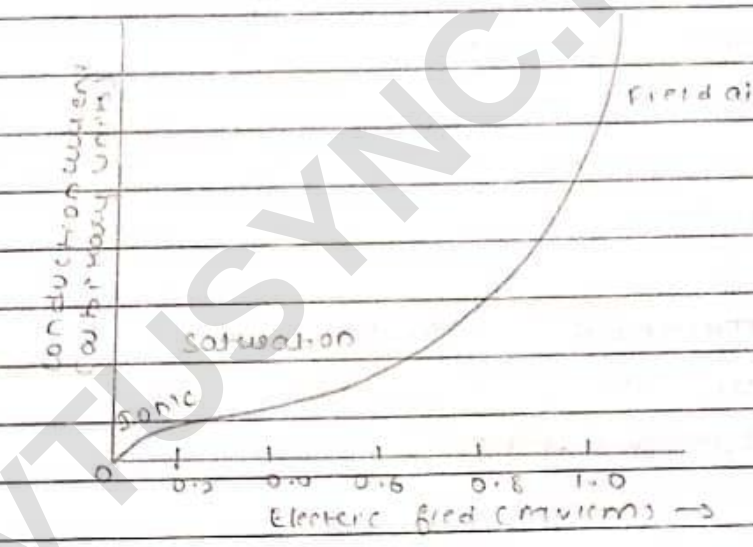

Fig: conduction current - Electric field characteristic in a hydrocarbon liquid.

-& The electrons so liberated get multiplied by a process similar to Townsend's primary and secondary ionization in gases.

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- As the breakdown field is approached, the current increases rapidly due to a process similar to the primary ionization process and also the positive ions reaching the cathode generate secondary electrons leading to breakdown.

- Breakdown voltage depends on the field, gap, separation, cathode work-function and the temperature of the cathode. In addition, the liquid viscosity, the liquid temperature, the density, and the molecular structure of liquid also influence.

Conduction and breakdown in commercial liquids

- commercial insulating liquids are not chemically pure and have impurities like gas bubbles, suspended particles etc.

- These impurities reduce the breakdown strength of these liquid considerably.

- When breakdown occurs in these liquids, additional gases and gas bubbles are evolved and solid decomposition products are formed.

- The electrode surfaces become rough, and at times explosive sounds are heard due to generation of impulsive pressure through the liquid.

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→ The breakdown mechanism in commercial liquids depends.

(i) on nature and condition of the electrodes.
(ii) the physical properties of the liquid, and
(iii) the impurities and gases present in liquid.

→ Several theories have been proposed to explain the breakdown in liquids, and they are classified as follows:
ⓐ suspended particle mechanism.
ⓑ cavitation and bubble mechanism.
ⓒ stressed oil volume mechanism.

Suspended particle mechanism

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

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

→ This force is directed towards areas of maximum stress.

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-> If the voltage is continuously applied (dc) or the duration of the voltage is long (ac), then this force drives the particles towards the areas of maximum stress. If the number of particles present are large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

-> If there is only a single conducting particle between the electrodes, it will give rise to local field enhancement depending on its shape. If this field exceeds the breakdown (~~will occur near the~~ particle, ~~and~~) strength of the liquid, local breakdown will occur near the particle, and this will result in the formation of gas bubbles which may lead to breakdown of the liquid.

-> The larger the size of the particles, the lower were the breakdown strengths.

Cavitation and the Bubble theory

-> The following processes have been suggested to be responsible for the formation of the vapour bubbles:

(a) gas pockets at the surfaces of the electrodes

(b) Electrostatic repulsive forces between space charges which may be sufficient to overcome the

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surface tension.

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

(d) vapourization of the liquid by corona type discharge from sharp points and irregularities on the electrode surfaces.

→ Once a bubble is formed, it will elongate in the direction of the electric field under the influence of electrostatic forces.

→ Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the minimum value on the paschen's curve for the gas in the bubble. The breakdown field is given as

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)} \left[\frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r} \left[\frac{\pi}{4} \sqrt{\left(\frac{V_b}{2r\varepsilon_0}\right)} - 1 \right] \right]^{1/2}$$

→ σ is the surface tension of the liquid.

→ ε_1 is the permittivity of the liquid.

→ ε_2 is the permittivity of gas bubble.

→ r is the initial radius of bubble assumed as a sphere.

→ V_b is the vtg drop in bubble (corresponding to minimum on Paschen's curve).

→ This theory does not take into account the production of initial bubble & hence, the results given by this theory do not agree well with experimental results.

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Thermal mechanism of Breakdown

→ This mechanism is based on the experimental observations of extremely large currents just before breakdown.

→ These high density current pulses give rise to localized heating of the oil which may lead to the formation of vapour bubbles.

→ The vapour bubbles are formed when the energy exceeds 10^7 J/cm³. When a bubble is formed, breakdown follows, either because of its elongation to a critical size or when it completely bridges the gap between the electrode

→ According to this mechanism, the breakdown strength depends on the pressure and the molecular structure of the liquid.

Effect of moisture content on Breakdown strength of Liquid Dielectrics

→ Usually, in commercial liquid like transformer oil, certain amount of moisture (water vapour) and a very little amount of water will be present. The maximum amount of water present in the oil of a good quality will be less than 50 ppm at an atmospheric temperature of about 30°c or less.

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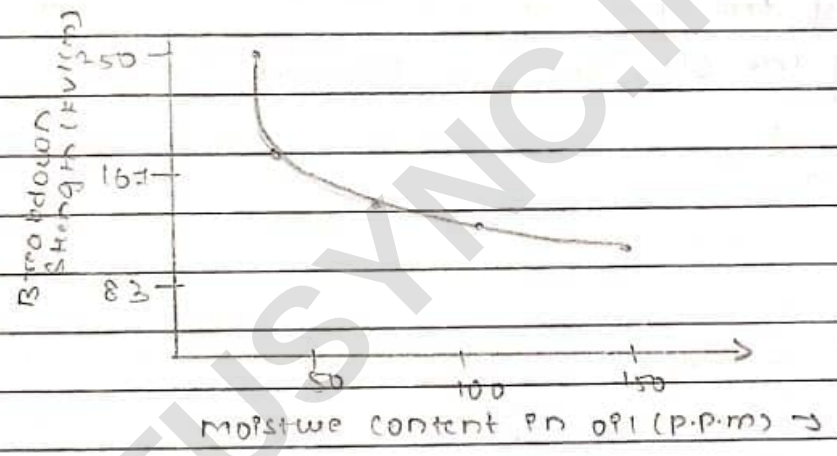
→ Water present in the oil lowers the dielectric strength. At lower temperatures, the moisture is distributed as minute water globules, whereas at high temperature (≥ 80°C), water begins to boil creating more number of vapour bubbles inside the liquid. Water globules or vapour bubbles are the reason for the reduction of dielectric strength. The variation (lowering of) the breakdown strength for a 6mm uniform field electrod gap is shown.



Stressed oil volume theory

→ In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by "largest possible impurity" or "weak link".

→ On a statiscal basis, it was proposed that the electrical breakdown strength of oil is defined by weakest region in oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region.

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→ In nonuniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress (E_{max}) contour and $0.9\,E_{max}$ contour.

→ According to this theory, the breakdown strength is inversely proportional to the stressed oil volume.

→ The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities.

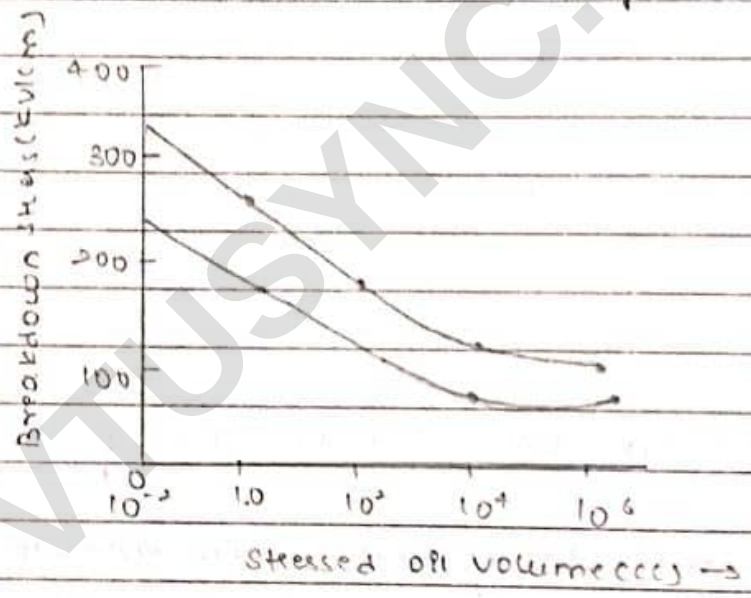

Fig:- Power frequency (50Hz) ac breakdown stress as a function of stressed oil volume

- With steady Vtg rise x one min withstand Vtg.

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Conclusion

-> It is clear that no single theory can explain all the experimental observations satisfactorily. Therefore, recently developed fast optical techniques have been widely used to study the processes of liquid dielectric breakdown. After a thorough analysis and review of the data with the use of optical techniques. All the theories discussed above do not consider the dependence of breakdown strength on the gap length.

-> They all try to account for the maximum obtainable breakdown strength only.

-> However, the experimental evidence showed that the breakdown strength of liquid depends on the gap length, given by the following expression

$$V_b = Ad^n$$

-> where d = gap length, A = constant & n = const always less than 1. The breakdown voltage also depends on nature of voltage, the mode in which the voltage is applied, and the time of application. The above relationship is of practical importance, and electrical stress of a given dielectric used in design is obtained from this.

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→ It may be summarized that the actual mechanism of breakdown in oil is not a simple phenomenon and the breakdown voltages are determined by experimental investigations only.

Solid Dielectric

→ Solid dielectric materials are used in all kinds of electrical apparatus and devices to insulate one current-carrying part from another when they operate at different voltages.

→ A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusions, and moisture, and be resistant to thermal and chemical deterioration.

→ Solid dielectrics have higher breakdown strength compared to liquids and gases. Solid insulating materials, which are generally used in practice, are of two types, namely, the organic materials such as paper, wood and rubber and the inorganic materials such as mica, glass & porcelain & synthetic polymers, such as perspex, PVC, Epoxy resins etc.

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-> Some important properties of these materials which are used for insulation purposes in high-voltage apparatus, studies of breakdown of solid dielectrics are of extreme importance in insulation studies.

-> When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field is removed. The mechanism of breakdown is a complex phenomenon in the case of solids and varies depending on time of application of voltage.

-> The various breakdown mechanisms can be classified as follows
(a) intrinsic or ionic breakdown.
(b) Electromechanical breakdown.
(c) thermal breakdown.

Intrinsic breakdown

-> When voltages are applied only for short durations of order of 10^{-8} s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength.

-> Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric. Usually, a small number of

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conduction electrons are present in solid dielectrics, along with some structural imperfections and small amounts of impurities.

-> The impurity atoms, or molecules, or both, act as traps for the conduction electrons up to certain ranges of electric fields and temperatures.

-> When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have been proposed.

1. Electronic breakdown

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

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2. Avalanche or streamer breakdown

-> This is similar to breakdown in gases due to cumulative ionization. Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collisions.

-> under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap. An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field & losses it during collisions. When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron.
This process repeats itself resulting in the formation of an electron avalanche. Breakd-own will occur, when the avalanche exceeds a certain size. In practice, breakdown does not occur by the formation of a single avalanche itself, but occurs as a result of many avalanches formed within the dielectric & extending step by step through the entire thickness of the material.

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Thermal Breakdown

The breakdown voltage of a solid dielectric should increase with its thickness. But this is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction. When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material. The current heats up the specimen and temperature rises. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat radiated out, equals the heat generated.

The heat generated under dc stress E is given as

$$W_{dc} = E^2 \sigma \quad W/cm^3$$

where σ is dc conductivity of specimen.

under AC fields, the heat generated

$$W_{ac} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \quad W/cm^3$$

where f = frequency in Hz

δ = loss angle of dielectric material; and

E = rms value.

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The heat dissipated (W_T) is given by

$$W_T = C_v \frac{dT}{dt} + \text{div}(k \, \text{grad} \, T)$$

where C_v = specific heat of specimen.

T = temperature of specimen

k = thermal conductivity of specimen

t = time over which heat is dissipated.

Equilibrium is reached when the heat generated (W_{dc} or W_{ac}) becomes equal to heat dissipated (W_T). In actual practice, there is always some heat that is radiated out.

Breakdown occurs when W_{dc} or W_{ac} exceeds W_T. The thermal instability condition is shown in fig. Here the heat lost is shown by straight line, while the heat generated at fields E_1 & E_2 are shown by separate curves. At field E_2 breakdown occurs both at temperatures T_A & T_B. In the temperature region of T_A & T_B heat generated is less than the heat lost for the field E_2 & hence the breakdown will not occur.

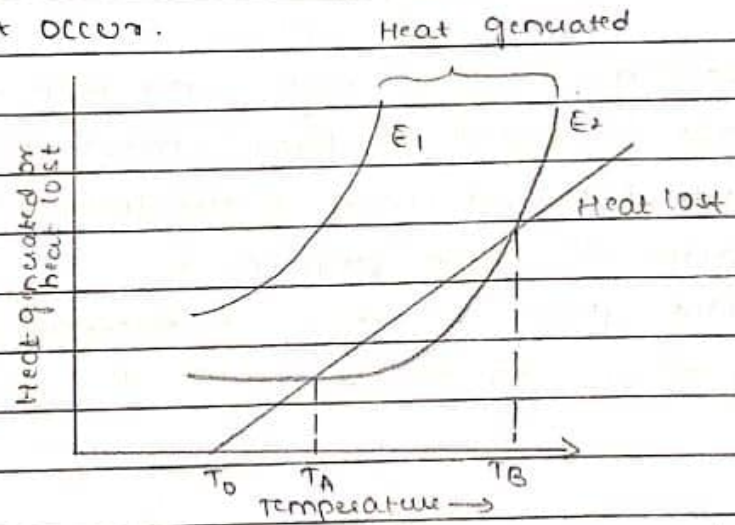

Fig: Thermal instability in solid dielectrics

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Table :- Thermal breakdown stresses in dielectrics

Material	Maximum thermal breakdown stress in MV/cm	
	dc	ac
Muscovite mica	04	7.18
Rock salt	38	1.4
High grade porcelain	–	0.8
HV steatite	–	9.8
Quartz - perpendicular to axis	1200	–
- Parallel to axis	66	–
Capacitor paper	–	3.4-4.4
Polythene	–	3.5
Polystyrene	–	5.0

This is of great importance to practicing Engineers, as most of the insulation failures in high-voltage power apparatus occur due to thermal breakdown. Thermal breakdown sets up an upper limit for increasing the breakdown voltage when the thickness of insulation is increased.

For a given loss angle and applied stress, the heat generated is proportional to the frequency and hence thermal breakdown is more serious at high frequencies.
Table gives the thermal breakdown voltages of various materials under dc & ac fields.

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It can be seen from the table that since the power loss under ac fields is higher, the heat generation is also high, and hence the thermal breakdown stresses are lower under ac conditions than under dc conditions.

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Questions

① Derive an expression for the current in the air gap that is $i = i_0 e^{\alpha d}$ considering Townsend first ionization coefficient.

② What are the limitation of Townsend's theory?

③ In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8} A at 8kV at a distance of 0.4cm between the plane electrodes. keeping the field constant and reducing the distance to 0.1cm results in a current of 5.5×10^{-9} A. Calculate Townsend's primary ionization coefficient α.

④ Explain briefly suspended particle theory of breakdown in liquid dielectric.

⑤ Explain the following breakdown mechanism in solid:
(i) Electro mechanical breakdown.
(ii) Thermal breakdown.

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MODULE-2

GENERATION OF HIGH VOLTAGES AND CURRENTS...

*In this fields of Electrical Engineering & applied physics, high V/gs [DC, AC, impulse] are required for several applications.

→ For Examples, $\varepsilon^{\ominus}$ microscopes & x-ray units requires high DC V/g of order of 100kV (or) more, Electrostatic precipitators, practice accelerates in nuclear physics etc required high V/g DC's of several volts & even mega volts.

→ High AC V/g of 1 million volts (or) Even more are required for testing power apparatus rated for extra high transmission V/g [100 V slip & above].

→ High impulse V/g are required for testing purposes to stimulate overvolts that occurs in power S/m due to lightenting (or) Switching action.

→ For Electrical Engineers, the main concern of high V/g is for the insulation testing of various components in power S/m for d/f types of V/g namely, power frequency (or) high frequency. AC Switching (or) lightening impulses. Hence, generation of high V/g in laboratories for testing purposes is Essential & is discussed in this chapter.

*Different forms of high voltages mentioned above are classified as:-

→ High DC V/g. b) High AC V/g of power frequency. c) High AC V/gs of high frequency. d) High transient (or) impulse V/g of very short duration such as lightening over V/g. e) Transient V/g of longer duration such as switching surges.

*Methods of generating hight DC voltages:- By using rectifier circuit.

→ Voltage doubler circuits. → Voltage multiplier circuit.

*Generation of high DC voltages:- It is mainly required in research work in the areas of pure & applied physics.

→ High direct V/g are needed in insulation test on cables & capacitors. Impulse generator charging units also require high DC V/g of about 100 to 200 kV.

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→ For the generation of DC V/o of upto 100kV, Electronic valve rectifier are used the O/P current are about 100mA.

* ~~Explain~~ Half wave and Full wave rectifier circuit :- A rectifier is a device that converts AC to DC.

→ It is done by using a diode (or) group of diodes.

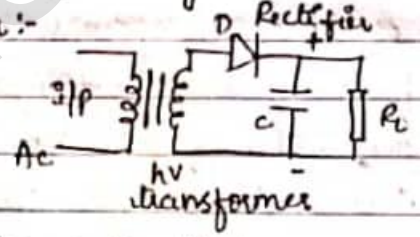
→ Rectifier circuits for producing high DC V/o from AC source maybe,
a) Half wave. b) Full wave. c) V/o doubler type rectifier.

* What is half wave rectifier ?

→ It is defined as a type of rectifier that only allows 1 half cycle of an AC V/o waveform to pass & blocks the other half cycle.

→ HWR are used to converts AC to DC V/o & only 1 diode is required

→ HWR consists of 3 main parts rectifier :-
a) Transformer. b) Resistive load.
c) Diode.



→ During +ve half cycle diode will be forward biased & the current flows through the diode.

→ During -ve half cycle diode will be reversed biased & flow of current is blocked.

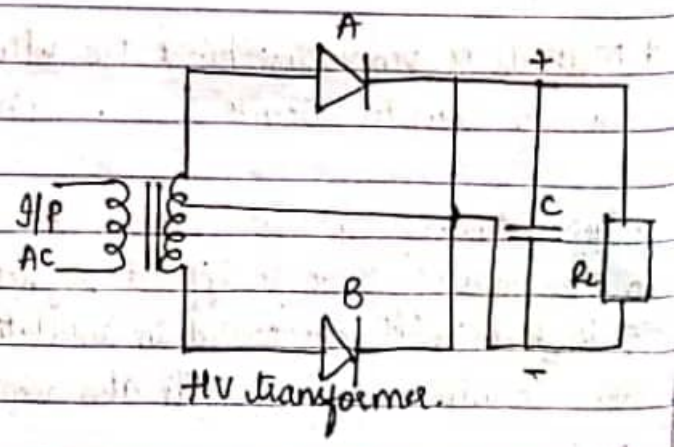
→ Significant amount of power gets wasted as only 1 half of each cycle passes through & the other half cycle gets blocked.

→ HWR Efficiency is only 40.6%.

* Full-wave rectifier :-

→ A full wave rectifier is shown in above fig.

→ In +ve half cycle, the rectifier "A" conducts & charges the capacitor "C" while in -ve cycle the rectifier "B" conducts & charges the capacitor "C".



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* **Voltage Doubler :-** Both full & half wave rectifier circuits produces a AC V/g less than the AC max. V/g. When higher DC V/g are needed, a V/g doubler (or) cascaded rectifier doubler circuits are used.

* **Negative half cycle :-** Rectifier "R_1" is forward biased & rectifier "R_2" is reversed biased. The capacitor "C_1" is charged through rectifier "R_1" to a V/g of ($4 V_{max}$).

→ **Positive half cycle :-** Rectifier "R_2", is forward biased & rectifier "R_1" is reversed biase.

→ The capacitor "C_2" is charged through rectifier "R_2" to a V/g of ($2V_{max}$).

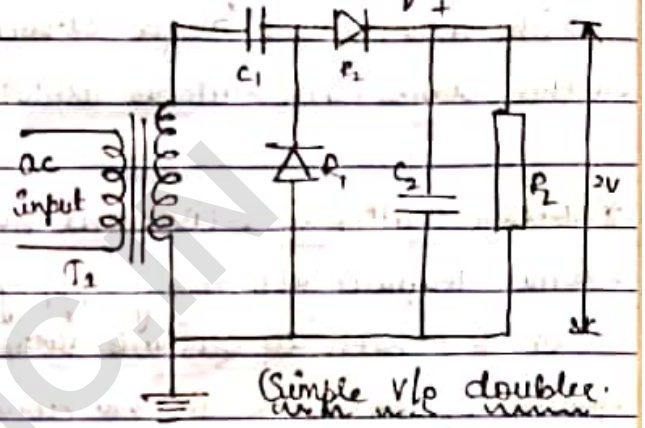
→ The o/p DC V/g on load will be less than ($2V_{max}$) depending on time constant "C_2R_1" & charging time constant.

→ The ripple V/g of these ckt will be able 8% for $R_L/r \leq 10$ & $X/r \leq 0.25$, When ($X<r$) are the reactance & resistance of i/p transformer.

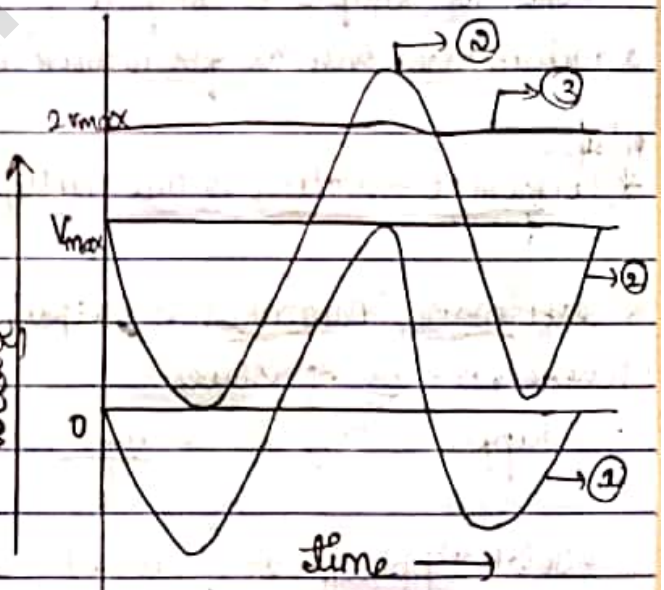
→ The rectifier are rated to a peak inverse V/g of ($2V_{max}$) & capacitor "C_1 & C_2" must also have same rating.

→ If the load current is large, the ripple also is more.

→ Cascaded V/g doubler are used when larger o/p V/g are needed without changing the i/p transformer V/g level.



Simple V/g doubler.



Cascaded V/g doubler.

1) Ac i/p V/g waveform.
2) Ac o/p V/g w.f with capacitor filter
3) DC. o/p V/g w.f with capacitor filter.

* **Cascaded voltage doubler :-** The rectifier "R_1 & R_2" with transformer "T_1" & capacitors "C_1 & C_2" produces an o/p V/g of 2V in the same way as described above.

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→ This crkt is duplicated & connected in series (or) cascaded to obtain a further v/g doubling to 4V.

→ "T" is an isolating transformer to give an insulation for (2Vmax). Since the transformer "T₁" is at a potential of 2Vmax above the ground.

→ The values of all capacitors "C1 & C2, C3 & C4" must be equal in order to maintain uniform v/g across the rectifier string "R1, R2, R3 & R4".

→ The arrangement maybe extended to give 6V, 8V & soon by repeating further stages with suitable isolating transformer.

* Voltage multiplier :- Cascaded v/g doubler circuits for higher v/g are cumbersome required too many supply & isolating transformers.

→ It is possible to generate very high DC v/g from single supply transformers by extending the v/g doubler ckt.

→ This is simple & compact when the load current requirement less than 1 milliampere. such as for cathode ray tubes etc.

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* Cockcraft - Walton voltage multiplier :-

* Performance parameter :- Output voltage (V_o) = $V_o = 2nV_{max}$.

Where, n = no of stages.

→ Ripple voltage (δV) = $\frac{nI_1}{fc}$. Where, I_1 = Load current, f = Frequency, C = Capacitance.

→ Total Ripple factor (δV_{total}) = $\frac{I_1}{fc}(1+2+\dots+n)$

$$\delta V_{total} = \frac{I_1}{fc}\frac{n(n+1)}{2}$$

→ % Ripple = $\frac{\delta V}{2nV_{max}} \times 100$.

→ Voltage regulation = $\frac{\text{V/g drop}}{\text{Total V/g}} \times 100 = \frac{\Delta V}{2nV_{max}} \times 100$.

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

→ Optimum no of stages (n_{opt}) = $\sqrt{\frac{V_{max} \cdot fc}{I}}$.

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1.* A cockcroft-Walton type voltage multiplier has 8 stages with capacitance = 0.05 μF. The supplied transformer 2° is 125 kV at frequency of 150 Hz. If the load current to be supplied is 5 mA. Find
a) Percentage ripple. b) Regulation. c) The optimum no of stages for minimum V/p regulation (or) V/p dropped.

→ Given :- $C = 0.05\,\mu F$, $f = 150\,Hz$; $I_L = 5\,mA$, $n = 8$

$$\delta V = \frac{I_1}{fc} \frac{n(n+1)}{2}$$

$$= \frac{5\times10^{-3}}{150\times0.05\times10^{-6}} \cdot \frac{16(16+1)}{2} = \boxed{90.66\,kV}$$

a) $$\% \text{ Ripple} = \frac{\delta V}{2nV_{max}} \times 100$$

$$= \frac{90.66\times10^{3}}{2\times8\times125\times10^{3}} \times 100 = \boxed{4.53\%}$$

b) $$\text{Regulation} = \frac{\text{Voltage drop}}{\text{Total voltage}} \times 100 = \frac{248}{2\times8\times125} \times 100 = \boxed{12.4\%}$$

$$\Delta V = \frac{I_1}{fc}\left[\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}\right]$$

$$= \frac{5\times10^{-3}}{150\times0.05\times10^{-6}}\left[\frac{2(8)^3}{3} + \frac{(8)^2}{2} - \frac{8}{6}\right] = \boxed{248\,kV}$$

c) $$n_{opt} = \sqrt{\frac{V_{max} fc}{I}}$$

$$= \sqrt{\frac{125\times10^{3}\times150\times0.05\times10^{-6}}{5\times10^{-3}}} = 13.69 \approx \boxed{14}$$

* **Cockcroft - Walton voltage multiplier** :- Voltage multiplier circuit using the cockcroft - walton principle is shown in fig. The stage ie., "D1, D2, C1, C2" & the transformer "T" are identical as in the voltage doubler.

→ For higher o/p V/p of 4, 6, ----, 2n of the i/p V/p "V1" the circuit is repeated with cascade (or) series connection.

→ Thus, the capacitor "C4" is charged to "4Vmax" & "C2n" to "2nVmax" above the earth potential. But the V/p across on the rectifiers "D1, D3, ---- D2n-1 operate & conduct during the +ve half cycle.

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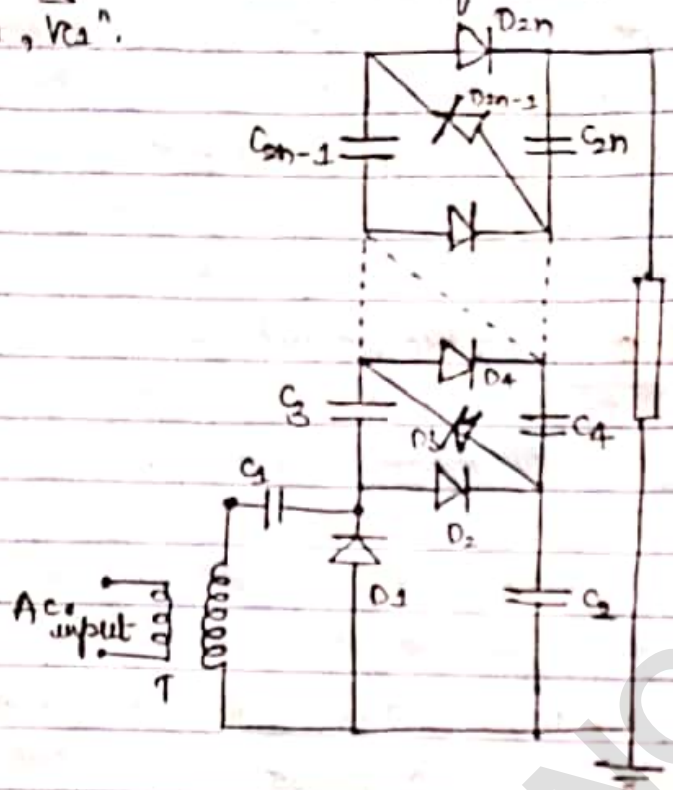
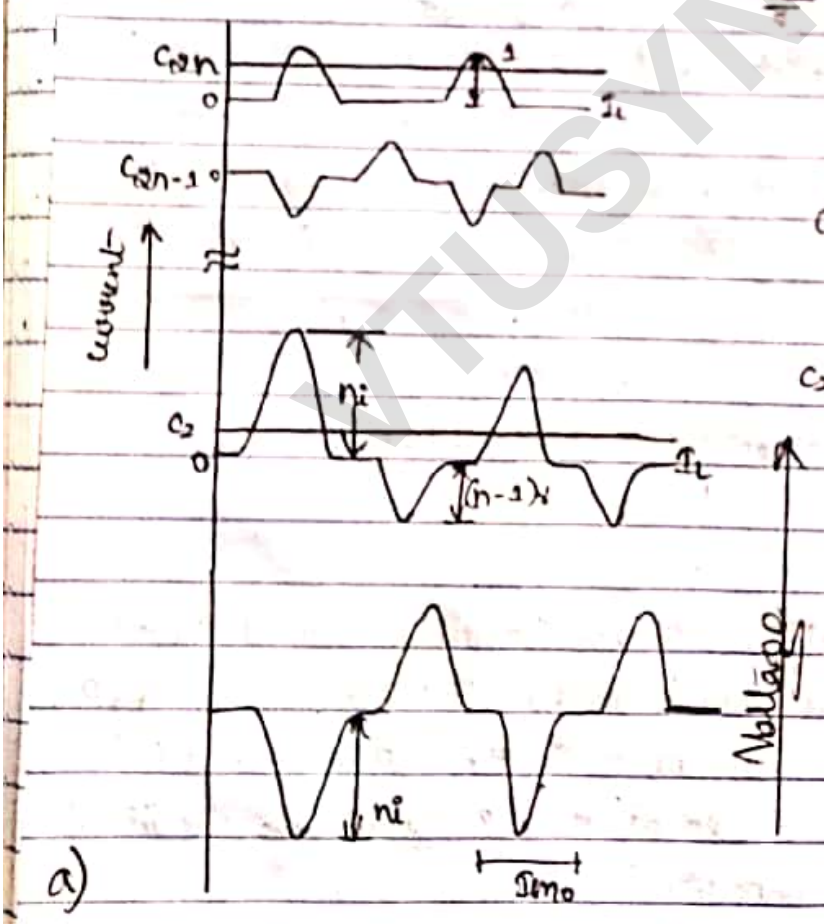
→ The rectifiers "$D_2, D_4, \ldots, D_{2n}$" conduct during the -ve half cycles.

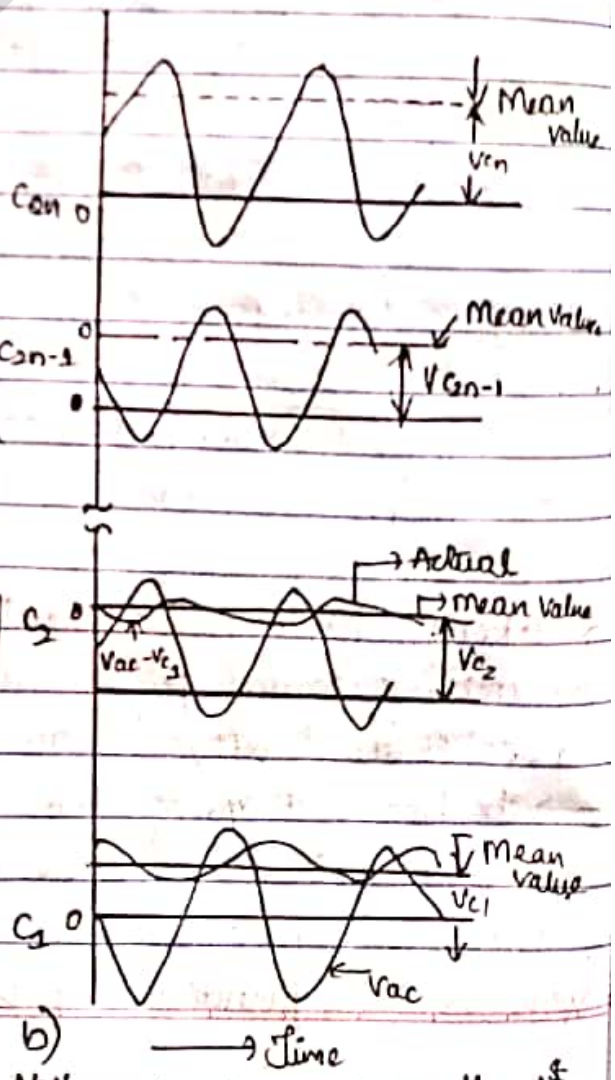
→ Typical current & V/g waveforms of such a circuit are shown in figure. The V/g on "C_2" is the sum of the i/p AC V/g, "V_{ac}" & the across capacitor "C_1, V_{c1}".



Cockcroft - Walton Voltage multiplier circuit.



a) Schematic current waveform across the 1st & last capacitors of the cascaded V/g multiplier circuit shown.



b) Voltage waveforms across the 1st & last cascaded V/g multiplier circuit.

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→ The V/g on "C2" is the sum of supply V/g "Vac" & the V/g across capacitor "C1, Vc1".

→ The mean V/g on "C2" is less than the positive peak charging V/g [Vac + Vc1].

→ The V/g across other capacitors "C2 to Cn" can be derived in the same manner, i.e.,

* Principle of Electrical Energy generation from Electrostatic machines:-

In Electromagnetic machines, current-carrying conductors are moved in a MF, so that the mechanical Energy is converted into Electrical Energy.

→ In Electrostatic machines, charged bodies are moved in an EF against the Electrostatic field in order that mechanical Energy is converted into Electrical Energy.

→ If an insulated belt with a charge & if the belt moves with a velocity "v", then the mechanical power "P", required to move the belts is P = F."v" is converted into the Electrical power, P = V.I.

* Van-de Graff Generation:- It is Electrostatic machine which generates very high V/g, with small o/p current.

→ In Electrostatic machines, charged bodies are removed in an EF against the Electrostatic field in order that mechanical Energy is converted into EE.

→ Charge density is more at sharp points.

→ Total charge of internal sphere move to the outer sphere.

→ Low Spray point.

→ Motor driven pulley.

→ Insulated belt.

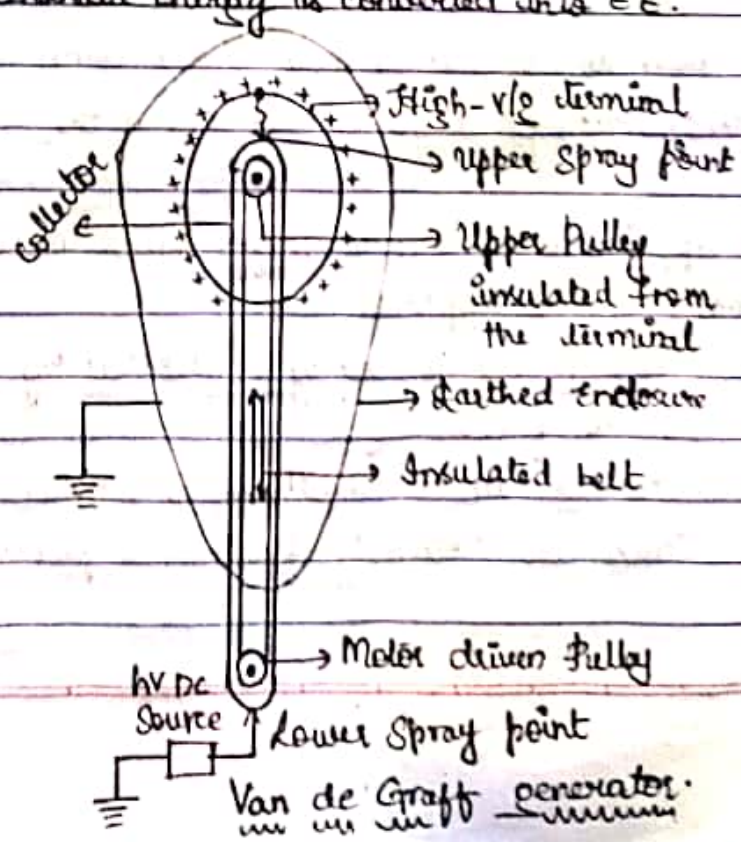
→ HV terminal.

→ Collector.

→ Insulated upper pulley.

→ Upper Spray point.

→ Earthed Enclosure



Van de Graff generator.

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* **Operation** :- The generator is usually enclosed in an earthed metallic cylindrical vessel & is operated under pressure (or) in vaccum.

→ Charge is sprayed onto an insulating moving belt from corona points at a potential of 10 to 100 kV above earth & is removed & collected from the belt connected to the inside of an insulated metal electrode through which the belt moves.

→ The belt is driven by an electric motor at a speed of 1000 to 2000 m/min

→ The charging of the belt is done by the lower spray points which are sharp needles & connected to a DC source of about 10 to 100 kV, so that the corona is maintained b/w the moving belt & the needles.

→ The charge from the corona points is collected by the collecting needles from the belt & is transferred on to the high-V/g electrode as the belt enters into the high-V/g electrode.

→ The belt returns with the charge dropped, & fresh charge is sprayed onto it as it passes through the lower corona point.

→ The upper pulleys is connected to the collector needle & is therefore maintained at a potential higher than that of the high-V/g terminal.

→ A 2nd row of corona points connected to the inside of the high-V/g terminal & directed towards the pulley above its point of entry into the terminal gives a corona discharge to the belt.

→ This neutralizes any charge on the belt & leaves an excess of opposite polarity to the terminal to travel down with the belt of the bottom charging point. Thus, for a given belt speed the rate of charging is doubled.

* **Applications** :- Van de Graff generators are useful for very high-V/g & low-current applications.

→ The o/p V/g is easily controlled by controlling the corona source V/g & the rate of charging.

→ The V/g can be stabilized to 0.01%.

→ These are extremely flexible & precise machines for V/g control.

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* Advantages :- Ripple free output.
→ Flexibility & Precision.

* Disadvantages :- Low current output.
→ Vibration in belt at high speeds.

12/11 * Performance parameter :-
→ output voltage Eqn :- $V_2 = \frac{MV_1}{\sigma L_1 L_2 C_1} \times \frac{1}{\delta_2^2 - \delta_1^2} [\cos r_1 t - \cos r_2 t]$.

Where, M = mutual inductance, V_1 = Input V/p.

$\sigma^2 = \frac{1 - M^2}{L_1 L_2} = 1 - k^2$; $k = \frac{M}{\sqrt{L_1 L_2}}$, $\sigma = \sqrt{1-k}$

k = coefficience of coupling, L_1 = Primary inductance, L_2 = 2° inductance.

$\delta_{12} = \frac{\omega_1^2 + \omega_2^2}{2} \pm \sqrt{\left(\frac{\omega_1 + \omega_2}{2}\right)^2 - \omega_1^2 \omega_2^2 (1-k^2)}$

$\omega_1 = \frac{1}{\sqrt{L_1 C_1}}$, $\omega_2 = \frac{1}{\sqrt{L_2 C_2}}$ Where, C_1 = High V/p Capacitance at primary Ckt.

C_2 = High V/p capacitance at 2° Ckt.

* Problems :-
1) A Tesla coil has 1° winding rated for 10kV. If L_1 & L_2 & coefficient of coupling 'k' 10mH, 200mH & 0.6 respectively.
Find the peak value of the V/p of C in the 1° side is 2.0μF & 2° side is 1nF. Neglect the ~~Neglect the~~ winding resistance. Find also the highest resonant frequency reduced with rated V/p applied.

→ Given :- $L_1 = 10$ mH, $L_2 = 200$ mH, $k = 0.6$, $C_1 = 2.0\mu F$, $C_2 = 1nF$.

$M = k\sqrt{L_1 L_2}$

$= 0.6\sqrt{2000 \times 10^{-6}} = 0.0268$

$\omega_1 = \frac{1}{\sqrt{L_1 C_1}}$; $\omega_2 = \frac{1}{\sqrt{L_2 C_2}} = \frac{1}{\sqrt{200 \times 10^{-3} \times 1 \times 10^{-9}}}$

$= 70710.67$

$\omega_1 = \frac{1}{\sqrt{10 \times 10^{-3} \times 2 \times 10^{-6}}}$

$= \boxed{7.071 \times 10^{4} \text{ rad/sec}}$.

$\omega_1 = 7071.06$

$= \boxed{7.071 \times 10^{3}}$ rad/sec

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$$\sigma = \sqrt{1-k^2}$$

$$= \sqrt{1-(0.6)^2} = \boxed{0.8}$$

$$\gamma_2^2 = \frac{\omega_1^2+\omega_2^2}{2} + \sqrt{\frac{\omega_1^2+\omega_2^2}{2} - \sigma^2\omega_1^2\omega_2^2}$$

$$= \frac{(7071.06)^2+(7071.67)^2}{2} + \sqrt{\frac{(7071.06)^2+(7071.67)^2}{2} - (0.8)^2 \sqrt{(7071.06)^2(7071.67)^2}}$$

$$\boxed{\gamma_2^2 = 70.83\times 10^3 \text{ rad/s}}.$$

$$\gamma_1^2 = \frac{\omega_1^2+\omega_2^2}{2} - \sqrt{\frac{\omega_1^2+\omega_2^2}{2} - \sigma^2\omega_1^2\omega_2^2}.$$

$$= \frac{(7071.06)^2+(7071.67)^2}{2} - \sqrt{\frac{(7071.06)^2+(7071.67)^2}{2} - (0.8)^2(7071.06)^2(7071.67)^2}$$

$$\boxed{\gamma_1^2 = 5.645\times 10^3 \text{ rad/s}}.$$

Highest frequency product $= \frac{\gamma_2}{2\pi}$

$$= \frac{70.83\times 10^3}{2\pi} = \boxed{11.27 \text{ KHz}}.$$

$$V_2(\text{Peak}) = \frac{V_m}{\sigma L_1 L_2 C_2} \cdot \frac{1}{\gamma_2^2-\gamma_1^2}$$

$$= \frac{10\times 10^3 \times 26.32\times 10^{-3}}{0.8(10\times 200\times 10^{-6})\,1\times 10^{-9}} \times \frac{1}{(70.83^2-5.645^2)\times 10^6}$$

$$\boxed{V_2(\text{Peak}) = 33.61 \text{ kV}}$$

$\therefore$ The turns ratio $= \sqrt{L_2/L_1}$

$$= \sqrt{\frac{200}{10}} = \boxed{4.47}$$ Hence o/p peak cannot be more than 44.7 kV.

* Generation of high alternating voltages:- When test voltage requirements are < 300 kV, a single transformer can be used for test purposes.

→ A third winding known as meter winding is provided to measure the o/p voltage.

→ For higher v/p requirements a single-unit construction becomes difficult & costly due to insulation problems.

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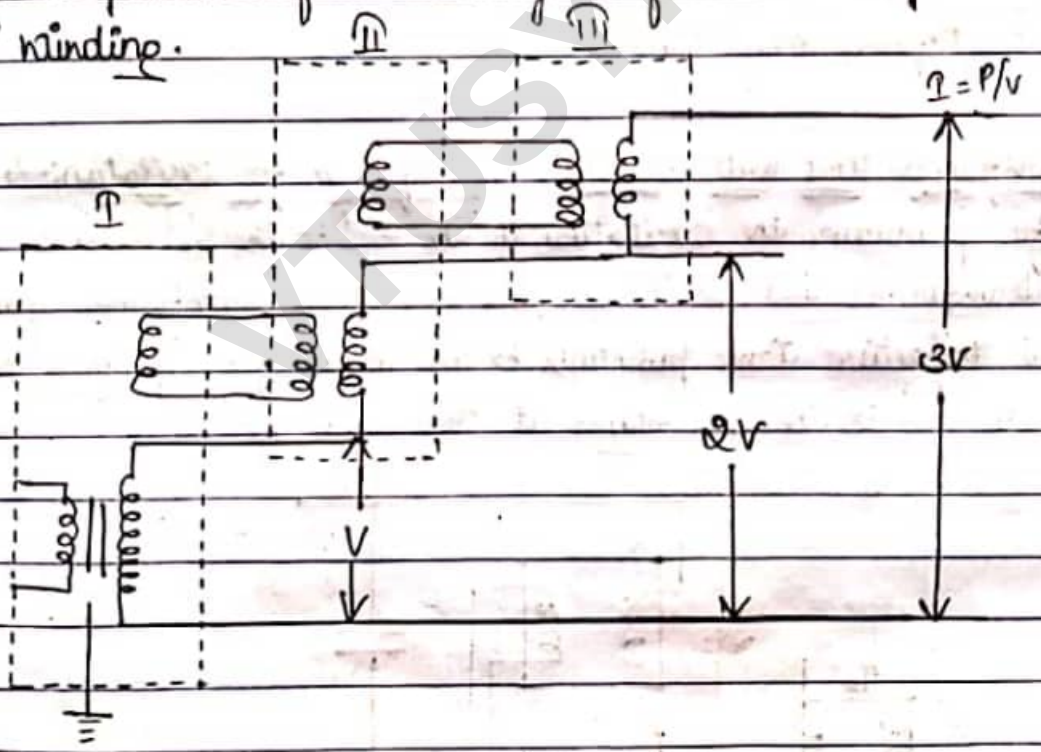
→ Transporation & Erection of large transformers become difficult.
→ These drawbacks are overcome by series connection (or) cascading of the several identical units of transformers, wherein the high V/p windings of all the units effectively come in series.

* Methods to generate high alternating voltages :- Cascaded transformer.
→ Resonant transformer. → Tesla coil.

* Cascade transformers :- It consists of HV & LV winding, meter winding
→ The 1° of the 1st stage transformer is connected to a low V/p supply.
→ V/p is available across the 2° of the same transformer.
→ The tertiary winding [Excitation winding] of the 1st stage has same no of turns as the 1° winding & feeds the 1° of the 2nd stage transformer.
→ The potential of the tertiary is fixed to the potential 'V' of the 2° winding.



→ The 2° winding of the 2nd stage transformer is connected in series with the 2° winding of 1st stage transformer, so that a V/p off 2V is available b/n the ground & the terminal of 2° of the 2nd stage transformer.
→ Similarly, the stage 3 transformer is connected in series with the 2nd stage transformer.

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→ V/g of 3V is available b/n the ground & the terminal of 2° of the 2nd stage transformer.

→ It is also noted that except the uppermost all the individual stages should have 3 winding.

* Advantages :- Multiple small transformer units makes transportation & installation easier.

→ Lower cost due to use of smaller units which require modern insulation.

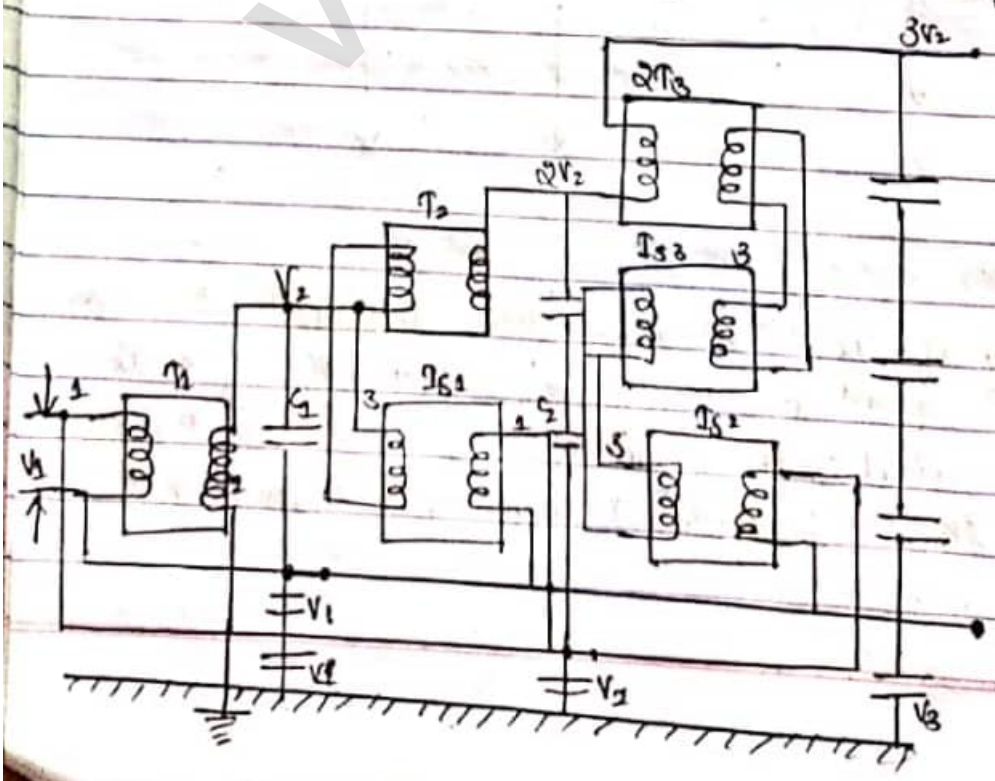
* Limitations :- Overall transformer circuit impedance of 2 stages is 3-4 times & for 3-stage it is 8-9 times that of individual transformer, hence low impedance transformer must be used.

→ The primaries of lower stage transformer are loaded more as compared to upper stages.

→ Expensive & requires more space.

* Cascade transformer unit with isolating transformer for excitation :- A 2nd scheme for providing the excitation to the 2nd & the 3rd stage is shown

→ Isolating transformer "T_{S1}, T_{S2} & T_{S3}" are 1:1 ratio transformers insulated to their respective tank potentials & are meant for supplying the excitation for the 2nd & the 3rd stages at their tank potentials.



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→ This scheme is expensive & requires more space. The advantage of this scheme is that the natural cooling is sufficient & the transformers are light & compact.

→ Transportation & assembly is easy. Also, the construction is identical for isolating transformers & the high-V/g cascade units.

*Power supply for AC test circuits :- Large cascade transformers units are supplied power through a separate motor-generator set (or) by means of V/g regulator.

→ Supply through a V/g regulator will be cheaper, & will be more flexible in the sense that the units in the cascade set can be operated in cascade, (or) in parallel, (or) as 3-phase units.

→ It is also necessary that the impedance of the V/g regulating transformer is low in all V/g positions, from the min. to the rated value.

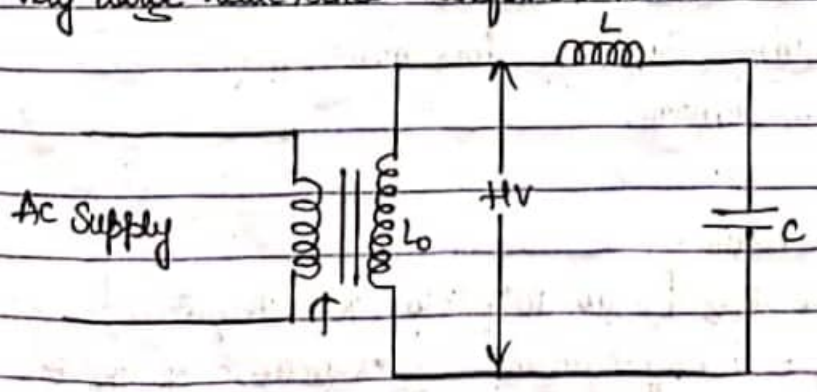
*Resonant transformer :- Cascading of transformers has some disadvantage such as, design in complicated, size is bulky, costly, losses are more.

→ Resonant transformer is 1 of the best choice for HV generation which operates on resonance phenomenon ($X_L = X_C$).

→ The transformer reactances and test object capacitance are connected to form a resonant circuit.

→ The resonance condition is achieved at power frequency by using additional variable choke connected on load side.

→ During the resonance condition the V/g across the test object will rise to very large value since transformer resistance is very small.



T = Testing transformer.
L = Choke.
L_0 = Magnetizing inductance
C = Capacitance of HV terminal & test object

Transformer.

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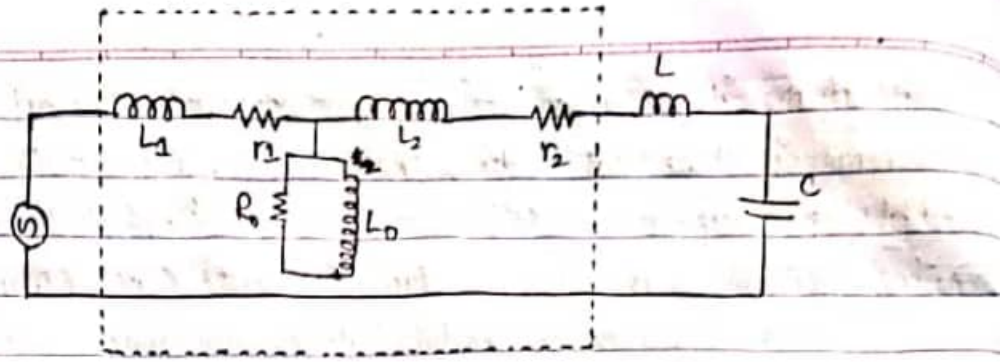
Equivalent circuit.



L_1, L_2 = Leakage inductance of the transformer.
r_1, r_2 = Resistance of the windings.
R_0 = Resistance due to core loss.

→ The equivalent circuit of HV testing transformer consists of leakage reactance of the windings, the winding resistances, the magnetising reactance & the shunt capacitance across the O/P terminal due to the bushing of the HV terminal & also that of the test object.

→ It may be seen that it is possible to have series resonance at power frequency "ω", if $(L_1+L_2) = 1/\omega C$.

→ With this condition, the current in the test object is very large & is limited only by the resistance of the circuit.

→ The waveform of the V/g across the test object will be purely sinusoid.

→ The magnitude of the V/g across the capacitance "C" of the test object will be, $V_C = \left|\frac{-jVX_C}{R+j(X_L-X_C)}\right| = \frac{V}{R}X_C = \boxed{\frac{V}{\omega CR}}$.

→ The "Q" factor of the circuit is $X_C/R = 1/\omega CR$.

→ The I/P V/g required for excitation is reduced by a factor "1/Q" & the O/P KVA required is also reduced by the same factor.

→ The 0° power factor of the circuit is unity.

* **Applications:-** Cable testing, Dielectric loss measurement.
→ Partial discharge measurement.

* **Advantages:-** Pure Sine-wave.
→ Power requirements are less [5 to 10% total KVA required].
→ No high-power arcing & heavy current surges occurs if the test object fails as resonance ceases.

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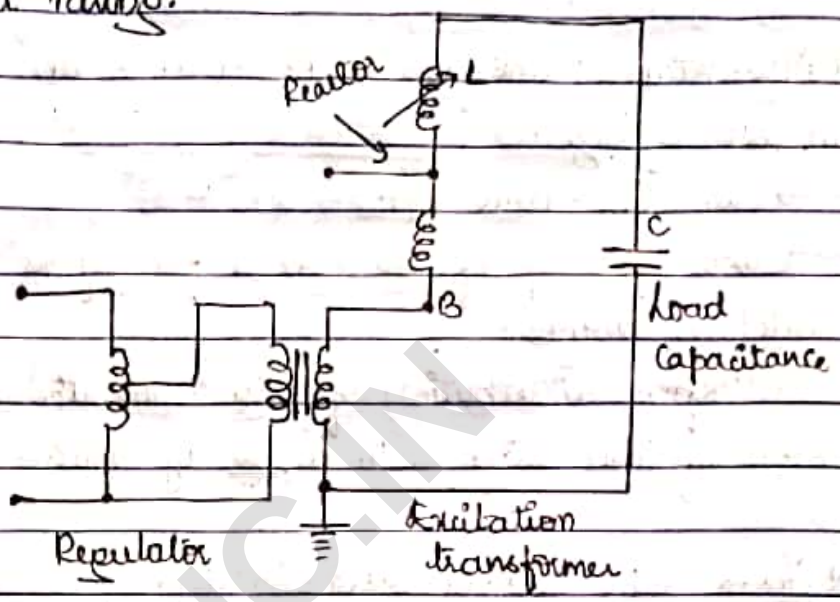
→ Cascading is also possible for very high V/g.
→ Simple & compact test arrangement.
→ No repeated flashovers.

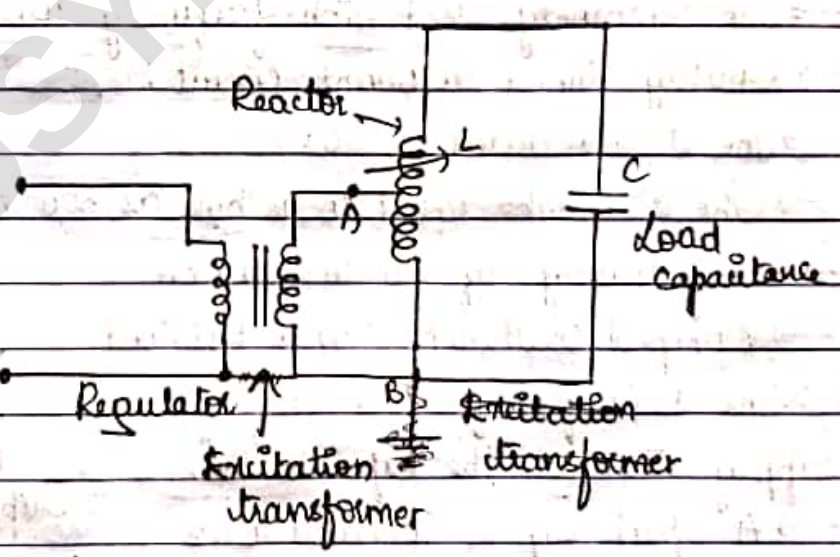
*Disadvantages :- A variable chokes capable of withstanding the full test V/g & the full current rating.

→ A V/g regulator of either the auto-transformer type (or) the inductions regulator type is connected to the supply mains & the secondary winding of the exciter transformer is connected across the HV reactor "L" & the capacitive load "C". The inductance of the reactor "L" is varied by varying its air gap & operating range is set in the ratio 10:1.



Series resonant AC test system.

→ Capacitance "C" comprises of the capacitance of the test object, capacitance of the measuring V/g divider, capacitance of the HV bushing etc.



Parallel resonant AC test system.

→ The Q-factor obtained in these circuits will be typically of the order of 50.

→ In the ||el resonant mode the HV reactor is connected as an auto-transformer & the circuit is connected as a ||el resonant circuit.

→ Single unit resonant test s/m are built for o/p V/g upto 500KV, while cascaded units for o/p upto 5000 KV, 50/60 Hz are available.

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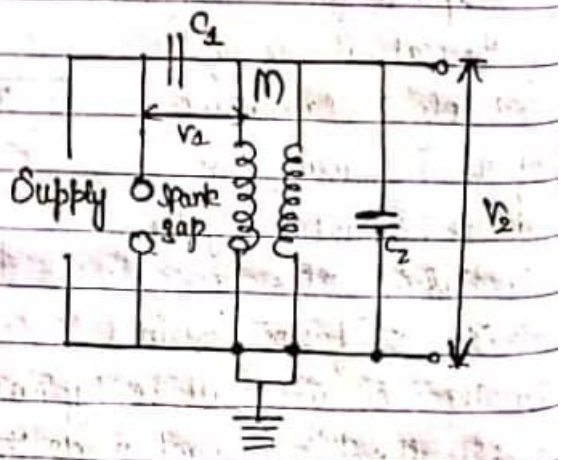
* Generation of high frequency AC high voltage :- High-frequency high V/gs are required for rectifier DC power supplies.
→ For testing electrical apparatus for switching surges, high frequency high V/g damped oscillations are needed which need HV, high frequency transformers.

* Advantages :- The absence of Fe core in transformer & hence saving in cost & size.
→ Pure sine-wave o/p.
→ Slow build-up of V/g over a few cycles & hence no damage due to switching surges.
→ Uniform distribution of V/g across the winding coils due to subdivision of coil stack into a no of units.

* Tesla coil :- Nikola Tesla [1891].
→ Main purpose in HVAC with high frequency.
→ The commonly used high-frequency resonant transform is the Tesla coil.
→ Doubly tuned resonant circuit.
→ The 1° V/g rated is 10kV.
→ The 2° maybe rated to as high as 500 to 1000 kV.
→ A frequency of 10 to 100 kV.
→ Damped oscillations can be obtained.
→ The 1° is fed from a DC (or) AC supply through the capacitor "C_1".
→ A spark gap "G" connected across the 1° is triggered at the desired V/g "V_1" which induces a high self-excitation in the 2°.
→ The 1° & the 2° windings [L_1 & L_2] are wound on an insulated former with no core [Air-cored] & are immersed in oil.



Equivalent circuit.

Tesla coil equivalent circuit and its output waveform

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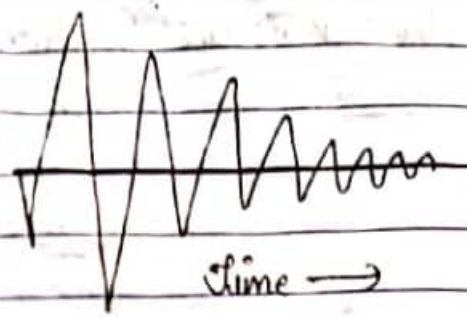
→ The windings are tuned to a frequency of 10 to 100 KHz by means of the capacitor "C_1 & C_2".

→ The 1° coil is wound on an insulator fibre tube of about 1m length to represent a cylindrical (or) helical winding & consists of a few tens of turns [Usually Cu strip (or) tubings].



Output waveform.

→ The 2° winding is spaced quite away from the 1° winding on another concentric fibre (or) pyrex tube with a few thousand turns.

→ The whole assembly will be immersed in an oil tank under pressure

→ With seperate bushings taken out for the 1° & 2° windings, the 1° winding is supplied through a HV capacitor rectifier unit rated for 10 KV to 50 KV (or) more & the power rating of the transformer maybe 10 KVA (or) more.

→ The o/p v/g "V_2" is a function of the parameters "L_1 & L_2", "C_1 & C_2" & the mutual inductance "M".

* Usually, the winding resistances will be small & contribute of the oscillations. The analysis of the o/p waveform can be done in a simple manner neglecting the winding resistances. Let the capacitor "C_1" be charged to a v/g "V_1" when the spark gap is triggered. Let a current "i_1" flow through the 1° winding "L_1" & produce a current "i_2" through "L_2" & "C_2".

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

$$0 = \frac{1}{C_1}\int_0^t i_2\,dt + L_2\frac{di_2}{dt} + M\frac{di}{dt}$$

$$\frac{V_1}{S} = \left(L_1 S + \frac{1}{C_1 S}\right) I_1 + MS I_2$$

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

Where "I_1 & I_2" are the Laplace transformed values of "i_1 & i_2".

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The o/p voltage "V_2" across the capacitor "C_2" is.

$$V_2 = \frac{1}{C_2}\int_0^T i_2\,dt \text{ (or)}$$

$$V_2(S) = \frac{I_2}{C_2 S}.$$

Where "$V_2(S)$" is the Laplace transform of "V_2".
The solⁿ for "V_2" from the above eqⁿ will be.

$$V_2 = \frac{-MV_S}{\sigma L_1 L_2 C_2 \gamma_2^2 - \gamma_1^2}\left[\cos\gamma_1 t - \cos\gamma_2 t\right].$$

$$\sigma^2 = 1 - \frac{ML^2}{L_1 L_2} = \boxed{1-k^2}$$

Where k = coefficient of coupling b/n the windings "L_1 & L_2".

$$\gamma_1^2 = \frac{\omega_1^2+\omega_2^2}{2} + \sqrt{\left(\frac{\omega_1^2+\omega_2^2}{2}\right)^2 - \sigma^2\omega_1^2\omega_2^2}.$$

$$\gamma_2^2 = \frac{\omega_1^2+\omega_2^2}{2} - \left[\left\{\left(\frac{\omega_1^2-\omega_2^2}{2}\right)\right\}^2 - \sigma^2\omega_1^2\omega_2^2\right]^{1/2}$$

$$\omega_1 = \frac{1}{\sqrt{L_1C_1}} \quad \& \quad \omega_2 = \frac{1}{\sqrt{L_2C_2}}.$$

The peak amplitude of the secondary v/o "V_2" can be expressed as.

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

Where, $e = \dfrac{2\sqrt{1-\sigma^2}}{\sqrt{(1+a)^2-4\sigma a}}$.

$$a = \frac{L_2C_2}{L_1C_1} = \frac{\omega_1^2}{\omega_2^2}.$$

The more specified analysis for the Tesla coil may be presented by considering that the energy stored that the 1° circuit in the capacitor "C_1" is transferred to "C_2" via the magnetic coupling. If "W_1" is the energy stored in "C_1" & "W_2" is the energy transferred to "C_2" & if the efficiency of the transformer is "η".

$$= \frac{1}{2}\eta C_1 V_1^2 = \left(\frac{1}{2}C_2V_2^2\right).$$

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

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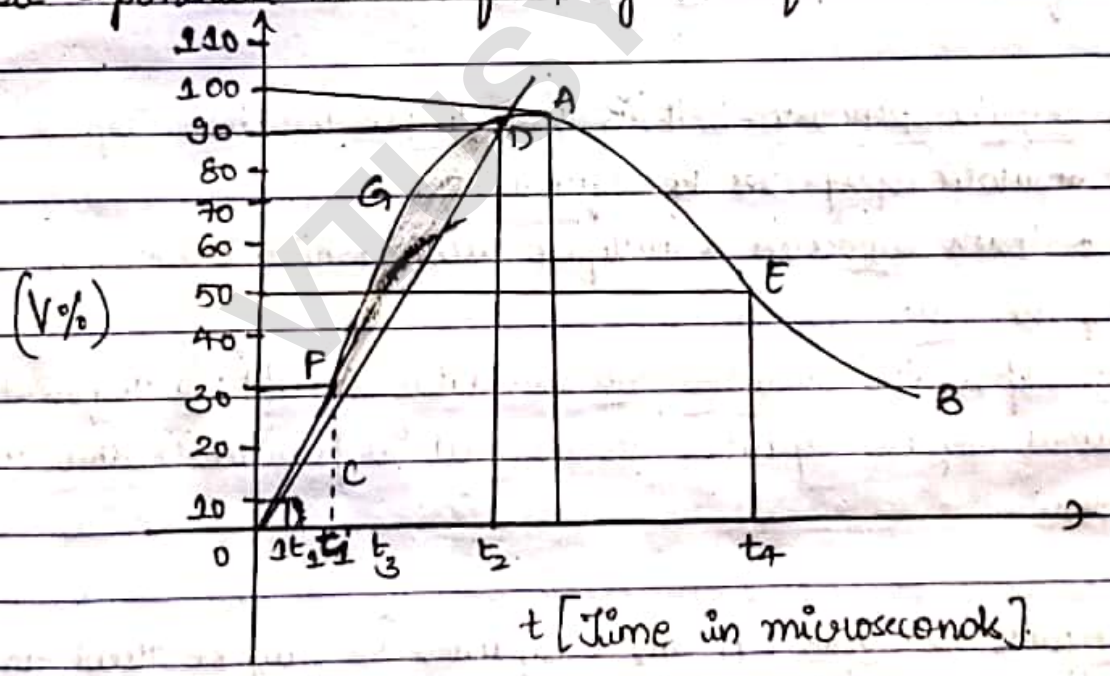
* Generation of impulse voltages :- Impulse voltage
→ Unidirectional voltage.
→ Rises rapidly to maximum value & falls slowly to zero.
→ It has 2 segments, Wavefront :- Time taken by the wave to reach its maximum value starting from zero.
→ Wave front time = $1.25 \times (0.1 t_2 - t_1)$.
→ Wave tail.

* Standard impulse waveshapes :- Transient overvoltages due to lightning & switching surges cause steep build-up of V/g on transmission lines & other electrical apparatus.
→ Experimental investigations showed that these waves have a rise time of 0.5 to 10 μs & decay time to 50% of the peak value of the order of 30 to 200 μs.
→ It is shown that lightning overvoltages wave can be represented as double exponential waves defined by the Eqn.



Impulse wave and its definitions.

* Circuit for producing impulse waves :- A capacitor [C_1 (or) C] previously charged to a particular DC voltage.
→ It is suddenly discharged into the wave shaping network [L-R (or) $R_1 R_2 C_2$ (or) other combination] by closing the switch "S".

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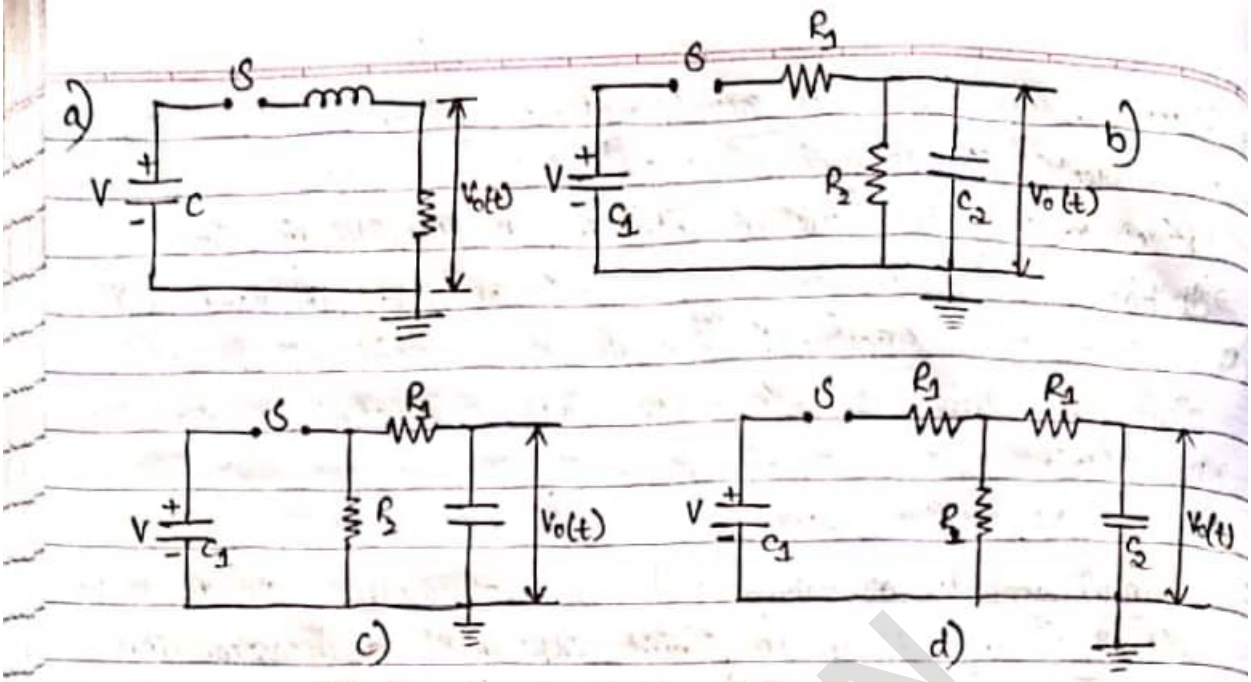

Circuits for producing impulse waves.

→ The discharge v/g "$V_0(t)$" shown in figure, gives rise to an impulse wave shape of desired value.

→ For a given waveshape, the choice of "R_1 & R_2" to control the wave-front & wave-tail times is not entirely independent but depends on the ratio of "C_1/C_2".

* Multistage impulse generator :- It is used to generate high impulse v/g to test the insulation properties of equipment.

→ In 1923 E. Marx suggested a multiplier circuit which is commonly used to obtain impulse v/g.

→ Depending upon the charging v/g available & o/p v/g required "The no of identical impulse capacitors are charged in parallel & then discharged in series."

* Need of impulse generator :- A single capacitor "C_1" may be used for v/gs upto 200 kV.

→ Beyond this v/g, a single capacitor & its charging unit may be too costly, & the size becomes very large.

→ Previously, the generator capacitance "C_1" is to be first charged & then discharged into the wave-shaping circuits.

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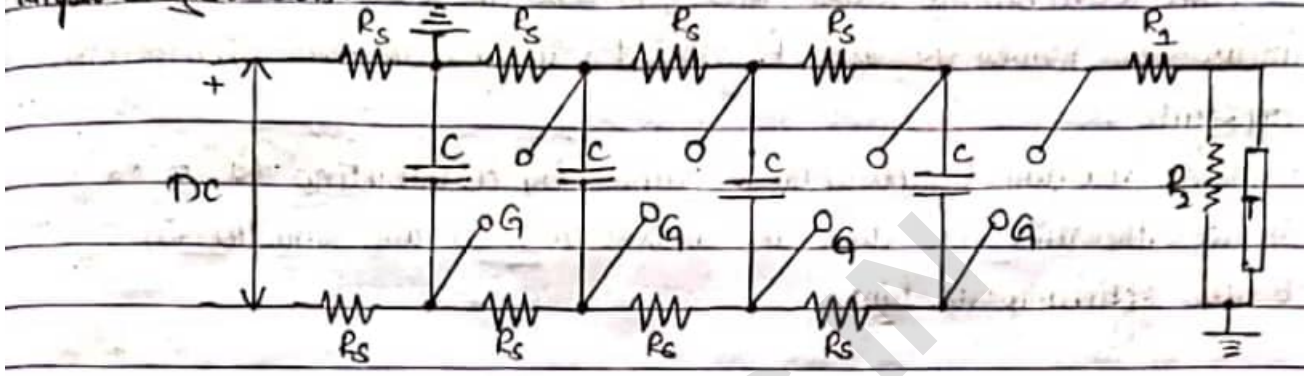
* Multistage impulse generators - Marx circuit :- Hence, for producing very high V/p, a bank of capacitors are charged in parallel & then discharged in series.

→ The arrangement for charging the capacitors in parallel & then connecting them in series for discharging was originally proposed by Marx

→ Now-a-days, modified Marx circuits are used for the multistage impulse generators.



C = Capacitance of the generator ; G = Spark gap ; T = Test object.
Rs = Charging resistors ; R1, R2 = Waveshaping resistors.

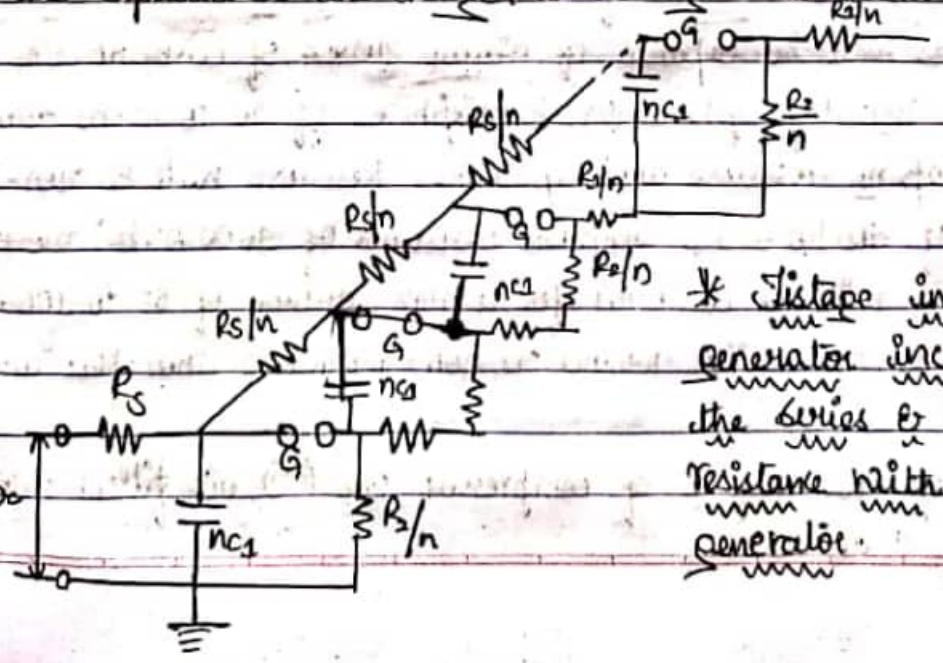
* Schematic diagram of Marx circuit arrangement for multistage impulse generator.

→ The charging resistance "Rs" is chosen to limit the charging current.

→ The generator capacitance "C" is choosen such that the product "CRs" is about 10s to 1 min.

→ The gap spacing is chosen such that the breakdown V/p of the gap "G" is greater than the charging V/p "V".

→ All the capacitances are charged to the V/p "V" in about in 1 min.



* 7 stage impulse generator incorporating the series & wave-tail resistance with in the generator.

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→ The figure shows the modified Marx circuit is shown, wherein the resistance "R_1 & R_2" are incorporated inside the unit.

→ "R_1" is divided into n-parts equal to "R_1/n" & put in series with the gap "G".

→ "R_2" is also divided into n-parts & arranged across each capacitor unit after the gap "G".

→ This arrangement saves spaces, & also the cost is reduced. But, incase the waveshape is to be varied widely, the variation becomes difficult.

→ The additional advantages gained by distributing "R_1" & "R_2" inside the unit are that the control resistors are smaller in size & the efficiency is high.

* Components of a multistages impulse generator :- DC charging set :- The charging unit should be capable of giving a variable DC V/g of either polarity to charge the generator capacitors to the required value.

→ Charging resistors :- Non-inductive high value resistors of about 10 to 100 K. Each resistor will be designed to have a maximum V/g b/n 50 & 100 kV.

→ Generator capacitors and Spark gaps :- These are arranged vertically 1 over the other with all the spark gaps aligned.

•) The capacitors are designed for several charging & discharging operations.

•) The capacitors will be capable of giving 10 kA of current. The spark gaps will be usually sphere (or) hemispheres of 10 to 25 cm diameter.

→ Wave-Shaping resistors and capacitors :- Resistors will be non-inductive wound type of discharging impulse currents of 1000 A (or) more.

•) Each resistor will be designed for a max. voltage of 50 to 100 kV.

•) The resistances are bifilar wound on non-inductive thin flat insulating sheets.

•) The load capacitor may be of compressed gas (or) oil filled with a capacitance of 1 to 10 nF.

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→ Triggering system :- This consists of trigger spark gaps to cause spark breakdown of the gaps.
→ Voltage dividers :- Damped capacitor (or) resistor type & an oscilloscope with recording arrangement are provided for measurement of the V/p across the test object.
→ Gas insulated impulse generators :- Impulse generators rated for 4MV (or) above will be very tall & require large space.
•) Usually located in open space & are housed in an insulated enclosure.
•) The height of a 4.8MV unit may be around 30m. To make the unit compact, a compressed gas, such as N_2 (or) SF_6 may be used as the insulation.

* Disadvantages and Applications :- Long charging time.
→ Short life span of spark gap.
→ Applications :- Test high V/p devices.
→ Impulse generator is used in nuclear physics experiment, fusion & plasma device industries.

* Generation of switching surges :- Now-a-days, in extra-high-V/p transmission lines & power s/m, switching surge is an important factor that affects the design of insulation.
→ A switching surge is a short duration transient V/p produced in the s/m due to a sudden opening (or) closing of a switch (or) circuit breaker (or) due to an arcing at a fault in the s/m.
→ It may also be considered as a slow rising impulse having a wave front time of 0.1 to 10 μs, & a tail time of 1 to several "μs".
→ Thus, switching surges contain larger energy than the lightning impulse V/p.
→ Several circuits have been adopted for producing switching surges.
→ They are grouped as, Impulse generator circuit modified to give longer duration waveshapes.

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→ Power transformer (or) testing transformer excited by DC v/p giving oscillatory waves & these include Tesla coils. Standard switching impulse v/p is defined, both by the indian standards & the IEC's as 250/2500 μs wave, with the same tolerances for time-to-front & time-to-tail as those for the lightning impulse v/p wave i.e., time-to-front of [250 ± 50] μs & time-to-half value of [2500 ± 500] μs. Other switching impulse v/p waves commonly used for testing the lightning arresters are 250/1500 μs with a tolerance of ± 500 μs in time-to-half value.

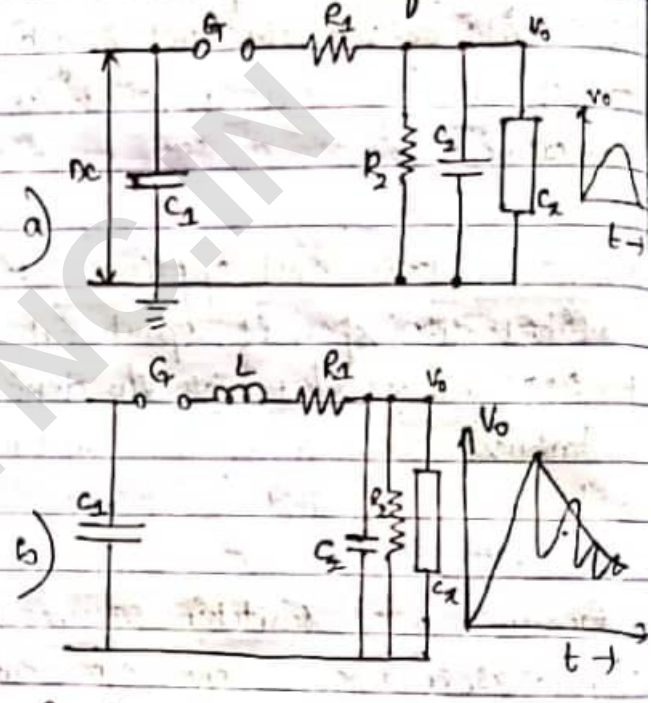
→ Fig shows the impulse generator circuits modified to give switching surges.

→ The arrangement is the same as that of an impulse generator.

→ The values of "R_1 & R_2" for producing waveshapes of long duration, such as 100/1000 μs (or) 400/4000 μs, will range from 1 to 5 KΩ & 5 to 20 KΩ respectively.

→ Thus "R_1" is about 20 to 50% of "R_2".

→ The efficiency of the generator gets considerably reduced to about 50% (or) even less.



Circuits for producing switching surge voltage. Also, shown are the output waveshape across the load "C_x".

→ The value of the charging resistors "R_1" are to be increased to very high values as these come in parallel with "R_2" in the discharge circuit.

→ The circuit given in the fig (b) produces unidirectional damped oscillations.

→ With the use of an inductor "L", the value of "R_1" is considerably reduced & the efficiency of the generator increases.

→ The damped oscillations may have a frequency of 1 to 10 kHz depending on the circuit parameters.

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→ Usually, the max. value of the switch surge obtained is 250 to 300 kV with an impulse generator having a nominal rating of 1000 kV & 25 kJs. Bellaschi & Al. Used only an inductor "L" of low resistance to produce switching impulse upto 500 kV.

→ A sphere gap was included in parallel with the test object for V/g measurement & also for producing chopped waves.

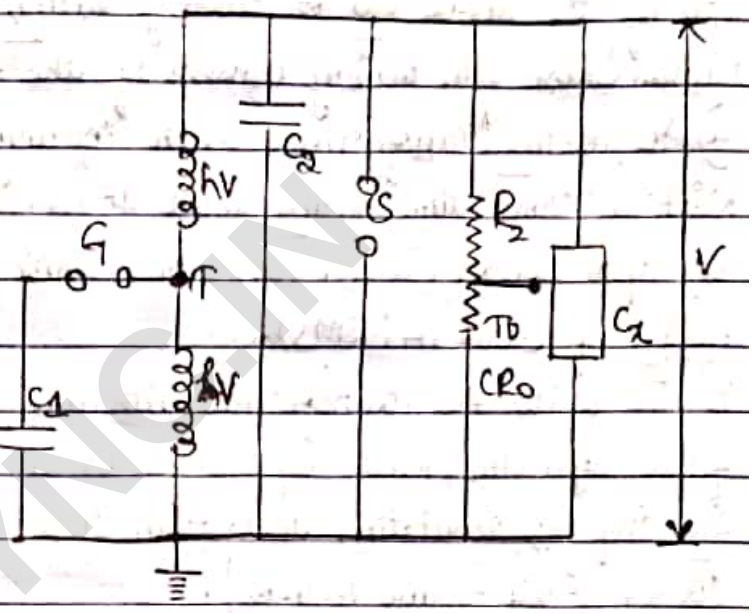
→ Switching surges of very high peaks & long duration can be obtained by using the circuit shown in fig.

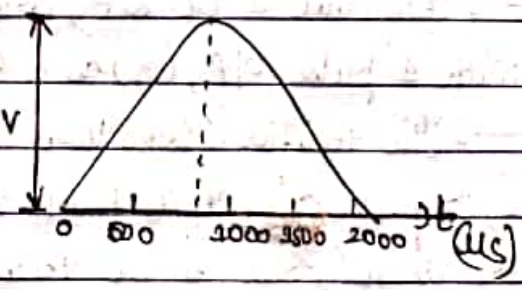
→ An impulse generator condenser "C1" charged to a low V/g DC [20 to 25 kV] is discharged into the low V/g winding of a power (or) testing transformer.

→ The high-V/g winding is connected in parallel to a load capacitance "C2", a potential divider "R2", a sphere gap "S", & test object.

→ Through an autotransformer action, switching surge of proper waveshape can be generated across the test object.

→ The efficiency obtained by this method is high but the transformer should be capable of withstanding very high V/g.





C1 = Surge generator, S = Sphere gap.
G = Triggering spark gap.
T = Testing transformer.
C2 = Load capacitance, Cx = Test object.
hV, LV = Transformer high & low-V/g windings.
R2 = Potential divider.

Circuit for producing switching surges using a transformer.

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→ Multi-test sets for high-v/g testing in many small laboratories like in the teaching institutions, small industries & utility organizations, the requirements of high v/g may be less than 300 kV, 50 Hz ac, 400 kV dc & 400 kV standard lightning & switching impulse v/g. The power requirements will be around 5 kW (or) kVA & the energy requirement will be less than 1.5 kJ. For such applications, flexible & universally interchangeable modular s/m of the above v/g & energy rating are available under different trade names. These s/m mainly consists of the following:

a) AC testing transformers with continuous power rating of 3 to 5 kVA with a short time rating about 150%. The unit can be 1 single transformer of upto 100 kV (RMS), (or) 2 to 3 units connected in cascade with v/g rating of 300 kVA (RMS).

b) DC units AC transformer with the addition of a rectifier unit & a filter capacitor, with ripple factor at rated current less than 5% & a v/g drop (or) regulation less than 10%, for a single stage o/p of about 100 kV [Half-wave rectifier].

→ Constitute a DC set, are available as multi-stage v/g doubler units with 1 pulse o/p, (or) as a quadruple unit of upto 400 continuous.

→ The rectifier stacks used are the selenium diode type. For more

c) Impulse v/g units Marx circuit of 2 to 4 stages can be assumed using the transformer & DC rectifier unit described earlier for an o/p v/g of about 400 kV (peak) using the transformer a 1 stage rectifier unit. The necessary wavefront & wavetail resistors & load capacitance are normally provided. The units are assembled with modular components mounted on suitable insulating columns. The units normally have v/g efficiency of about 90%. All the basic units are clearly & compactly arranged. By having increased no of units the s/m can be expanded to obtain higher & desired type of v/g. Control cubicles/boxes are provided for the control & measurement of v/g. The units can be mounted on wheels (or) located permanently in a test hall of size 4m x 3m x 3m. Multi-test sets are currently being manufactured & assembled in India by some leading manufactures of high v/g test equipments.

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* Tripping and control of impulse generators :- In large impulse generators, the spark gaps are generally sphere gaps (or) gaps formed by hemispherical electrodes.

→ The gaps are arranged such that sparking of 1 gap results in automatic sparking of other gaps as overvoltage is impressed on the other.

→ In other order to have consistency in sparking, irradiation from an ultra-violet lamp is provided from the bottom to all the gaps.

→ To trip the generator at a predetermined time, the spark gaps may be mounted on the movable frame, & the gap distance is reduced by moving the movable electrodes closer.

→ This method of controlled tripping consists of making the first gap a 3 electrode gap & firing it from a controlled source.

→ Fig. shows the schematic with arrangement of a 3-electrode gap.

→ The 1st stage of the impulse generator is fitted with a 3-electrode gap, & the central electrode is maintained at a potential in b/n that of the top & bottom electrodes with the resistor "R_2 & R_3".

→ The tripping is initiated by applying a pulse to the thyratron "G" by closing the switch "S".

→ The capacitor "C" produces an exponentially decaying pulse of +ve polarity.

→ The pulse goes & initiates the oscilloscope time base.

→ The tyratron conducts on receiving the pulse from the switch "S" & produces a -ve pulse through the capacitance "C_1" at the central electrode of the 3-electrode gap.

→ Hence, the V_g b/n the central electrode & the top electrode of the 3-electrode gap goes above the sparking potential & thus the gap conducts.

→ The time lag required for the thyratron firing & breakdown of the 3-electrode gap ensure that the sweep circuit of the oscilloscope begins before the start of the impulse generator V_g.

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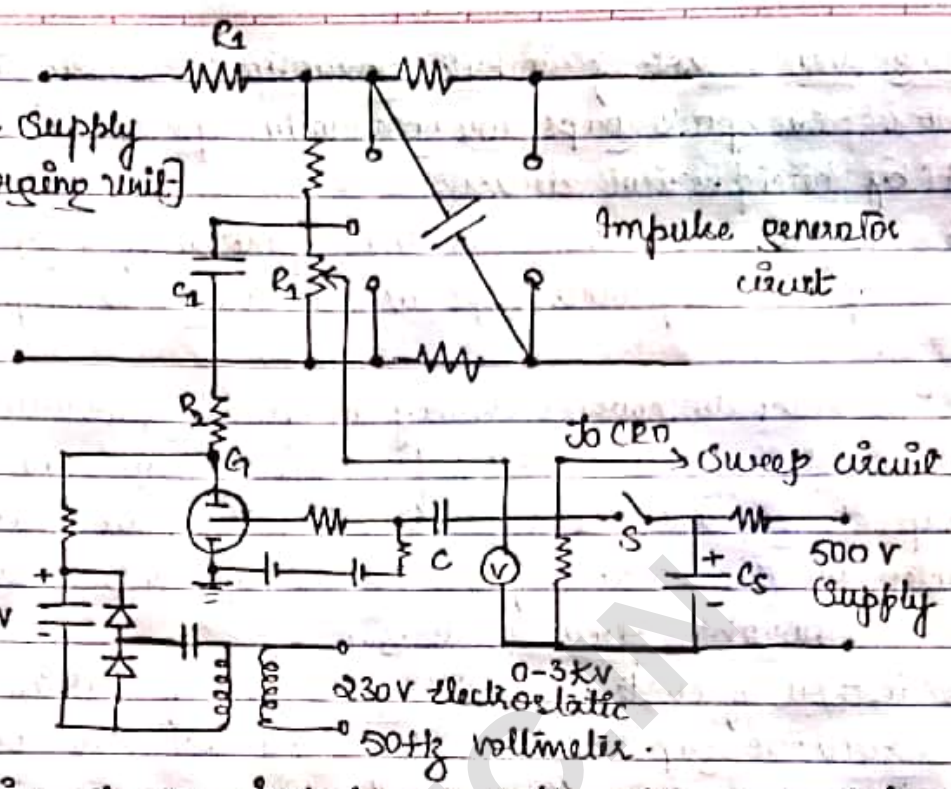


* Tripping of an impulse generator with a 3-Electrode gap.

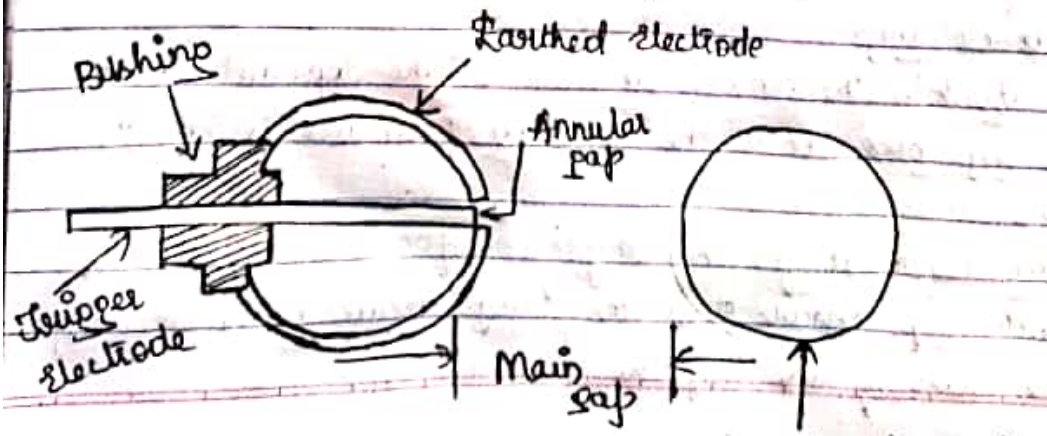
→ The 3-Electrode gap requires larger space & an elaborate construction. Now-a-days, a tripatron gap is shown in the below fig.

→ It is used much smaller V/p for operation compared to the 3-Electrode gap.

→ A tripatron gap consists of a high-V/p spherical electrode of suitable size, an earthed main electrode of spherical shape, & a trigger electrode through the main electrode.

→ The trigger electrode is a metal rod with an annular clearance of about 1mm fitted into the main electrode through a bushing.

→ The tripatron gap is polarity sensitive & a proper polarity pulse should be applied for correct operation.



* Tripatron gap.

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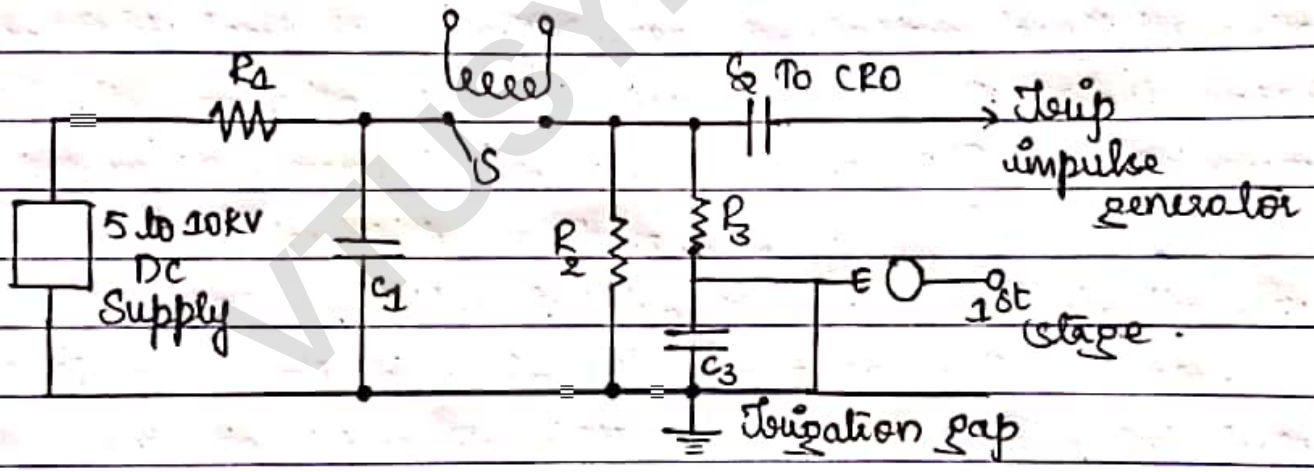
→ The trigatron is connected to a pulse circuit as shown in below fig. Tripping of the impulse generated is effected by a trip pulse which produces a spark b/w the trigger electrode & the earthed sphere.

→ Due to space charge effects & distortion of the field in the main gap, sparkover of the main gap occurs.



* Tripping circuit using a trigatron.

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MODULE - 3.

MEASUREMENT OF HIGH VOLTAGE AND CURRENT...

* Why measurement :- Safety to the personnel & equipment.
→ Electromagnetic interference has to be avoided (or) minimised.
→ Magnitude.
→ Calibration.
→ Location & layout of equipment.

* High - voltage measurement techniques :-

Types of voltage	Method (or) technique.
→ DC voltages.	→ Series resistance microammeter. → Resistance potential divider. → Generating voltmeter. → Sphere & other spark gaps.
→ AC voltage [Power frequency]	→ Series impedance ammeter. → Potential dividers [Resistance (or) Capacitance] → Potential transformers [Electromagnetic (or) CVT]. → Electrostatic voltmeter. → Sphere gaps.
→ AC high frequency voltage, Impulse voltage, & other rapidly changing voltages.	→ Potential dividers with a cathode ray oscillograph [Resistive (or) Capacitive divider] → Peak Voltmeter. → Sphere gaps.

* High-current measurement techniques :-

Types of current	Device (or) Techniques.
→ Direct current.	→ Resistive shunts with milliammeter. → Hall effect generators. → Magnetic links.
→ Alternating current [Power frequency]	→ Resistive shunts. → Electromagnetic current transformers.

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→ High frequency AC, Impulse & rapidly → Chopping currents.	→ Resistive shunts.
	→ Magnetic potentiometer (or) Rogowski coil.
	→ Magnetic links.
	→ Hall Effect generator.

o/p

* Series resistance with microammeter :- Measure HVDC.

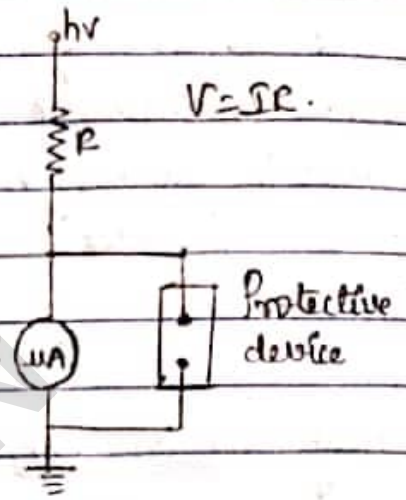
→ Upto 500kV.

→ Construction :- Wire wound resistor [Mohms].

→ Microammeter.

→ Protective device.

→ High DC V/p are usually measured by connecting a very high resistance [Few hundreds of Mohms] in series with a microammeter.



→ Only the current flowing through the large calibrated resistance "R" is measured by the moving coil microammeter.

→ The V/p of the source is given by $V = IR$.

→ A protective device like a paper gap, a neon glow tube (or) a Zener diode with a suitable series resistance is connected across the meter as a protection against high V/p in case the series resistance "R" fails (or) flashes over.

→ The Ohmic value of the series resistance 'R' is chosen such that a current of 1 to 10mA is allowed for full scale deflection.

→ The resistance is constructed from a large no of wire wound resistors in series. The V/p drop in each resistor element is chosen to avoid surface flashovers & discharges.

→ The material for resistive elements is usually a carbon alloy with temp. coefficient less than $10^{-4}/°C$.

* Advantages :- Simple.

→ Low cost. → Easy to operate.

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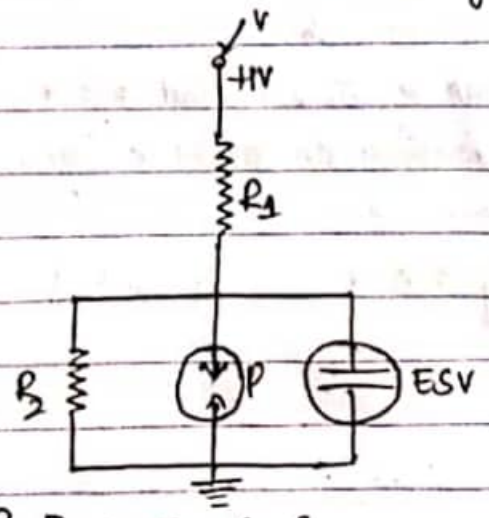
* Limitations :- Power dissipation & source loading.
→ Temp. effects & long time stability.
→ Voltage dependence of resistive elements
→ Sensitivity to mechanical stresses.

* Resistance potential divider for DC voltage :- It uses electrostatic voltmeter
→ The influence of temp. & v/g on the element is eliminated in the v/o dividers arrangement.
→ Let "V_1" across "V_2".
→ $V_1 = V_2 [(R_1 + R_2)/R_2]$, where "$V_2$" is the DC v/g across the low-v/g arm "R_2".
→

* With sudden change in voltage :- Switching operations.
→ Flashover of the test object.
→ Source short circuit, flashover
→ Damage may occur to the divider element due to the stray capacitor across the elements.
→ To avoid these transient v/g, v/g controlling capacitors are connected across the elements. A corona free termination is also neccessary to avoid unnecessary discharges at HV ends.
→ A series resistor with a parallel capacitor connection for linearization of transient potential distribution is shown in fig. Potential dividers are made with 0.05% accuracy upto 100kV, with 0.1% accuracy upto 300kV.



* Resistance potential divider with an electrostatic voltmeter.

P = Protective device
ESV = Electrostatic voltmeter

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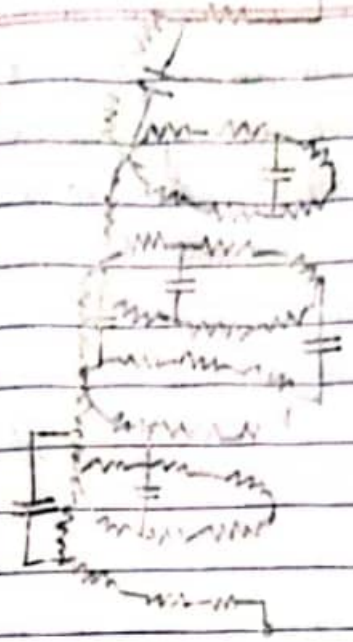
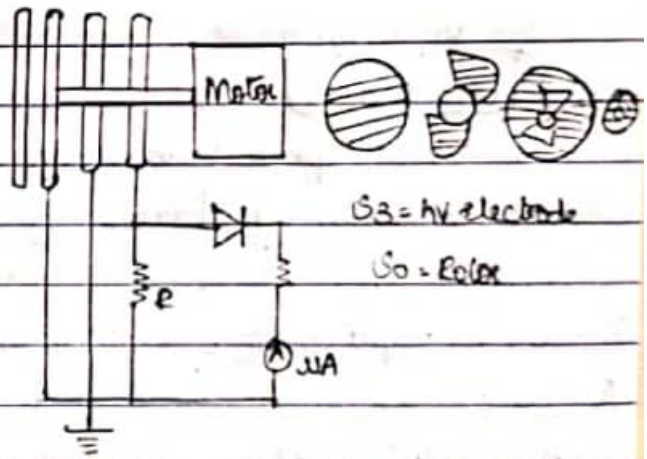
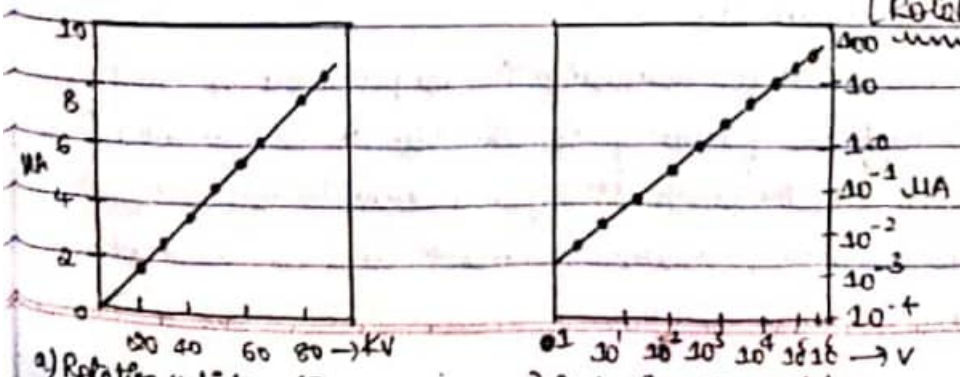


* Series resistor with parallel capacitors for potential linearization for transient voltage.

* Generating voltmeter:- Used to measure low freq AC V/p.
→ High I/P impedance it prevents short circuit.
→ No direct connection to HV.
→ Also known as variable capacitor electrostatic voltmeter.
→ Device is driven by external synchronous motor.
→ Device generates current which is proportional to applied HV.
→ HV electrode S3 disc.
→ LV electrode S0, S1, S2.
→ S0 rotor segment.
→ Motor operates at d/f speeds.
→ 1500, 3000, 3600 rpm.
→ Linear scale device.
→ Area of electrodes / sensitivity.
→ Based on constant.
→ Rotating vane.
→ Rotating cylinder.



* Schematic diagram of generating voltmeter [Rotating vane type]



a) Rotating cylinder type b) Rotating vane type.

* Calibration curves for a generating voltmeter.

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* Principle of operation :- The charge stored in a capacitor of capacitance 'c' is given by $q = CV$. If the capacitance of the capacitor varies with time when connected to the source of V/p "V", the current through the capacitor. $i = \frac{q}{t}$.

$$\frac{dq}{dt} = \frac{d}{dt}(CV).$$

For DC V/p $dV/dt = 0$.

$$\text{i.e., } i = C \cdot \cancel{\frac{dV}{dt}}^{0} + V\frac{dC}{dt}$$

$$\boxed{i = V \cdot \frac{dC}{dt}}$$

→ If the capacitance "c" varies b/n the limits "Co & (Co+Cm)" sinusoidally as $C = C_o + C_m \sin\omega t$.

$$i = V \cdot \frac{d}{dt}(C_o + C_m \cdot \sin\omega t).$$

$$i = V \cdot C_m\omega \cdot \cos\omega t.$$

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

$$\therefore \boxed{i_m = V C_m \omega}$$

→ "i_m" is the peak value of the current. The RMS values of the current is given by :- $\boxed{i_{RMS} = \frac{V C_m \omega}{\sqrt{2}}}$.

Where, V = Applied V/p, ω = Angular speed, Cm = Meter cap, $\omega = \frac{2\pi N}{60}$, N = Linear speed.

→ A generating voltmeter with a rotating cylinder consists of 2 exciting field electrodes & a rotating two pole armature driven by a synchronous motor at a constant speed "n".

→ This device can be used for measuring AC V/p provided the speed of the drive-motor is half the frequency of the V/p to be measured. Thus a 4-pole synchronous motor with 1500 rpm is suitable for 50 Hz.

→ Generating voltmeter employ rotating sectors or vanes for variation of capacitance gives a schematic diagram of a generating voltmeter. The

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High voltage source is connected to a disc Electrode "S_3" which is kept at a fixed distance on the axis of the other two v/g electrode "S_0, S_1 & S_2".

→ The rotor "S_0" is driven at a constant speed by a synchronous motor at a suitable speed [1500, 1800, 3000 (or) 3600 rpm]. The rotor vanes of "S_0" cause periodic change in capacitance b/n the insulated disc "S_2" & the HV electrode "S_3".

→ The shape & no of the vanes of "S_0 & S_1" are so designed that they produce sinusoidal variation in the capacitance.

→ The generated AC current through the resistance "R" is rectified & read by a moving coil instrument.

→ An amplifier is needed, if the shunt capacitor is large (or) longer leads are used for connection to rectifier & meter.

→ The instrument is calibrated using a potential divider (or) sphere gap.

→ The meter scale is linear & its range can be extended by extrapolation. Typical calibration curves of a generating voltmeter are given.

*Advantages of generating voltmeter:- No source loading by the meter.

→ No direct connection to HV Electrode.

→ Scale is linear & extension of range is easy.

→ A very convention instrument for electrostatic devices such as Van de Graff generator & particle accelerators.

*Limitations of generating voltmeter:- They require calibration.

→ Careful construction is needed & is a cumbersom instrument requiring an auxillary drive.

→ Disturbance is position & mounting of the electrodes makes the calibration invalid.

*Measurement of high AC & impulse voltage:- In series impedance voltmeter, potential dividers, potential transformers (or) electrostatic voltmeters.

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→ Peak measurement :- Peak voltmeter or sphere gaps can be used. Sphere gaps are used for calibration purpose.

→ Impulse & high frequency AC measurements :- Potential dividers with a cathode ray oscillograph.

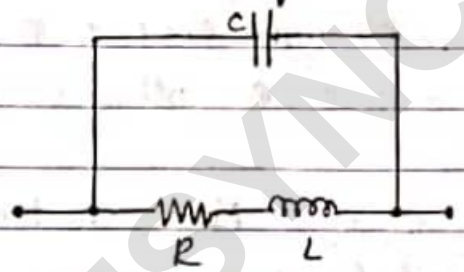
* Series impedance voltmeter :- For power frequency AC measurements the series impedance maybe pure resistance (or) a reactance.

→ But use of resistance yields the following.

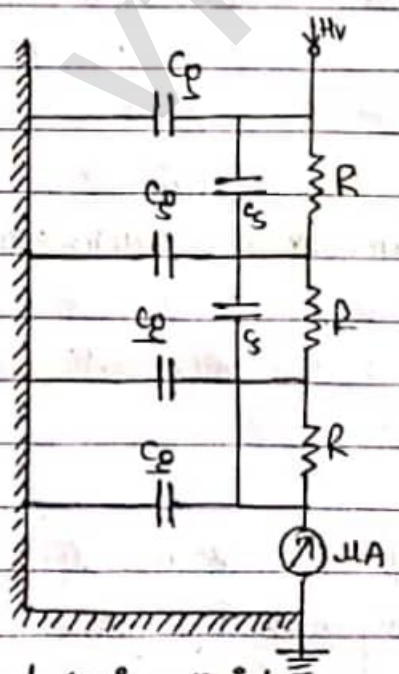
→ Power losses, temperature problem, residual inductances of the resistance gives rise to an impedance diff from its ohmic resistance.

→ For power frequency AC measurements the series impedance maybe a pure resistance (or) a reactance.

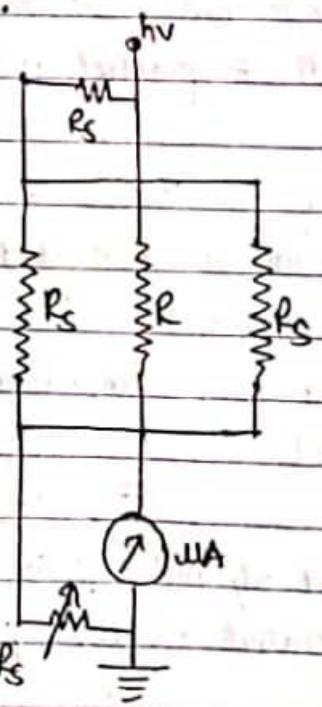
→ High resistance units for high v/g have stray capacitances & hence a unit resistance will have an equivalent circuit as shown in fig.



Simplified lumped parameter equivalent circuit of a high ohmic resistance "R".



a) Extended series resistance with inductance neglected.



b) Series resistance with guard & tunning resistances.

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Where, C_g = Stray capacitance to ground, C_s = Winding capacitance.
R = Series resistor, R_s = Guard resistor, R_t = Tuning resistor.

→ The ground (or) stray capacitance of each element influences the current flowing in the unit & the indication of the meter results in an error.

→ The equivalent circuit of a high v/g resistor neglecting inductance & the circuit of compensated series resistor using guard & tuning resistor is shown in fig (a) & (b) respectively.

→ Stray guard capacitance effects from fig (b) can be removed by shielding the resistor "R" by a 2nd surrounding spiral "R_s", which shunts the actual resistor but doesn't contribute to the current through the instrument.

→ By tuning the resistors "R_a", the shielding resistor & potentials may be adjusted w.r.t the actual measuring resistor so that the resulting compensation current b/n the shield & the measuring resistors provide a minimum phase angle.

* Series Capacitance voltmeter :- To avoid the drawbacks pointed out earlier, a series capacitor is used to instead of a resistor for AC HV measurement. The schematic diagram is shown below. The current "I", "C" through the meter.

Where, C = Capacitance of the series capacitor, V = Applied AC v/g.
ω = Angular frequency.

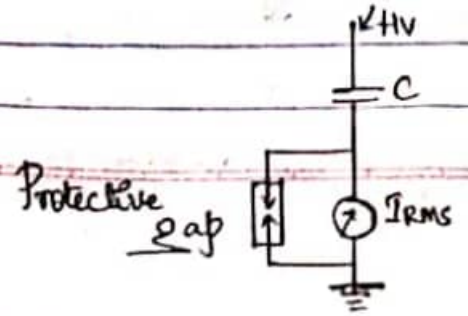
→ If the AC v/g contains harmonics, error due to change in series impedance occurs. The rms value of the v/g "V" with harmonic is given by

$$V = \sqrt{V_1^2 + V_2^2 + \cdots + V_n^2}.$$

Where, "$V_1, V_2, V_3, \ldots, V_n$" represent the RMS value of the fundamental, second,... & n^{th} harmonics.

→ The currents due to these harmonics are $I_1 = \omega C V_1$.
$= I_2 = 2\omega C V_2, \ldots,$ and $I_n = n\omega C V_n$.

Hence, the resultant RMS current is $I = \omega C (V_1^2 + 4V_2^2 + \cdots + n^2 V_n^2)^{1/2}$.



Series capacitance with a milliammeter for measurement of high AC voltages.

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→ This method is not recommended when AC v/g are not pure sinusoidal waves but contain considerable harmonics.

→ Series capacitance voltmeter were used in cascaded transformer for measuring RMS values upto 1000 kV.

→ The series capacitance was formed as a parallel plate capacitor b/n the HV terminal of the transformer & a ground plate suspended above it.

→ A rectifier ammeter was used as an indicating instrument & was directly calibrated in HV RMS value.

* Capacitance potential dividers and capacitance voltage transformers:-

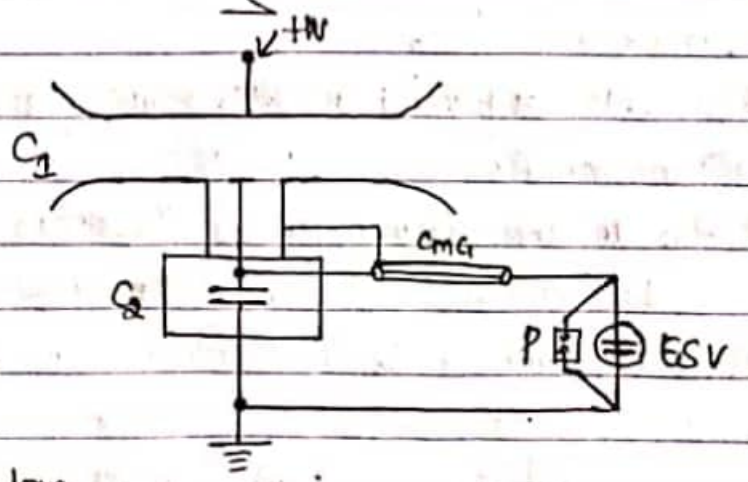
→ The errors due to harmonic v/g can be eliminated by the use of capacitive v/g dividers with an electrostatic voltmeter (or) a high impedance meter such as a TVM.

→ If the meter is connected through a long cable, its capacitance has to be taken into account in calibration. Usually, a standard compressed air (or) gas capacitor is used as "C_1" & "C_2" may be any large capacitor [mica, paper (or) any low loss capacitor].

→ "C_1" is a 3 terminal capacitor & is connected to "C_2" through a shielded cable, & "C_2" is completely shielded in a box to avoid stray capacitance.

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

→ Where, C_m = Capacitance of the meter & the connecting cable & the leads "V_2" is the meter reading.



C_1 = Standard compressed gas HV capacitor.

C_2 = Standard low voltage capacitor.

Capacitance potential divider.

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ESV = Electrostatic voltmeter, P = protective gap, C.C = connecting cable.

* Capacitance voltage transformer :-

→ Capacitance divider with a suitable matching (or) isolating potential transformer tuned for resonance condition is often used in power s/m for V/g measurements.

→ This is often referred to as CVT.

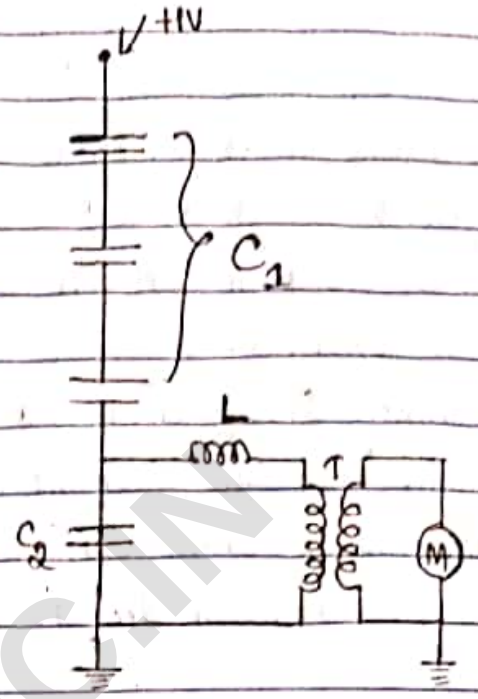
→ A CVT can be connected to a low impedance device like a wattmeter pressure coil (or) a relay coil.

→ The schematic diagram of a CVT with its equivalent circuit is given in the figure.

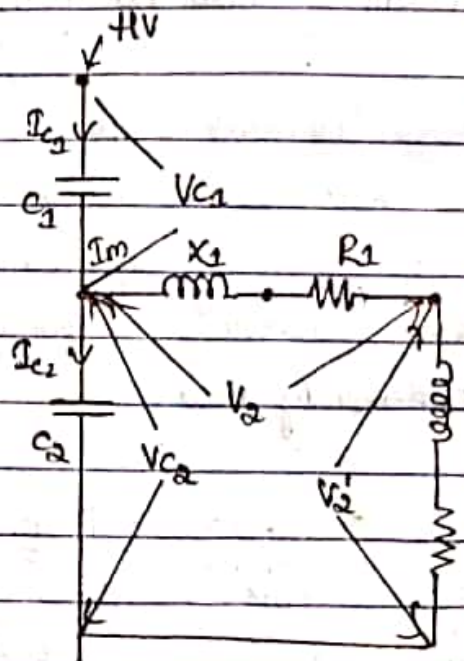
→ "C_1" is made of a few units of HV capacitors, & the total capacitance will be around a few thousand pico-farads as against a gas filled standard capacitor of about 100 pf.

→ A matching transformer is connected b/n the load (or) meter "M & C_2".

→ The value of the tuning choke "L" is chosen to make the equivalent circuit of the CVT purely resistive (or) to bring resonance condition.



a) Schematic representation.



b) Equivalent circuit.

Where, L = Inductance of the choke.

L_T = Equivalent inductance of the transformer referred to +HV side.

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→ The potential transformer resistance & reactance are not shown separately & are included in "R_1 & X_p" the resistance & reactance of tuning inductor "L".

∴ The V/g ratio, $a = \frac{V_1}{V_2} = \frac{V_{C_1} + V_{C_2} + V_2}{V_2}$

* Advantages of a CVT:- Simple design & easy installation.

→ Can be used both as a V/g measuring device for meter & relaying purposes & also as a coupling condenser for power line carrier communication & relaying.

→ Frequency independent V/g distribution along elements as against conventional magnetic potential transformers which require additional insulation design against suppest surges.

→ Provides isolation b/n the high-V/g terminal & low-V/g metering.

* Disadvantages of a CVT :- V/g ratio is susceptible to temperature variations.

→ Problem of inducing ferro-resonance in power s/m.

* Resistance potential dividers:- It suffers from the same disadvantages as series resistance voltmeters for AC applications.

→ Moreover, stray capacitances & inductances associated with the resistance make them inaccurate & compensation has to be provided. Hence, they are not generally used.

* Potential transformers:- Magnetic potential transformers are the oldest device for AC measurement. They are simple in construction & can be designed for any V/g. For every high V/g, cascading of the transformers is possible. The V/g ratio is, $\frac{V_1}{V_2} = a = \frac{N_1}{N_2}$.

→ Where "V_1 & V_2" are the 1° & 2° V/gs, & "N_1 & N_2" are the respective turns in the windings.

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→ These device suffer from the ratio & phase angle error caused by the magnetizing & leakage impedance of the transformer winding.
→ The errors are compensated by adjusting the turns ratio with the tappings on the HV side under load conditions.
→ Potential transformers [PT] do not permit fast rising transient (or) high frequency V/g along with the supply frequency but harmonic V/g are usually measured with sufficient accuracy.
→ With HV testing transformers, no separate potential transformer is used, but a PT winding is incorporated with the HV windings of the testing transformers.
→ With test object like insulators, cables etc which are capacitive in nature, a V/g rise occurs on load with the testing transformer & the potential transformer winding gives V/g values less than the actual V/g applied to the test object.
→ If the percentage impedance of the testing transformer is known, the following correction can be applied to the V/g measurement of the transformer.

$$\therefore V_2 = V_{20}(1 + 0.01 V_x C/C_N).$$

→ Where, V20 = Open circuit V/g of the PT winding, CN = load C used for testing, C = Test object capacitance [C << CN] & Vx = % reactance drop in the transformer.

---

* **Electrostatic Voltmeter** :- Principle in electrostatic field, the attractive force b/n the electrodes of a ||el plate capacitor is given by where,
V = applied V/g b/n plates, C = Capacitance b/n the plates, A = area of cross-section of the plates, d = Diameter of plate, S = Separation b/n the plates, ε_0 = permittivity of the medium [Air (or) free space], WS = Work done in displacing a plate.
→ When 1 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 counter weight. For high-V/g measurements, a small displacement of 1 of the electrodes by a fraction of a millimeter to a few millimeter is

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is usually sufficient for V/p measurements. As the force is proportional to the square of the applied V/p, the measurement can be made for AC (or) DC V/p.

* → Construction:- Electrostatic voltmeters are made with parallel plate configuration using guard rings to avoid corona & field fringing at the edges.

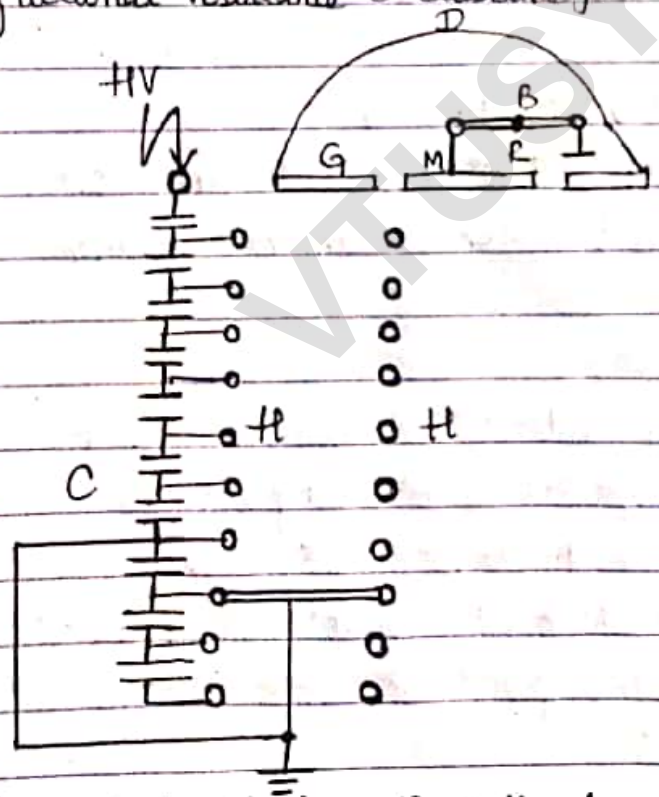
→ Usually the electrostatic voltmeters have a small capacitances [5 to 50pF] & high insulation resistance [$R > 10^{13}\,\Omega$].

→ Hence, they are considered devices with high i/p impedance. The upper frequency limit for AC applications is determined from the following considerations.

i) Natural frequency of the moving s/m.

ii) Resonant frequency of the lead & stray inductances with meter capacitance.,

iii) The RC-behaviour of the retaining (or) control spring [due to the frictional resistance & elastance].



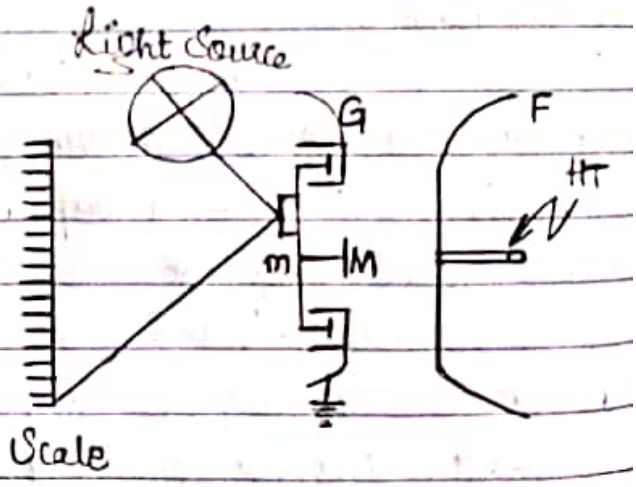
a) Absolute Electrostatic Voltmeter.

M = Mounting plate.

G = Guard plate.

F = Fixed plate.

H = Guard hoops (or) rings.



b) Light beam arrangement.

m = Mirror.

B = Balance.

C = Capacitance divider.

D = Dome.

R = Balancing weight.

Electrostatic Voltmeter.

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→ The schematic diagram of an absolute Electrostatic voltmeter is given as shown in fig. It consists of $\parallel^{el}$-plane disc-type Electrodes separated by a small distance.

→ The moving Electrode is surrounded by a fixed guard ring to make the field uniform in the central region. In order to measure the given V/g with precision, the disc diameter is to be increased, & the gap distances is to be made less.

→ The limitation on the gap distance is the safe working stress (V/S) allowed in air which is normally 5kV. 1cm (or) less.

→ The main difference b/n several forms of voltmeter lies in the manner in which the restoring force is obtained.

→ 2 air vane dampers are used to reduce vibrational tendencies in the moving s/m, & the elongation of the spring is kept minimum to avoid field disturbances.

→ The constructional details of an absolute Electrostatic voltmeter is given as shown in fig (a). The control torque is provided by a balancing weight.

→ The moving disc "M" forms the central core of the guard ring "G" which is of the same diameter as the fixed plate "F".

→ The cap "D" encloses a sensitive balance "B", 1 arm of which carries the suspension of the moving disc. The balance beam carries a mirror which reflects a beam of light.

→ The guard rings "H" are maintained at a constant potential in space by a capacitance divider ensuring a uniform special potential distribution.

* Peak Voltmeters :- It is used to measure peak value of HVAC suggested by Chubb Fortescue in 1913 upto peak V/g of 1kV.

→ Peak value is responsible for breakdown of dielectric.

→ When the waveform is sinusoidal, $V_{rms} = V_m/\sqrt{2}$ i.e., $V_m = V_{rms} \times \sqrt{2}$.

→ Hence a separate peak value instrument is desirable in High V/g applications.

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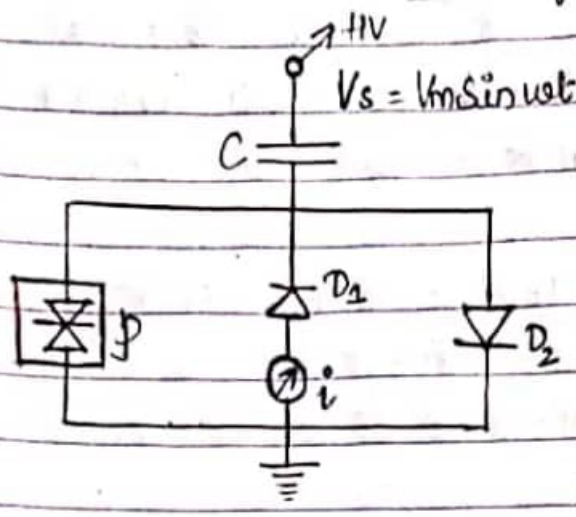
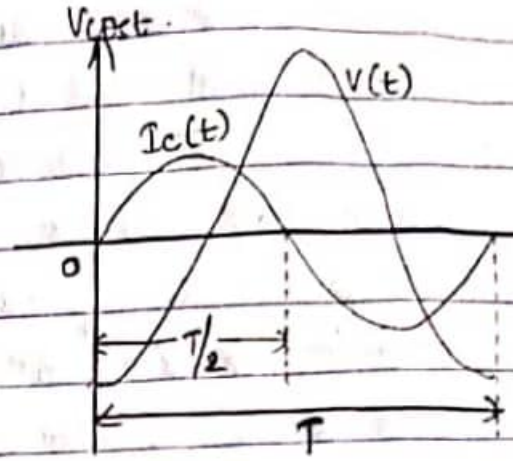
* Series Capacitor peak voltmeter :- When a capacitor is connected to a sinusoidal v/p source, $V_m = IZ = IX_C = I/C\omega = I/C2\pi f$ (or) $I/C_{2\pi f}$

→ The schematic diagram of the circuit arrangement is shown in fig.





V(t) = v/p waveform.

Ic(t) = Capacitance current waveform.

T = Period.

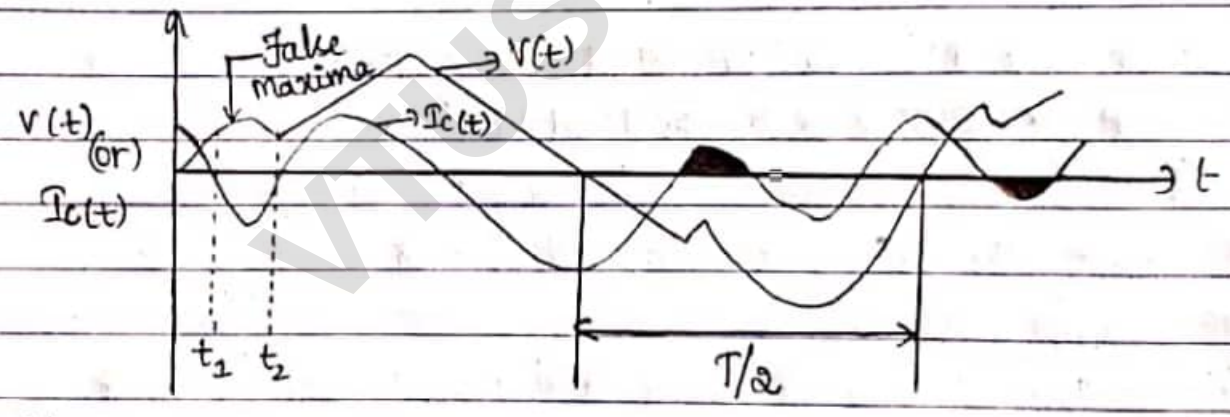
C = Capacitor.

D1, D2 = Diodes.

P = Protective devices.

i = Induction motor [Rectified current indicated].

* Peak voltmeter with a series capacitance *



Voltage waveform with harmonic content showing false maxima.

→ Pros, Quite accurate.

→ It is used for calibration of other measuring devices.

* → Construction :- Non-Uniform current waveform.

→ Waveshapes contains oscillations (or) fluctuations.

→ Peak voltmeters with potential dividers peak voltmeter using capacitance dividers, designed by Boulder & Al., are shown in figure below @.

→ The v/p across "Cs" is made use of in charging the storage capacitor "Cs". "Rd" is a discharge resistor employed to permit variation of "Vm"

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Whenever is "V_2" reduced. "C_s" is charged to a V/g proportional to the peak value to be measured.

→ The indicating meter is either an electrostatic voltmeter (or) a high impedance VTVm. This discharge time constant "$C_s R_d$" is designed to be about 1 to 10s. This gives rise to a discharge error which depends on the frequency of supply V/g.

→ To compensate for the charging & discharging errors due to resistances, the ckt is modified as shown in fig (b).

→ Measurement of average peak is done by a microammeter. Rabus modification to compensate the charging errors is given in fig (c).

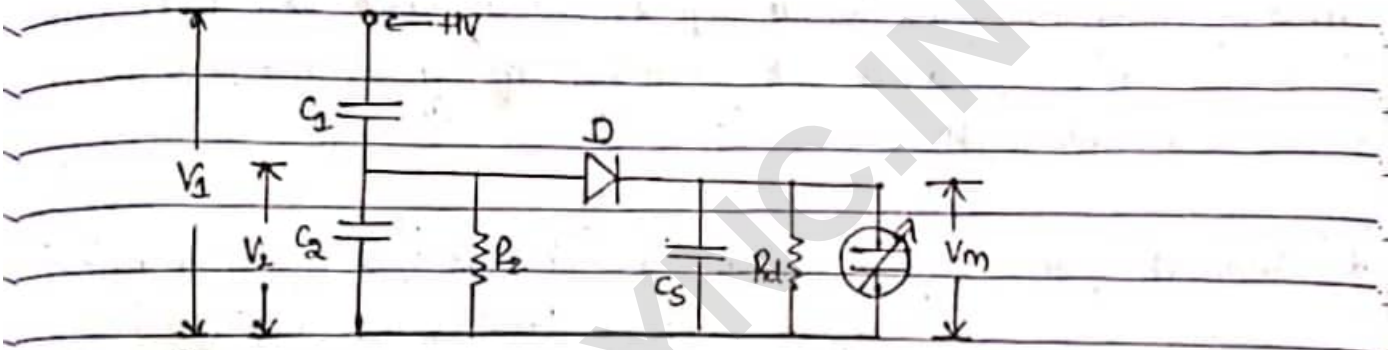

Fig (a). Peak voltmeter with a capacitor potential divider & electrostatic voltmeter.

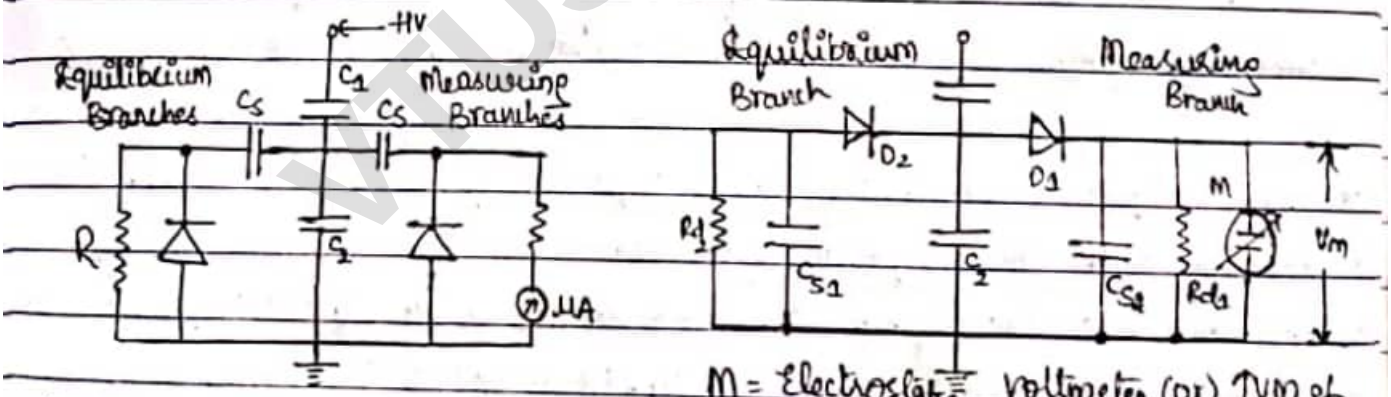

Fig (b) Peak voltmeter as modified by Hoefly.

M = Electrostatic voltmeter (or) TVM of high impedance.

$C_{s2} - C_{s1} + C_{meter}$; $R_{d2} - R_{d1}$.

Fig (c). Peak voltmeter with equilibrium branch as designed by Rabus.

* Measurement of high DC, AC & impulse voltage [Peak values]:- A uniform field spark gap will always have a sparkover V/g within a known tolerance under constant atmospheric condition.

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→ Hence a spark gap can be used for measurement of the peak value of the V/g, if the gap distance is known. A spark over V/g of 30 kV [Peak] at 1cm spacing in air at 20°c & 760 torr pressure occurs for a sphere gap (or) any uniform field gap. But experience has shown that these measurements are reliable only for certain gap configurations.

→ Normally, only sphere gaps are used for V/g measurements. In certain cases uniform field gaps & rod gaps are also used, but their accuracy is less.

→ The space gap breakdown, especially the sphere gap breakdown is independent of the V/g waveform & hence is highly suitable for all types of waveforms from DC to impulse V/g of short rise times [>0.5μs]. As such, sphere gaps can be used for radio frequency AC V/g peak measurement also [upto 1MHZ].

* Standard sphere gap measurements :- What is sphere gap measurement?

→ Possible to measure the peak value of HVAC, peak value of HVDC & impulse V/g.

→ Peak values can be measured if the distance b/n the 2 spheres is known.

i) Horizontal sphere gap arrangement. ii) Vertical sphere gap arrangement.

* Sphere gap measurements :- Sphere gaps can be arranged either.

i) Vertically with lower sphere ground.

ii) Horizontal with both spheres connected to the source V/g (or) 1 sphere grounded

→ Spheres are generally made of Cu, brass (or) Al. The latter is used due to low cost. The standard diameter for the spheres are 2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150 & 200 cm.

→ The schematic arrangement is shown in fig (a) & (b)

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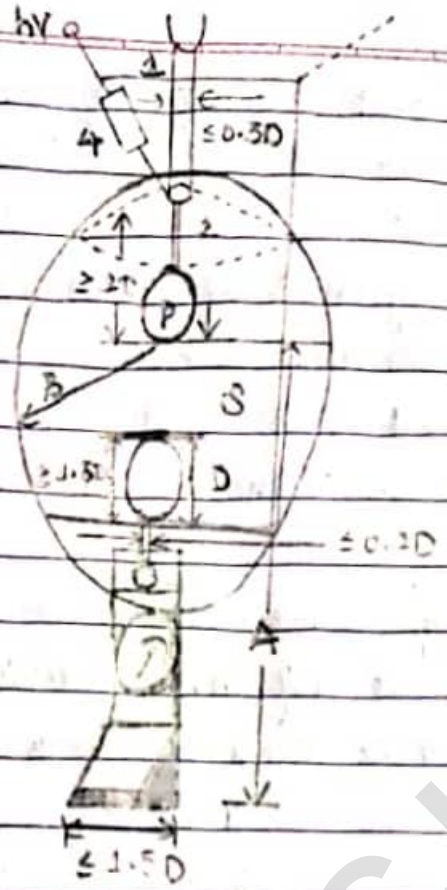
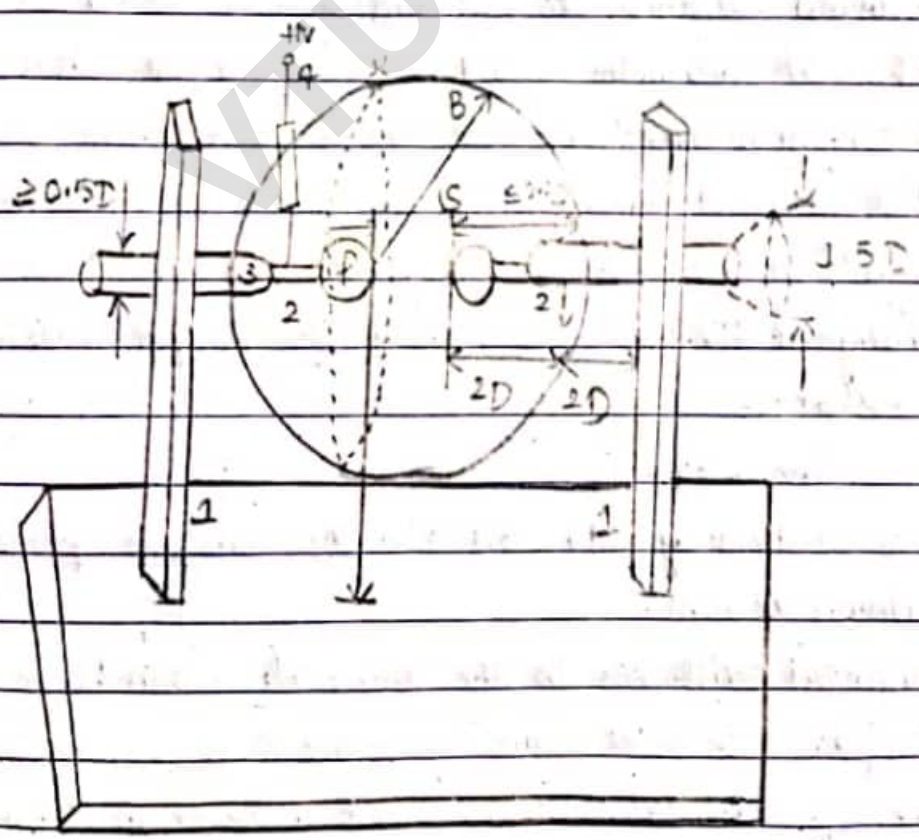


1 = Insulator support.
2 = Sphere shank.
3 = Operating motor for changing gap distance.
4 = +HV connection.
P = Sparking point.
D = Diameter of the sphere.
S = Spacing.
A = Height of "P" above earth.
B = Radius of the clearance from external structure.
X = High V/g lead should not pass through this plane with in a distance "B from P".

a) Vertical arrangement of Sphere gap.



b) Horizontal arrangement of sphere gap.

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*Sphere gap construction and assembly :- Sphere gaps made with 2 metal spheres of identical diameter "D" with their shanks, operating gear & insulator supports [Fig ⓐ & ⓑ].

→ Sphere gaps are generally made of Cu, brass (or) Al, the latter is used due to low cost. The standard diameter for sphere are 2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150 & 200 cm.

→ The spacing is so designed & chosen such that flashover occurs near the sparking point "P".

→ The sphere are carefully designed & fabricated so that their surfaces are smooth & the curvature is uniform. The radius of curvature measured with a spherometer at various points over an area enclosed by a circle of 0.3D around the sparking point should not differ by more than ±2% (or) the nominal value. The surface of sphere should be free from dust, grease (or) any other coating.

→ The surface should be maintained clean but need not be polished. If excessive pitting occurs due to repeated sparkovers, they should be smoothened.

→ The dimensions of the shanks used the grading ring used [if necessary] with spheres, the ground clearance etc., should follow the values indicated in fig ⓐ & ⓑ. The high V/g conductor should be arranged such that it does not affect the field configuration. Series resistance connected should be outside the shanks at a distance 2D away from the HV sphere (or) sparking point.

→ In horizontal configurations, it is generally arranged such that both spheres are symmetrically at HV above the ground. The 2 sphere used are identical in size & shape.

→ Both electrodes are insulated.

→ A series resistance is usually connected b/n the source & sphere gap to

i) Limit the breakdown current.

ii) To suppress unwanted oscillations in the source V/g when breakdown occurs [In case of impulse V/g]. The value of series resistance may vary from 100 to 1000 kΩ for AC (or) DC V/g & not more than 500 in case of impulse V/g.

→ Sphere should be carefully designed & fabricated.

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→ In both horizontal & vertical, sphere gap must be less than the diameter of the sphere.
→ Uniform radius of curvature has to be maintained both electrodes are not insulated. Epoxy fibre structure, anti tracking point.

* Working :- Clean the electrodes. → Measure the breakdown v/g.
→ Zero settings. → Set the gap. → Apply HV.

* Factors influencing the sparkover voltage of sphere gap :- Various factors that affecting the sparkover v/g of a sphere gap are :-
→ Near by earthed object → Irradiation.
→ Atmospheric condition & humidity.
→ Polarity & rise time of v/g waveform.
→ Detailed investigations of the above factors have been made & analysed by Craggs & Meek, Kuffel & Abdullah, Kuffel, Davis & Bowlder, several other investigations.

* Nearby earthed objects :- The effects of nearby earthed object was investigated by Kuffel by enclosing the earthed sphere inside an earthed cylinder. It was observed that sparkover v/g is reduced.
→ The reduction was observed to be, $\Delta V = m \log(B/D) + c$.
Where, ΔV = % reduction ; D = diameter of sphere ; S = spacing.
B = diameter of earthed enclosing cylinder ; "m & c" are constants.

* Effects of atmospheric conditions and humidity :- The sparkover v/g of a spark gap depends on the air density which varies with the changes in both temp. & pressure.
→ If the sparkover v/g is "V" under dist conditions of temp. "T" & pressure "P" torr & if the sparkover v/g is "V_0" under standard condition of temp. T = 20°C & pressure P = 760 torr then $\boxed{V = kV_0}$.
Where "k" is a function of air density factor "d" given by,

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

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→ The relationship b/n "d & k" is given in table.

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

→ Hence it may be concluded that spark V/g is directly proportional to humidity.

→ Humidity affect increase w.r.t size of sphere.

→ Sparkover V/g is proportional to partial pressure of H_2O vapour in air.

* Effects of irradiation :- Presence of X-ray & UV-rays is proportional to spark over V/g.

* Effects of polarity and waveforms :- It has been observed that the sparkover V/g for +ve & -ve polarity impulse are d/f. Experimental investigation showed that for sphere gaps of 6.25 to 25cm diameter, the difference b/n +ve & -ve DC V/g is not more than 1%.

→ For small sphere gaps [2cm diameter & less] the difference was about 8% b/n +ve & -ve impulses of 1/50 μs waveform.

→ Similarly, the wavefront & wavetail durations also influence the breakdown V/g. For wavefronts of less than 0.5 μs. & wavetail less than 5 μs the breakdown V/g are not consistent & hence the use of sphere gap is not recommended for V/g measurement in such cases.

* Rodgap measurement :- It is used for approximate measurement of peak values of power frequency V/g & impulse V/g.

→ IEEE recognises that this method gives an accuracy within ± 8%.

→ The rods will be either square edged (or) circular in cross-section.

→ The length of the rods may be 15 to 75cm & the spacing varies from 0 to 200 cm.

→ The sparkover V/g, as in other gaps, is affected by humidity & air density.

→ The power frequency breakdown V/g for 1.27cm square rods in air at 27°C & at a pressure of 760 torr with the vapour pressure of water of 15.5 torr.

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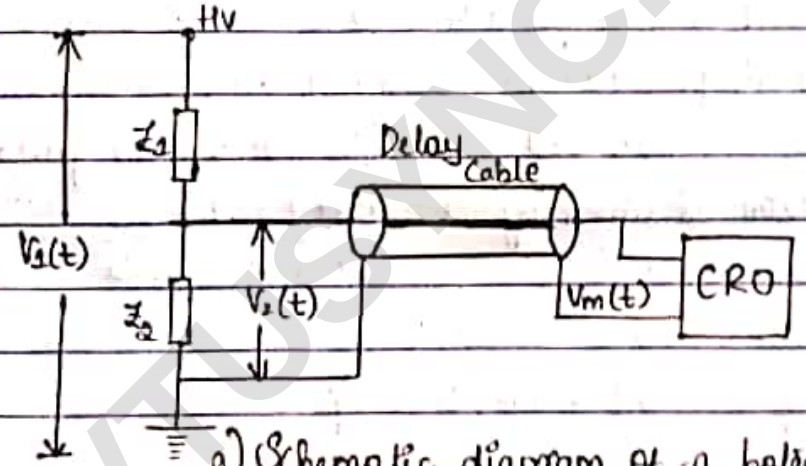
* Potential divider for HV measurement :- It is used to measure HVAC, HVDC & impulse v/g.

→ It obeys v/g divider rule i.e.., $V_1 = \frac{VR_2}{R_1 + R_2}$.

→ The low v/g arm of the divider is usually connected to a fast recording oscillograph (or) a peak reading instrument capacitor (or) an RC impedance depending upon the type of the divider.

→ Each element in the divider, in case of HV dividers, has a self-resistance (or) capacitance. In addition, the resistive elements have residual inductances, a terminal stray capacitances to ground through a delay cable.

→ A schematic diagram of a potential divider with its terminating equipment is given in below fig.



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

→ "Z_1" is usually a resistor (or) a series of resistors in case of resistance potential divider, (or) a single (or) a no of capacitors in case of a capacitance divider. It can also be a combination of both resistor & capacitors.

→ "Z_2" will be resistor (or) a, & terminal to terminal capacitances.

→ The lumped-circuit equivalent of a resistive element is already shown in fig. The equivalent circuit of the divider with inductance neglected is of form shown in fig.

→ When a step (or) fast rising v/g is applied at the HV terminal, the v/g developed across the element "Z_2" will not have the true waveform as that of the applied v/g. The cable can also introduce distortion in wave shape.

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→ The following elements mainly constitute the d/f errors in measurement:

i) Residual inductance in the elements.

ii) Stray capacitance occuring b/n the elements.

- From sections & terminals of elements to gnd.
- From high V/g lead to elements (or) sections.

iii) The impedance errors due to connecting leads b/n the divider & the test object.

- Gnd return leads & extraneous current in gnd leads.

iv) Parasitic oscillations due to lead & cable inductances & capacitance of HV terminal to gnd. The effects to residual & lead inductance becomes pronounced when fast rising impulses of less than 1μs are to be measured. The residual inductances damp & slow down the fast.

* **Resistance potential divider for a very low impulse voltages and fast rising pulses** :- A simple resistance potential divider consists of 2 resistances "R_1 & R_2" in series [$R_1 >> R_2$]. The attenuation factor of the divider (or) V/g ratio is given by $a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{R_1}{R_2}$.

* **Classification of potential divider** :- 3 types :-

→ Resistive potential divider = HVAC & HVDC.

→ Capacitance potential divider = Impulse V/g.

→ Mixed RC potential divider.

* **Resistance potential divider** :-

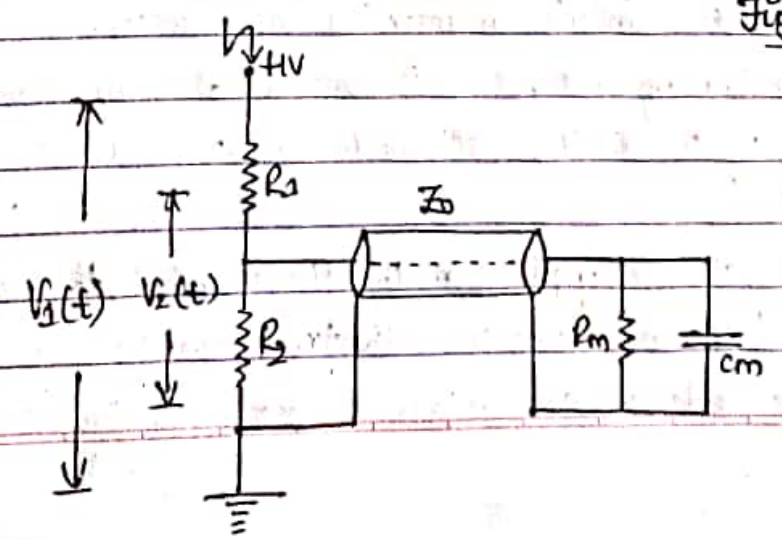

Fig (a). Resistance potential divider with surge cable & oscilloscope termination.

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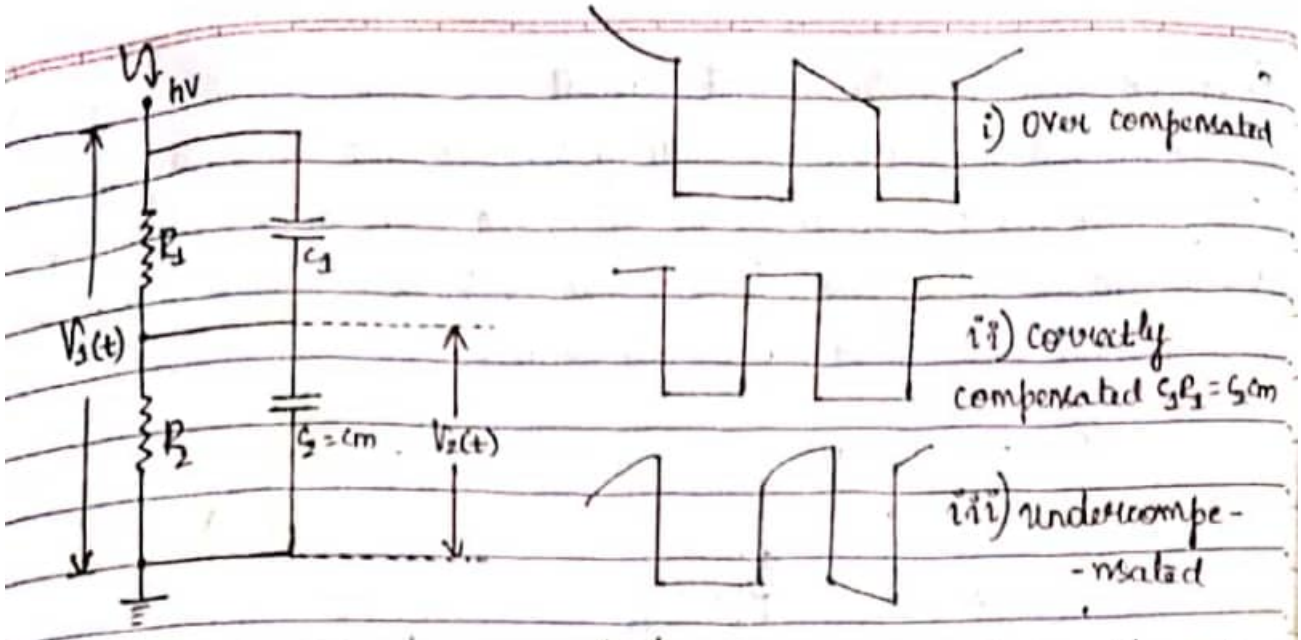

b) Compensated resistance potential divider.

c) O/P of compensated resistance V/g divider for d/f durees of compensated.

* Capacitance potential divider :- Measure fast rising V/g, impulse V/g upto 1MV.

→ Harmonic effects can be eliminated.

→ V/g division rule.

→ Capacitive V/g divider with Electrostatic voltmeter is used to measurement.

* Measurement of high currents :- Direct, alternating and impulse :- In power s/m, it is often necessary to measure high current, arising due to short circuits.

→ For conducting temp. rise & heat run tests on power equipments like conductors, cables, circuit breakers etc., measurement of high currents is required.

→ During lightening discharges & switching transients also, large magnit-
-udes of impulse & switching surge currents occurs, which required special measuring techniques at high potential level.

* Measurement of high direct currents :- High magnitude direct currents are measured using a resistive shunt of low ohmic value. The V/g drop across the resistance is measured with a millivoltmeter. The value of the resistance varies usually b/n 10μΩ to 10mΩ. This depends on the heating effect

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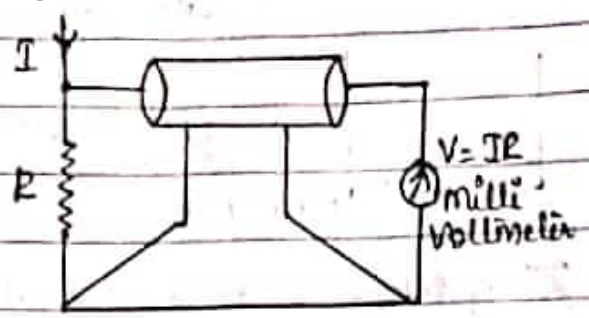
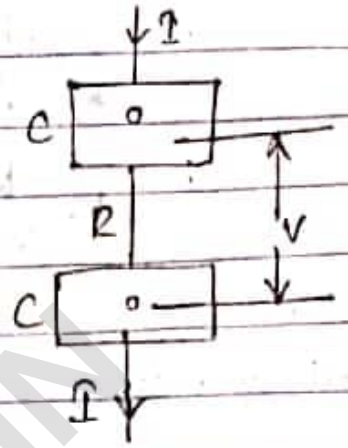
& the loading permitted in the circuit.

→ High current resistors are usually oil immersed & are made as 3 (or) 4 terminal resistances. The V/p drop across the shunt, which is an analog signal is converted into a digital optical signal is sent via a fibre optic cable to end level instrument.



a) Low ohmic shunt with millivoltmeter for current measurement.



b) Four terminal shunt

CC = Current terminals.

PP = Potential terminals ; R = ohmic elements.

→ Two methods :- DC current transformer, hall generator for DC measurement.

* DC current transformer :- Principle :- Transformer operates on the principle of ampere turn balance i.e., the 1° ampere turns [$N_1/1$] are balanced by the 2° ampere turns [$N_2/2$] where "N_1 & N_2" are the turns in 1° & 2° windings with DC current in 1° winding, core saturation occurs due to the non-linearity of the B-H curve of the core.

→ When a high frequency excitation is given to the 3rd (or) excitation winding located on the same core, the current through the 2° will have a distorted waveform containing a large amplitude 2nd harmonic. A 4th harmonic current is injected in the opposite direction to make the harmonic current zero. The injected current will be proportional to the 1° DC current & hence will give the measurement of DC current. Schematic diagram of DC current transformer is shown in fig.

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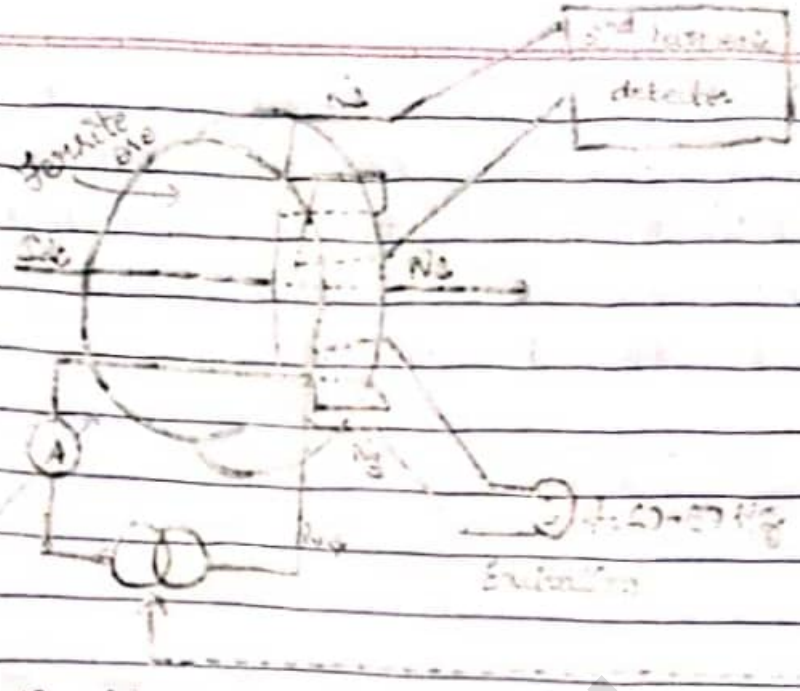

Fig. DC CT Schematic diagram.

* Advantages of DC CT :- It gives isolation to high v/g.
→ Power loss is much less compared to DC Shunt & the conductor through which the DC current flows need not be broken for connecting to the mains.

* Hall generators for DC measurement :- The principle of the "Hall effect" is made use of in measuring very high DC. If an Electric current flows through a metal plate located in a magnetic field ⊥ar to it, Lorenz forces will deflect the $e^{\ominus}$ in the metal structure in a direction normal to the direction of both the current & the MF. The charge displacement generates an Emf in the normal direction called the "Hall voltage". The hall v/g is proportional to the current "i" the magnetic flux density "B" & the reciprocal of plate thickness "d", the proportionality constant "R" is called the Hall coefficient. i.e.,

$$V_H = R \cdot \frac{Bi}{d}$$

→ For metals, the hall coefficient is very small & hence semi-conductor materials are used for which the hall coefficient is high. In large current measurements, the current carrying conductor is surrounded by an Fe cored magnetic circuit, so that the MF intensity $H = (I/\delta)$, produced in a small air gap in the core. The hall elements is placed in the air gap of

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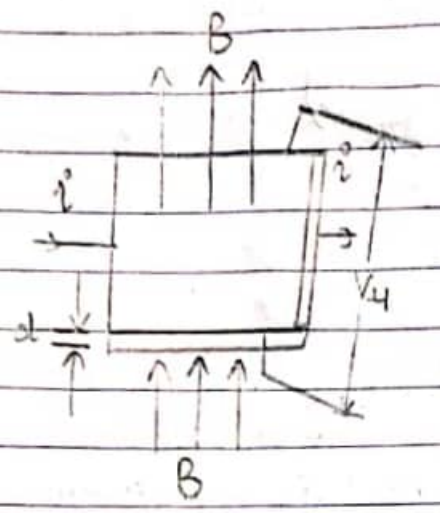
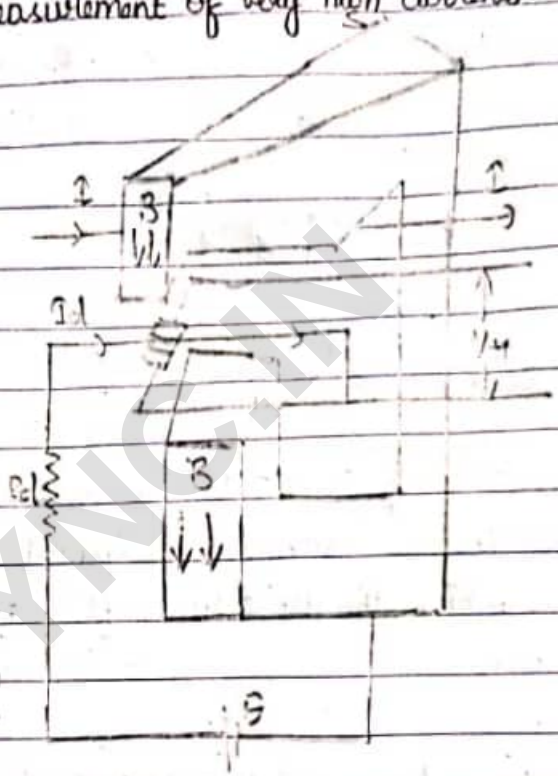
thickness & a small constant DC current is passed through the element. The V/g developed across the hall-element in the normal direction is prop-ortional to the DC current "I". It may be noted that the hall coefficient "R" depends on temp. & high MF strength, & suitable compensation has to be provided when used for measurement of very high currents.





$V_H = R \cdot \frac{Bi}{d}$; R = hall coefficient

a) Hall effect.

b) Hall generator.

* Hall generator for measuring high dc current.

→ Half generators can be used for measurement of unidirectional AC & impulse current also, with proper design of hall-element dimensions & addition of compensation circuits, the bandwidth of the hall generator can be increased to about 50MHz. As such, these generators can be used for measurement of post arc current & unidirectional impulse currents.

* Measurement of high power frequency alternating currents :- Measure of power frequency currents are normally done using current transformer only, as use of current shunts involves unnecessarily power loss. Also the current transformer provide electrical isolation from HV circuits in power s/m. Current transformers used for extra HV [EHV] s/m are quite d/f from the conventional designs as they have to be kep at very HV from the gnd.

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A new scheme of current transformer measurements, introducing electro-optical technique is described in fig. A V/p signal proportional to the measuring current is generated & is transmitted to the gnd through an electro-optical device.

→ Light pulses proportional to the V/p signal are transmitted by a glass optical fibre bundle to a photo-detector & converted back into an analog V/p signal. Accuracies better than ± 0.5% have been obtained at rated current as well as for high S C currents. The required power for signal converters & optical device are obtained from suitable current & V/p transformers as shown in fig.

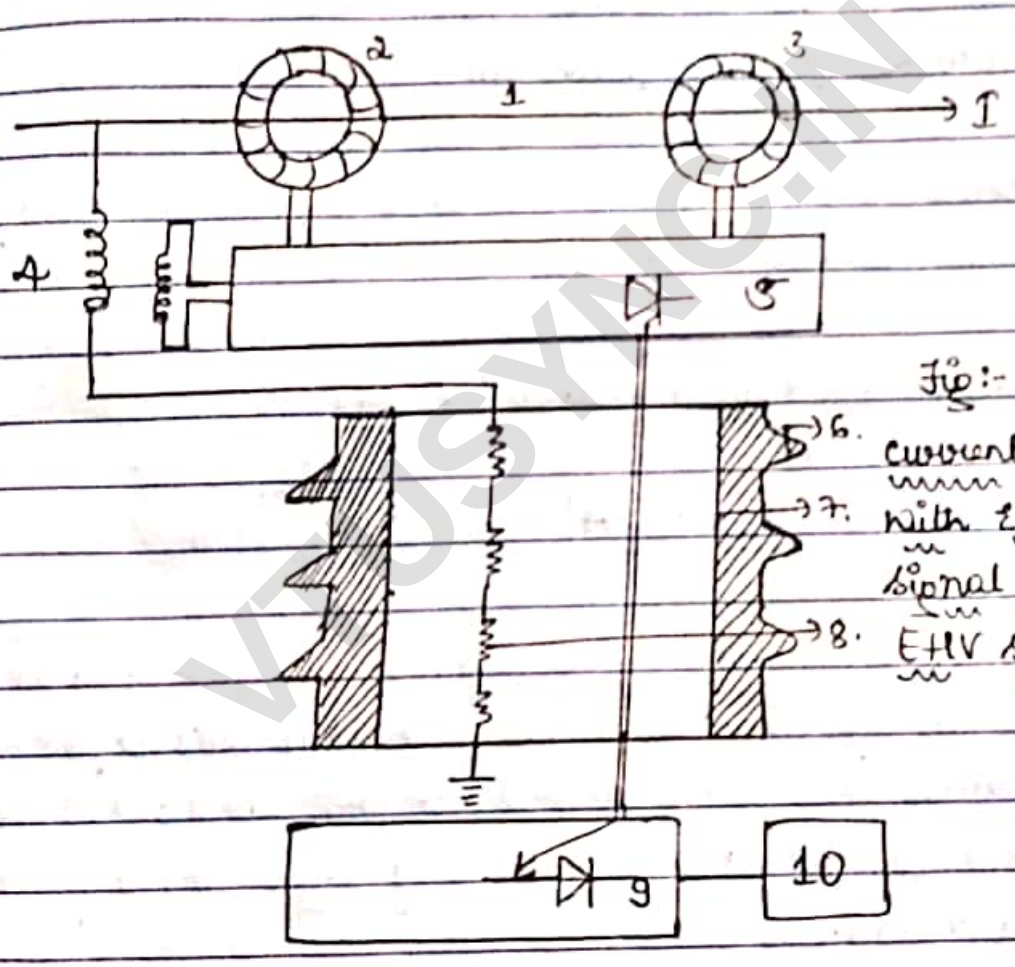

Fig:- current transformer with electro-optical signal converter for EHV s/m.

1= EHV conductor.
2= Current Sensing transformer.
3= Power supply CT.
4= Power Supply PT.
5= Analog-digital signal converter.
6= Insulator for EHV.
7= Electrooptical glass fibres.
8= Series high ohmic resistance.
9= Digital analog converter.
10= Indicating (or) recording Unit.

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* Problems :-

1) A generating voltmeter has to be design so that it can average from 20 to 200 kV. If the indicating meter takes a minimum current of 2mA & maximum current of 25mA. What should be the capacitance of the generating voltmeter ?

→ Given :- $i_{max} = 25mA$, $i_{min} = 2mA$, $V = 20kV$, $N = 1500$, $C_m = ?$.

Assume the synchronous speed of 1500 at 20 kV.

$$i_{max} = \frac{V C_m \omega}{\sqrt{2}}$$

$$25 \times 10^{-6} = \frac{20 \times 10^3 C_m \, 2\pi N}{\sqrt{2} \cdot 60}$$

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

$$C_m = \frac{2 \times 10^{-6} \times \sqrt{2} \times 60}{20 \times 10^3 \times 2\pi \times 1500} = 9.0031 \times 10^{-13} = \boxed{0.9 PF}.$$

At = 200 kV.

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

$$\therefore \boxed{I_{rms} = 1.999 \times 10^{-5} A}.$$

* Measurement of high frequency & impulse currents :- High impulse currents occur in lightning discharges, electrical arcs & post-arc phenomenon studies with circuit breakers, & with electric discharge studies in plasma physics. The current amplitudes may range from a few amperes to few hundred kiloamperes.

→ The rate of rise for such currents can be as high as 10^6 to 10^{12} A/s, & rise times can vary from few microseconds to few nanoseconds.

→ The methods that are frequently employed are i) Resistive shunt. ii) Magnetic potentiometer (or) probes, iii) The Faraday & hall effect devices.

* Resistive shunts :- The current through the resistive element "R" produces a v/g drop "$v(t)$" $= i(t) \cdot R$.

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→ The V/s signal generated is transmitted to a CRO through a coaxial cable of surge impedance "Z_0".

→ The cable at the oscilloscope end is terminated by a resistance "$R_i = Z_0$" to avoid reflections.

→ The resistance "L" may be neglected at low frequencies (ω), but becomes appreciable at higher frequencies (ω) when "ωL" is of the order of "R".

→ The value of the resistance is determined by the thermal capacity to heat dissipation of the shunt.

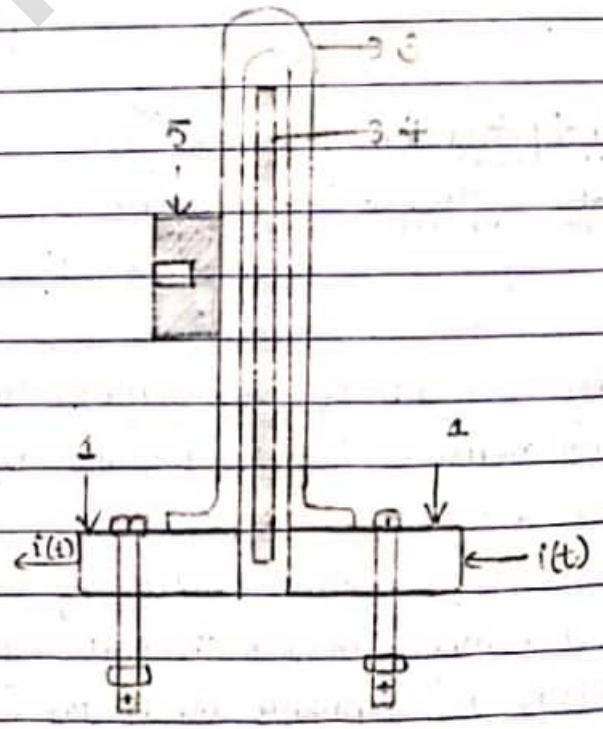
→ The V/s drop across the shunt in the complex frequency domain may be written as, $\boxed{V_s(s) = \frac{R + Ls}{1 + RCs + LCs^2} \cdot I(s)}$.

→ Where "s" is the complex frequency (or) Laplace transform operator & "V_s" & "$I(s)$" are the transformed quantities of the signals "$V(t)$" & "$i(t)$". With the value of "C" neglected it may be approximated as $\boxed{V(s) = (R + Ls) I(s)}$

→ The resistance shunt is usually designed in the following manner to reduce the stray effects i) Bifilar flat strip design. ii) Coaxial tube (or) parker's shunt design. iii) Coaxial squirrel cage design.

→ The bifilar design in fig. consists of resistor element wound in opp. directions & folded back, with both ends insulated by a teflon (or) other high quality insulation. The V/s signal is picked up through a ultra high frequency [UHF] coaxial connector.

→ The shunt suffers from stray inductance associated with the resistance element, & its potential leads are linked to a small part of the magnetic flux generated by the current that is measured.



a) Schematic Arrangement:

1) Metal base.
2) Current terminals [C_1 & C_2].
3) Bifilar resistance strip.
4) Insulating spacer [Teflon (or) Bakelite]
5) Coaxial UHF connector.

P_1, P_2 = Potential terminals.

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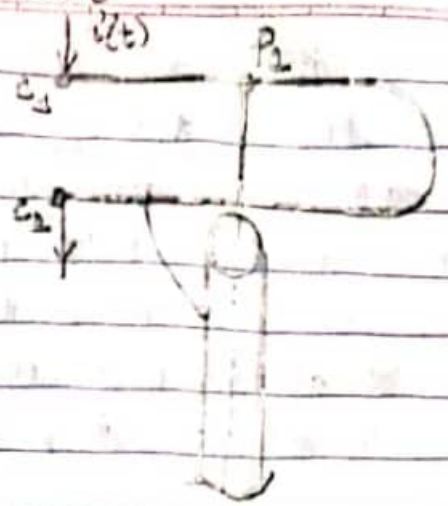
* Bifilar flat strip resistive shunt.

→ To overcome these problems, coaxial shunts are chosen.

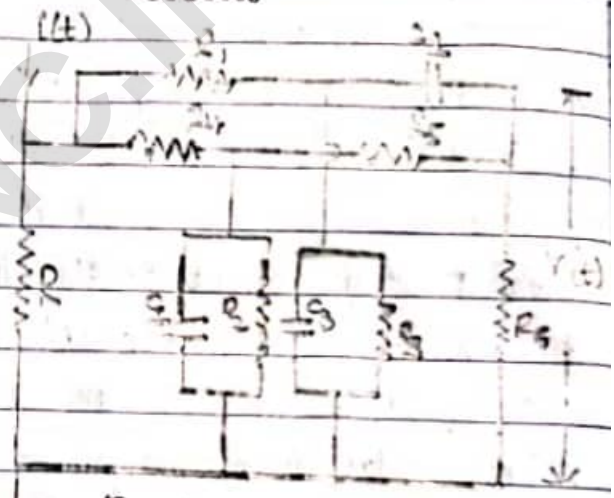
→ Squirrel-cage shunts in certain application, such as post arc current measurements, high ohmic value shunts which can dissipated larger energy are required.

→ In such cases tubular shunts are not suitable due to their limitation of heat dissipation, larger wall thickness, & the skin effect.

→ To overcome these problems, the resistive cylinder is replaced by thick rods (or) strips, & the structure resembles the rotor construction of double squirrel-cage induction motor.



b) Connection for potential & current terminals.



R = Shunt resistance.

R1 - R6 = Resistance & Capacitance in Compensating double "T" Network & "C1 - C3".

* Compensating network for squirrel cage shunts *

* Measurement of high impulse currents :- Rogowski.

→ It measure impulse currents, high speed current, AC current with power frequency.

→ While Rogowski consists of helical coil of wire with the lead from 1 end returning through the centre of the coil to the other end.

→ Both the terminals are at the same end of coil.

→ The whole assemble is wrapped around the straight conductor whose current is to be measured.

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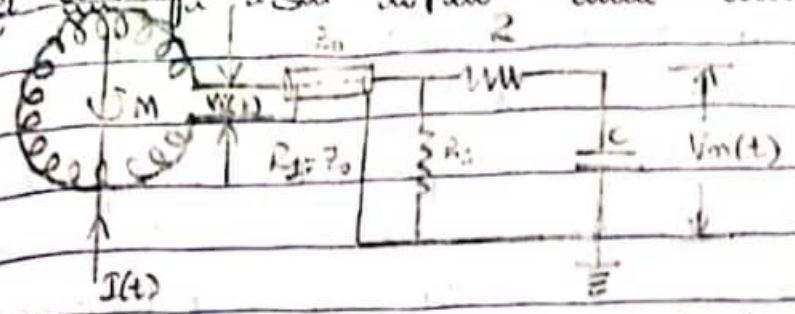
* Rogowski coil for high impulse current measurement *



Where, $V_i(t)$ = Induced V/g in the coil $= M \cdot \frac{d(I(t))}{dt}$

Z_0 = coaxial cable of surge impedance "Z_0".

R-C = Integrating network.

→ If a coil is placed surrounding a current carrying conductor, the V/g signal induced in the coil is "$V_t = M dI(t)/dt$. Where "M" is the mutual inductance b/n the conductor & the coil, & "I(t)" is the current flowing in the conductor.

→ Usually, the coil is wound on a nonmagnetic former of toroidal shape & is coaxially placed surrounding the current-carrying conductor.

→ The no of turns on the coil is chosen to be large, to get enough signal induced. The coil is wound cross-wise to reduce the leakage inductance. Usually, an integrating circuit as shown in above fig. Is employed to get the o/p signal V/g proportional to the current to be measured.

* Advantages :- No Fe core to saturate.

→ Simple temperature compensation.

→ Low construction cost.

→ No current upper limit.

* Disadvantage :- Design & maintainance of integrator.

* Magnetic links :- Peak value of impulse current can be measured.

→ Magnetic links are high retentively steel strips arranged in circular shape.

→ Strips shows the property of remanent magnetism.

→ Strips are kept certain distance from current carrying conductor.

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* Cathode-Ray oscillograph for impulse measurements :- Modern oscillographs are sealed tube, hot cathode oscilloscopes with photographic arrangement for recording the waveforms.

→ The cathode ray oscilloscope for impulse work normally has i/p v/p range from 5mV/cm to about 20V/cm.

→ In addition, there are probes & attenuators to handle signals upto 60kV [Peak to peak]. The bandwidth & rise time of the oscilloscope should be adequate.

→ oscilloscope are fitted with good cameras for recording purposes.

→ 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 required an accurate initiation of the horizontal time base & is known as triggering.

→ Oscilloscopes are normally provided with both internal & external triggering facility. When external triggering is used, as with recording of impulses, the signal is directly fed to actuate the time base & 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 the following :-

1) A long interconnecting coaxial cable 20 to 50 m along. The required triggering is obtained from an antenna whose induced v/p 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. The arrangement is shown in the below figure.

3) The impulse generator & the time base of the CRO are triggered a from an electronic tripping device. A first pulse from the device starts the CRO time base & after a predetermined time a second pulse to triggers the impulse generator.

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

* Simplified block diagram of surge test oscilloscopes.

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MODULE - 4.

OVERVOLTAGE PHENOMENON AND INSULATION COORDINATION IN EPS...

→ It is essential for electrical power engineers to reduce the no of outages & preserve the continuity of service & electric supply.

→ Therefore, it is necessary to direct special attenuation towards the protection of transmission line & power apparatus from the chief causes of overv/g in electric s/ms, namely lightening overv/g or switching overv/g.

→ Lightening overv/g is a natural phenomenon, while switching overv/g originates in the s/m itself by the connection & disconnection of circuit breakers contacts (or) due to initiation (or) interruption of faults.

→ Switching overv/g are highly damped short duration overv/g. They are temporary overv/g of power frequency (or) its harmonic frequency either sustained (or) weakly damped, & originate in switching & fault-clearing processes in power supply s/m.

→ Although both switching & power frequency have no common origin, they may occur together, & their combined effect is imp. in insulation design. The probability of lightning & switching overv/g coinciding together is very small & hence can be neglected.

→ For the study of overv/g, a basic knowledge of the origin of overv/g surge phenomenon, & its propagation is desirable. The present chapter is therefore devoted to a summary of the above topics.

*Natural causes for overvoltage - lightning phenomenon :- It is a peak discharge in which charge accumulated in the clouds discharges into a neighbouring cloud (or) to the ground.

→ The electrode separation i.e., cloud to cloud (or) cloud-to-ground is very large, perhaps 10 km (or) more. The mechanism of charge formation in the clouds & their discharge is quite at complicated & uncertain processes.

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* Charge formation in the clouds :- The factors that contribute to the formation or accumulation of charge in the clouds are too many & uncertain.

→ But during thunderstorms, +ve & -ve charges becomes seperated by the heavy air currents with ice crystals in the upper part & rain in the lower parts of the cloud.

→ The volume of the clouds that participate in lightening flashover are uncertain, but the charge inside the cloud may be as high as 1 to 100 C.

→ The upper region of clouds are usually participated +ve charged, whereas the lower region & the base are predominantly -ve except the local region, near the base the head, which is +ve.

→ The max. gradient reached at the ground level due to a charged cloud maybe as high as 300 V/cm, while the fair weather gradients are about 1 V/cm. A probable charge distribution model is given in fig. with the corresponding field gradient near the ground.

* Cloud model according to Simpson's Theory :- There are three Essential regions in the cloud to be considered for charge formation.

→ Below region "A", air currents travels above 800 cm/s & no rain drops fall through.

→ In region "A", air velocity is high enough to break the falling raindrops causing a +ve charge spray in the cloud & -ve charge in the air. The spray is blown upwards, but as the velocity of air decreases, the +vely charged water drops recombine with the larger drops & fall again. Thus region "A", Eventually becomes predominantly +vely charged.

→ While region "B" above it, becomes -vely charged by air currents. In the upper regions in the cloud, the temp. is low [Below freezing point] & only ice crystal makes them -vely charged. Thus the distribution of the charge within the cloud becomes as shown in below fig. However, the above theory is obsolete & the explanation presented is not satisfactory.

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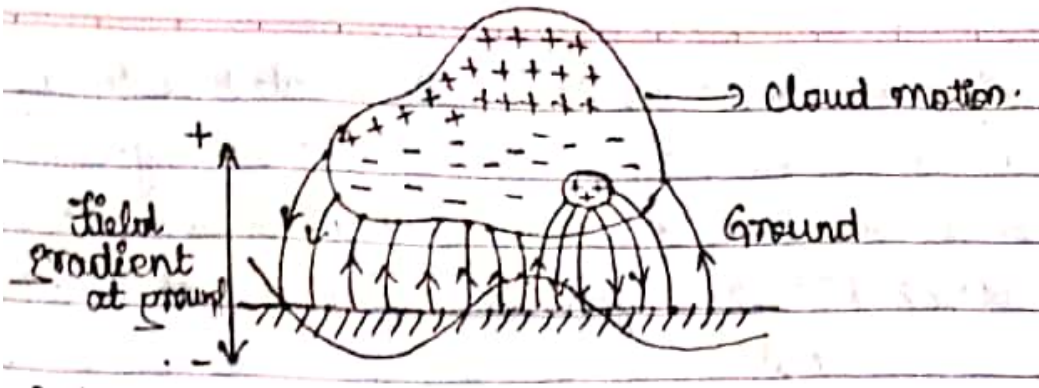
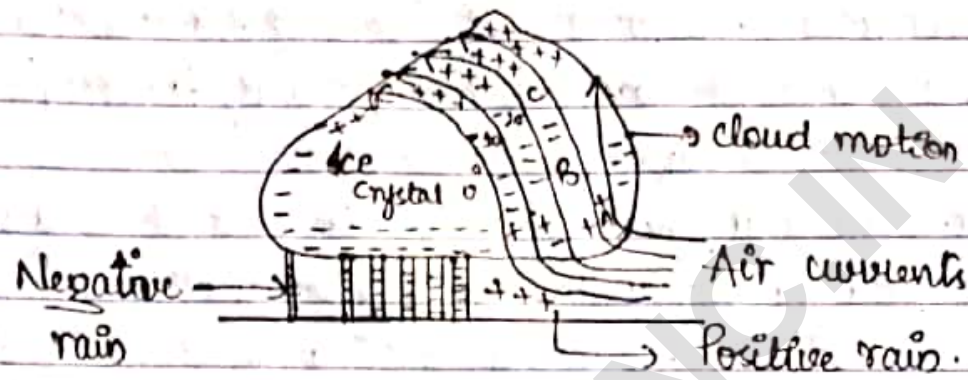


a) Probable field gradient near the ground corresponding to the probable charge distribution in a cloud.



b) Cloud model according to Simpson's theory.

→ Reynolds and Mason proposed modification according to which the thunder clouds are developed at heights 1 to 2 km above the gnd level & may extend upto 12 to 14 km above the gnd. For thunder clouds & charge formation air currents, moisture & specific temp. range are required.

→ The air currents controlled by the temp. gradient move upwards carrying moisture & water droplets.

→ But water droplets don't freeze as soon as the temp. is 0°c. They freez below −40°c only as said particles on which crystalline ice patterns develop & grow.

→ The water droplets in the thunder cloud are blown up by air currents & get super cooled over a range of heights & temp. When such freezing occurs, the crystals grows into large masses & due to their weight & gravitational force start moving downwards. Thus, a thunder cloud consists of supercooled water droplets moving upwards & large hail stones moving downwards.

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→ When the upward moving supercooled water droplets acts on cooler hail stone, it freezes partially i.e., the outer layer of the water droplets freezes forming a shell with water inside.

→ When the process of cooling extends to inside warmer water in the core, it expands, thereby splintering & spraying the frozen ice shell.

→ The splinters being fine in size are moved up by the air currents & carry a net positive charge to the upper region of the cloud.

→ The hail stones that travel downwards carry an equivalent -ve charge to the lower regions of the cloud & thus -ve charge builds up in the bottom side of the cloud.

→ Acc. to Mason the ice splinters should carry +ve charge upwards. Water being ionic in nature has concentration of H^+ & OH^- ions.

→ H^+ ions are much lighter, they diffuse much faster all over the volume.

→ Therefore, the lower portion which is warmer will have a net -ve charge density, & hence the upper portion i.e., cooler region will have a net +ve charge density. Hence, it must be appreciated, that the outer shell of the frozen water droplets coming into contact with hail stones will be relatively cooler [than their inner core - warmer water] & therefore acquire a net +ve charge.

→ When the shell splinters, the charge carried by them in the upward direction is +ve.

→ Acc. to the Reynold's theory, which is based on experimental results, the hail packets get -vely charged when impinged upon by warmer ice crystals.

→ When the temp. conditions are reversed, the charging polarity reverses.

→ However, the extent of the charging & consequently the rate of charge generation was found to disagree with the practical observations relating to thunder clouds. This type of phenomenon also occurs in thunder clouds.

* **Mechanism of lightning strokes** :- When the electric field intensity at some point in the charge concentrated cloud exceeds the breakdown value of the most ionized air (≈ 10 kV/cm), an electric streamer with plasma starts

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towards the ground with a velocity of about 1/10 times that of the light, but may progress only about 50m (or) so before it comes to a halt emitting a bright flash of light.

→ The halt may be due to insufficient build-up of electric charge at its head to not sufficient to maintain the necessary field gradient for further progress of the steamer.

→ But after a short interval of about 100 μs, the steamer again starts out repeating its performance. The total time req. for such a stepped leader to reach the ground may be 20ms. The path may be quite tortuous, depending on the local conditions in air as well as the EF gradients. Branches from the initial leader may also be formed. Since the progress of this leader stroke is by a series of jumps, it is referred as stepped lead.

→ The picture of a typical leader stroke taken with a Boy's camera is shown in fig. The lightning stroke or the electrical discharges due to lightning are explained based on the "streamer" (or) "Kanal" theory for spark discharges in long gaps with non-uniform EF. The lightning consists of a few separate discharge starting from a leader discharge or culminates in return strokes (or) main discharges.

→ After the leader touches the ground, the return stroke follows. As the leader moves towards the ground, the charge is directly accumulated under the head of the stroke (or) canal.

→ By the time the stroke reaches the ground (or) comes sufficiently near the ground, the electrical field intensity on the ground side is sufficiently large to build up the path.

→ The velocity of the return (or) main stroke ranges from 0.05 to 0.5 times the velocity of light, & currents will be of the order of 1000 to 250000 A.

→ The duration of the main (or) return stroke is about 100 μs (or) more. The diameters of the return strokes were estimated to be about 1 to 2cm but the corona envelop may be approximately 50 cm. The return stroke also may develop branches but the charges in the branches are neutralized.

→ In successive their further progress is arrested. After the completion of the return stroke, a much smaller current of 100 to 1000 A may continue to

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flow which persists approximately for 20 ms.

→ Due to these currents, the initial breakdown points in the cloud are considerably reduced & discharges concentrated towards this point. Therefore, additional reservoirs of charge become available due to penetration of a cloud mass.

* Parameters and Characteristics of the lightning strokes :- The parameters & characteristics of lightning include the amplitude of the currents, the rate of rise, the probability distribution of the above, & the wave shapes of the lightning v/s & currents.

→ Lightning strokes on transmission lines are classified into 2 groups - The direct strokes & the induced strokes. When a thunder cloud directly discharges onto a transmission line tower (or) line wires it is called a direct stroke.

→ This is the most severe form of the stroke. However, for bulk of the transmission s/m the direct strokes are rare & only the induced stroke occur.

→ When the thunderstorm generates -ve charge at its ground end, the earth objects develop induced +ve charges.

→ Normally, it is expected that the lines are unaffected because they are insulated by string insulators.

→ However, because of high field gradients involved, the +ve charges leak from the tower along the insulator surfaces to the line conductor.

→ The process may take quite a long time, of the order of some hundreds of sec

→ When the cloud discharge to some earthed object other than the line, the transmission line is left with a huge concentration of charge [+ve] which cannot leak suddenly.

→ The transmission line & the ground will act as a huge capacitor charged with a +ve charge & hence over v/s occur due to these induced charges. This would result in a stroke & hence the name "Induced Lightning Stroke".

* Overvoltages due to indirect strokes :- A direct lightning stroke is a that hits either a shielding wire [ground wire], tower (or) phase conductor of a overhead powerline.

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with.

→ An indirect stroke is defined as 1 that strikes the ground, a nearby object around a power line (or) an earthed structure longer & higher than the power line & causes induced v/g.

→ The v/g induced on the power line by an indirect stroke can be due to the following reasons: a) A charged cloud above the power line induces bound charges when the cloud discharges. Bound charges are released giving rise to travelling waves on power lines.

b) Charges released by stepped leader strokes of a lightning stroke also give rise to the above effect.

c) Residual charge in the return stroke induced over v/g [Electrostatic effect].

d) The rate of change of current in the return stroke induces overv/g due to electromagnetic effects.

* Travelling waves on transmission lines :- Any disturbance on a transmission line (or) s/m such as sudden opening (or) closing of line, a short circuit (or) a fault results in the development of over v/g (or) over current at that point.

→ This disturbance propagates as a travelling wave to the ends of the line (or) to a termination such as substation.

→ Usually, these travelling waves are high frequency disturbances & travel as waves. They may be reflected, transmitted, attenuated (or) distorted during propagation until the energy is absorbed.

* Overvoltage due to switching surges, system faults and other abnormal conditions :- Till the time when the transmission v/g were about 220kV & below, overv/g due to lightning were of very high order & overv/g generated inside the s/m were not of much consequence.

→ In later yrs, with increase in transmission v/g [400kV & above], the overv/g generated inside the s/m reached the same order of magnitude as those of lightning overv/g (or) higher.

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→ Secondly, the overvlg thus generated last for longer durations & therefore are severe & more dangerous to the s/m. Unlike the lightning overvlg, the switching & other types of overvlg depends on the normal V/g of the s/m & have increase with increased in s/m V/g.

→ In insulation co-ordination, where the protective level of any particular kind of surge diverter is proportional to the max. V/g, the insulation level & the cost of the equipment depends on the magnitude of these overvlg.

→ In the EHV range, it is switching surge & other type of overvlg that determine the insulation level of the lines & other equipment & consequently, they also determine their dimensions & cost.

* Origin of switching surges :- The making & breaking of electric circuits with switchgear may result in abnormal overvlg in power s/m having large inductance & capacitance.

→ The overvlg may go as high as 6 times the normal power frequency V/g.

→ In circuit breaking operation, switching surges with a high rate of rise of V/g may cause repeated restriking of the arc b/n the contacts of a circuit breaker, thereby causing destruction of the circuit breaker contacts.

* Characteristics of Switching Surges :- The waveshapes of switching surges are quite diff & may have origin from any of the following sources.

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

→ Disconnection of unload transformer, reactors etc.

→ Energization (or) reclosing of lines & reactive loads.

→ Sudden switching off of loads.

→ Short circuit & fault clearance.

→ Resonance phenomenon like ferro-resonance, arcing grounds etc. From the fig. of the switching surges it is clear that the overvlg are irregular [oscillatory (or) unipolar] & can be high frequency (or) power frequency with its harmonics.

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*Switching overvoltages in EHV and UHV system:- The insulation has its lowest strength for switching surges with regard to long air gaps. Further, switching overv/s are of relatively higher magnitudes as compared to the lightning overv/s for UHV s/m.

→ Overv/s are generated in EHV s/m when there is a sudden release of internal energy stored either in the Electrostatic [In the Capacitance] (or) in the electromagnetic form [In the inductance].

→ The diff situations under which this happens are summarized as

i) Interruption of low inductive currents [current chopping] by high speed circuit breakers. This occurs when the transformers (or) reactors are switched off

ii) Interruption of small capacitive currents, such as switching off of unloaded lines etc.

iii) Ferro-resonance condition this may occur when poles of a ckt breaker don't close simultaneously.

iv) Energization of long EHV (or) UHV lines.

→ The other situations of switching that give rise to switching overv/s of short duration [0.5 to 5ms] & lower magnitudes [2 to 2.5pu] are:

i) Single pole closing of ckt breakers.

ii) Interruption of fault current when the L-G (or) L-L fault is cleared.

iii) Resistance switching used in ckt breakers.

iv) Switching lines terminated by transformers.

v) Series capacitor compensated lines.

vi) Sparking of the surge diverter located at the receiving end of the line to limit the lightning overv/s.

*Overvoltages due to the above conditions are studied (or) calculated:-

→ Mathematical modelling of a s/m using digital computers.

→ Scale modelling using transient network analysers.

→ By conducting field tests to determine the expected max. amplitude of the overv/s & their duration at diff points on the line.

→ The main factors that are investigated in the above studies are:-

i) The effect of line parameters, series capacitors & shunt reactor on the magni-

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-tude & duration of the transients.
ii) The damping factor needed to reduce the magnitude of overv/s.
iii) The effect of single pole closing, restriking & switching with series resistors in ckt breakers on the overv/s.
iv) The lightning arrester spark over characteristics. It is necessary in EHV & UHV s/m to control the switching surges to a safe value of less than 2.5pu (or) preferably to 2.0 pu (or) even less.

* Measures taken to control (or) reduce the overvoltage :- i) 1 (Step (or) multi-step energization of lines by preinsertion of resistors.
ii) Phase controlled closing (or) ckt breakers with proper sensor.
iii) Drainage of trapped charges on long lines before the reclosing of the lines.
→ Limiting the overv/s by using surge diverters.
→ The first 3 methods, if used properly will limit the switching overv/s b/n 1.5 to 2.0 pu.

* Overvoltage due to switching operations in gas-insulated sub-station:-
→ Now-a-days, gas-insulated sub-stations & s/m in v/s ranges of 33KV to 400KV have come up due to land space limitations in urban & highly populated areas. Very fast transient v/s are generated during switching operations such as:
i) Closing ground switch.
ii) Fault clearing.
iii) Opening (or) closing a disconnector switch underload, etc.
→ A large no of pre-or re-strikes occurs during a disconnector switch (or) ckt breaker operations. The switching behavior & pattern of v/s is shown. During the opening operation, sparking occurs as soon as the v/s b/n the source & loadside exceeds the dielectric strength of the gap b/w the contacts. After restrike high frequency current flows through the spark gap & will equalise the capacitive load v/s & source v/s. The frequency of pulse generated is given by, $f = \frac{1}{4T} = \frac{75}{d}$ Where T = Transit time of the line in GIS (μs).
d = Duct length in mtrs.

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* Power frequency overvoltages in power systems :- The power frequency over-v/s occur in large power s/m & they are of much concern in EHV s/m, i.e. s/m of 400kV & above. The main causes for power frequency & its harmonic overv/s are :-

i) Sudden loss of loads.

ii) Disconnection of inductive loads (or) connection of capacitive loads.

iii) Ferranti effect, Unsymmetrical faults.

iv) Saturation in transformer etc.

→ Overv/s of power frequency harmonics & v/s with frequencies nearer to the operating frequency are with frequencies nearer to the operating frequency are caused during tap changing operations, by magnetic (or) ferro-resonance phenomenon in large power transformers, & by resonating overv/s due to series capacitors with shunt reactors (or) transformers.

→ The duration of these overv/s may be from 1 to 2 cycles to a few seconds depending on the overv/s protection employed.

* Sudden load rejection :- It is on large power s/m causes the speeding up of generator prime movers. The speed governors & automatic v/s regulators will intervene to restore normal conditions. But initially both the frequency & v/s increase. The approximate v/s rise, neglecting losses etc may be taken as.

$$V = \frac{f}{f_0} E' \left[\left(1 - \frac{f}{f_0} \right) \frac{X_s}{X_c} \right]$$

Where "X_s" is the reactance of the generator [i.e. The sum of the transient reactance of the generator & the transformer], "X_c" is the capacitive reactance of the line at open end at increased frequency, "E'" the v/s generated before the over-speeding & load rejection, "f" is the instaneous increased frequency, & "f_0" is the normal frequency.

→ This increase in v/s may go as high as 2.0 pu value with 200kV lines. The v/s at the sending end is affected by the line length, short circuit MVA at sending end bus, & reactive power generation of the line [due to line capacitive reactance & any shunt (or) series capacitors]. Such reactors may reduce the v/s to 1.2 to 1.4 pu.

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* Ground faults and their effects :- Single line to gnd faults cause rise in v/g in other healthy phase. Usually, with solidly grounded sys, the increases in v/g [Phase to gnd value] with be less than the line-to-line v/g with effectively gnd sys i.e., with

$$\frac{X_0}{X_1} \leq 3.0 \quad \& \quad \frac{R_0}{X_1} \leq 1.0$$

Where, "R_0 & X_0" are zero sequence resistance & reactance & "X_1" is the +ve sequence reactance of the sys, the rise in v/g of the healthy phase doesn't usually exceed 1.4PU.

* Saturation Effects :- When v/g above the rated value are applied to transformers, their magnetizing currents [No load current also] increase rapidly & may be about the full rated current for 50% over v/g. These magnetizing currents are not sinusoidal in nature but are of a peaky waveform. The 3rd, 5th & 7th harmonic contents may be 65%, 35% & 25% of the exciting current of the fundamental frequency corresponding to an over v/g of 1.0pu. For 3rd & its multiple harmonics, zero sequence impedance values are effective, & delta connected windings suppress them. But the shunt connected capacitors & line capacitances can form resonant ckt & cause high 3rd harmonic over v/g. When such over v/g are added, the v/g rise in lines may be significant. For higher harmonics a series resonance b/n the transformer inductance & the lines may occur which may produce even higher v/g.

→ Control of over v/g due to switching the over v/g due to switching & power frequency may be controlled by

i) Energization of transmission lines in 1 (or) more steps by inserting resistances & withdrawing them afterwards.

ii) Phase controlled closing of ckt breakers.

iii) Drainage of trapped charges before reclosing.

iv) Use of shunt reactor.

v) Limiting switching surges by suitable surge diverters.

→ Insertion of resistors it is normal & a common practice to insert resistance "R" in series with ckt breaker contacts when switching on but short

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circuiting them after a few cycles. This will reduce the transient occuring due to switching. Pre-insertion of suitable value resistor in practice is done to limit the overv/s to less than 2.0 to 2.5 pu. Normal time of insertion is 6 to 10 ms.

→ Phase-controlled switching overv/s can be avoided by controlling the exact instances of the closing of the 3-ϕ seperately. But this necessitates the use of complicated controlling equipment & therefore is not adopted.

→ Drainage of trapped charge when lines are suddenly switching off, Electric charge may be left on capacitors & line conductors. This charge will normally leak through the leakage path of the insulators etc. Conventional potential transformers [magnetic] may also help the drainage of the charge. An effective way to reduce the trapped charges during the lead time before reclosing is by temporary insertion of resistors to gnd (or) in series with shunt reactors & removing before the closure of the switches.

→ Shunt reactances normally, all EHV lines will have shunt reactors to limit the v/s rise due to the ferranti effect. They also help in reducing surges caused due to sudden energizing. However, shunt reactors cannot drain the trapped charge but will give rise to oscillations with the capacitance of the s/m. Since the compensation given by the reactors will be less than the power frequency & overv/s produced may be as high as 1.2pu. Resistors in series with these reactors will suppress the oscillations & limit the overv/s. Limiting the switching & power frequency overv/s by using surge diverters is discussed.

* Protection of transmission line against overvoltages :- It is natural (or) lightning overv/s & minimizing the lightning overv/s are done by suitable the designs, providing guard & gnd wires, & using surge diverters. Switching surges & power frequency overv/s are accounted for by providing greater insulation levels & with proper insulation co-ordination.

→ Protection against lightning overv/s & switching surges of short duration overv/s due to lightning strokes can be avoided (or) minimized in practice by

i) Shielding the overhead lines by using gnd wires above the phase wire.

ii) Using gnd rods & counter-poise wires.

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iii) Including protective devices like expulsion gaps, protector tubes on the lines & surge diverters at the line termination & substations.

* Lightning protection using Shielded wires (or) ground wires:- Gnd wires is a conductor run parallel to the main conductor of the transmission line supported on the same tower & earthed at every equally & regularly spaced towers.

→ It is run above the main conductor of the line.

→ The gnd wires shields the transmission line conductor from induced charges, from clouds as well as from a lightning discharge. The arrangement of gnd wires over the line conductor is shown in fig.

→ The mechanism by which the line is protected may be explained as follows. If a +ve charged cloud is assumed to be above the line, it induces a -ve charge on the portion below it, of the transmission line.

→ With the gnd wire present, both the gnd wire & the line conductor get the induced charge.

→ But the gnd wire present is earthed at regular intervals, & as such the induced charge is drained to the earth, only the potential difference b/n the gnd wire & the transmission line wire will be in the inverse ratio of their respective capacitance [Assuming the cloud to be a perfect conductor & the atmospheric medium (air) a dielectric].

→ As the ground wire is nearer to the line wire, the induced charge on it will be much less & hence the potential rise will be quite small.

→ The effective protection (or) shielding given by the gnd wire depends on the ht. of the gnd wire above the gnd (h) & the protection (or) shielding angle.

→ The shielding angle $\theta_s = 30^\circ$ was considered adequate for tower heights of 30m (or) less.

→ The shielding wires may be 1 (or) more depending on the type of the towers used. But for EHV lines, the tower heights may be upto 50m, & the lightning strokes sometimes occur directly to the line wire as shown in fig.

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* **Protection using ground rods and counter-poise wire** :- When a line is shielded, the lightning strikes either the tower (or) the gnd wire. The path for drainage of the charge & lightning current is

i) Through the tower frame to gnd.

ii) Through the gnd line in opp. directions from the point of striking.

→ Thus the gnd wire reduces the instaneous potential to which the tower top rises considerably, as the current path is in 3 directions. The instaneous potential to which tower top can rise is $V_T = \frac{I_0 Z_T}{1 + Z_T/Z_S}$.

Where, Z_T = Surge impedance of the tower.

Z_S = Surge impedance of the gnd wire.

→ If the surge impedance of the tower, which is the effectively tower & footing resistance, is reduced the surge V_p developed is also reduced considerably

→ This is accomplished by providing driven gnd rods & counter-poise wire connected to tower legs at the tower foundation.

→ Ground rods are a no. of rods about 15mm diameter & 2.5 to 3m long, driven into the gnd.

→ In hard soils the rods may be much longer & can be driven to depth of say 50m. They are usually made of galvanized Fe (or) Cu-bearing steel. The spacings of the rods, the no. of rods, & the depth to which they are driven depend on the desired tower footing resistances.

→ Counter-poise wires are wires buried in the gnd at a depth of 0.5 to 1m, running ||el to the transmission line conductors & connected to the tower legs.

→ These wires may be 50 to 100m long. These are found to be more effective than driven rods & the surge impedance of the tower may be reduced to as low as 25Ω. The depth does not materially affect the resistance of the counter-poise & it is only necessary to bury them to a depth enough to prevent theft. It is desirable to use a large no. of potential wires than a single wire.

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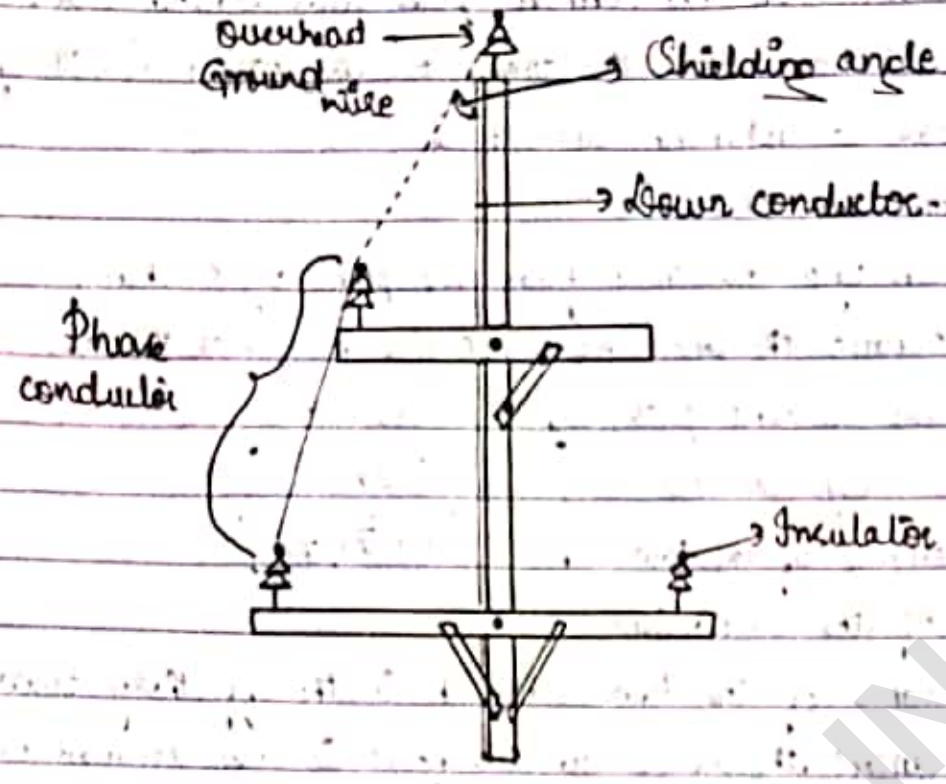

* Protective devices :- In regions where lightning strokes are intense (or) heavy, the overhead lines with these zones are fitted with shunt protected devices.

→ On the lines itself, 2 devices known as expulsion gaps & protector tubes are used.

→ Line terminations, junctions of lines & sub-stations are usually fitted with surge arresters.

* Expulsion gaps :- It is a device which consists of spark gap together with an arc quenching device which extinguishes the current arc when the gaps breakdown due to overvolt.

→ A typical such arrangement as shown in fig.

→ This essentially consists of a rod gap in air in series with a 2nd gap enclosed within a fibre tube. In the event of an overvolt, both the spark gap breakdown simultaneously. The current due to the overvolt is limited only by the tower footing resistance & the surge impedance of the gnd wires. The internal arc in the fibre tube due to lightning current vaporizes a small portion of the fibre material.

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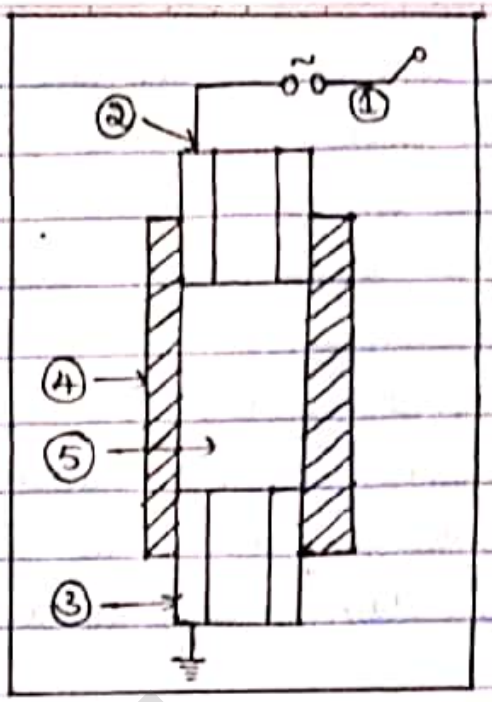
→ When the follow-on power frequency current passes through zero value, the arc is extinguished & the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, & the normal conditions are established. The lightning & follow-up power frequency currents together can last for 2 to 3 half cycles only. Therefore, generally no disturbance in the network is produced.



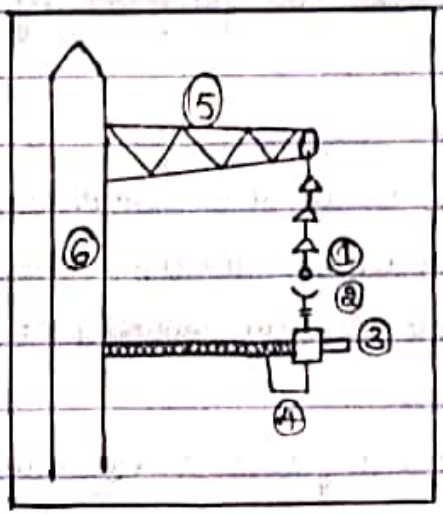
① External Series gap.
② Upper Electrode.
③ Ground electrode.
④ Fibre tube.
⑤ Hollow Space.

* Protector tubes :- It is similar to the expulsion gap, in construction & principle. It also consists of a rod (or) spark gap in air formed by the line conductor & its high-V/g terminal. It is mounted underneath the line conductor on a tower.

→ The arrangement is shown in fig.

→ The hollow gap in the expulsion tube is replaced by a non-linear element which offers a very high impedance at low currents but has low impedance for high (or) lightning currents.

→ When an overv/g occurs & the spark gap breaks down, the current is limited both by its own resistance & the tower footing resistance.



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

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→ The overv/p on the line is reduced to the v/p drop across the protector tube.

→ After the surge current is diverted & discharged to the gnd, the follow-on normal power frequency current will be limited by its high resistances.

→ After the current zero of power frequency, the spark gap recovers the insulation strength quickly.

→ The flashover v/p of the protector tube is less than that of the line insulation, & hence it can discharge the lightning overv/p effectively.

* Rod gaps :- A much simplier & effective protection device is a rod gap.

→ However, it does not meet the complete requirements.

→ The sparkover v/p of a rod gap depends on the atmospheric conditions. A typical volt-time characteristics of a 67cm-rod gap is shown in fig, with its protective margin.

→ There is no current limiting device provided so as to limit the current after sparkover, & hence a series resistance is often used.

→ Without a series resistance, the sparking current may be very high & the applied impulse v/p suddenly collapses to zero thus creating a steep step v/p, which sometimes proves to be very dangerous to the apparatus to be protected, such as transformer (or) the machine winding. Nevertheless, rod gaps do provide efficient protection where thunderstorm activity is less & the lines are protected by gnd wires.

* Surge arrestors (or) lightning arrestors :- These are the devices used at sub-stations & at line terminations to discharge the lightning overv/p & & short duration switching surges.

→ These are usually mounted at the line end at the nearest point to the sub-stations.

→ They have a flashover v/p lower than that of any other insulation (or) apparatus at the sub-station. These are capable of discharging 10 to 20 KA

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of long duration surges [8/20 μs] & 100 to 250 kA of short duration surge currents [1/5 μs]. The characteristics & detailed discussion of the surge arresters are presented in Sec.

* **Principles of insulation coordination on high-voltage and Extra-high-voltage power systems** :- Electric power supply should Ensure reliability & continuity to the Utility concerns.

→ Hence, the power lines & sub-stations are to be operated & protected against overvolt such that the no of failures are as few as possible.

→ To minimize the cost involved in the design, installation, & operation of the protective devices.

→ Generally, Sub-Stations contains transformers, switchgear, & other valuable Equipment with nonself-restoring insulation, which have to be protected against failures & internal destruction.

→ But the flashovers should be kept to a mini. so that the s/m dis-turbances are the least.

→ Hence, lightning & switching surge protection requires Establishment of protective v/g levels called Shunt protection levels, by means of protective dev-ices like lightning arresters.

* **What is insulation coordination** :- A Series of steps used to select the dielectric strength of Equipment in relation to the operating v/g & transient v/g switch can appear on the s/m for which the equipment is intended.

→ The lightning impulse withstand level known as the Basic Impulse level [BIL] is established for Each s/m nominal v/g for diff apparatus.

→ Various Equipment & their component parts should have their BIL above the s/m protective level, by a suitable margin. This margin is usually determined with respect to air insulation by statistical methods. For non-Self-restoring insulation like the transformer insulation, the margin limit is fixed using conventional methods.

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* Surge arrester :- These are non-linear resistors in series with spark gaps which act as fast switches. A typical surge arrester (or) lightning arrester is shown in fig (b) & its characteristics are given in fig (c)

→ A no of non-linear resistors elements made of Silicon carbide are stacked 1 over the other into 2 (or) 3 sections.

→ They are usually separated by spark gap [see in fig (b)]. The entire assembly is housed in a porcelain water-tight housing. The volt-ampere characteristics of a resistance element is of the form

$$\boxed{I = KV^a}$$

Where, Id = Discharge current, V = Applied V/g across the element.

K & a = constants depending on the material & dimensions of the element

→ The dynamic characteristics are shown in fig (a). When a surge V/g "Vi" of fig (b) is applied to the surge arrester, it breaks down giving the discharge current "id" & maintains a V/g "Vd" across it. Thus, it provides a protection to the apparatus to be protected above the protective level "Vp" as shown in fig (b).

→ The lighter designs operate for smaller duration of currents, while the heavy duty surge arrester with assisted (or) active gaps are designed for high current & long duration surges.

→ The lighter design arresters can interrupt 100 to 300A of power frequency follow-ON current & about 5000A of surge currents.

→ During lightning discharges, a high V/g is induced in the coil by the steep front of the surge, & sparking occurs in an auxially gap.

→ For power frequency follow-ON currents, the auxiliary gap is extinguished as sufficient V/g will not be present across the auxiliary gap to maintain an arc.

→ The main gap arcs occur in the magnetic field of the coils. The magnetic field, aided by the horn-shaped main gap electrodes, elongates the arc & quenches it rapidly.

→ Typical characteristics of surge arresters in the V/g range 100 to 200kV, 10 kA [Heavy duty type].

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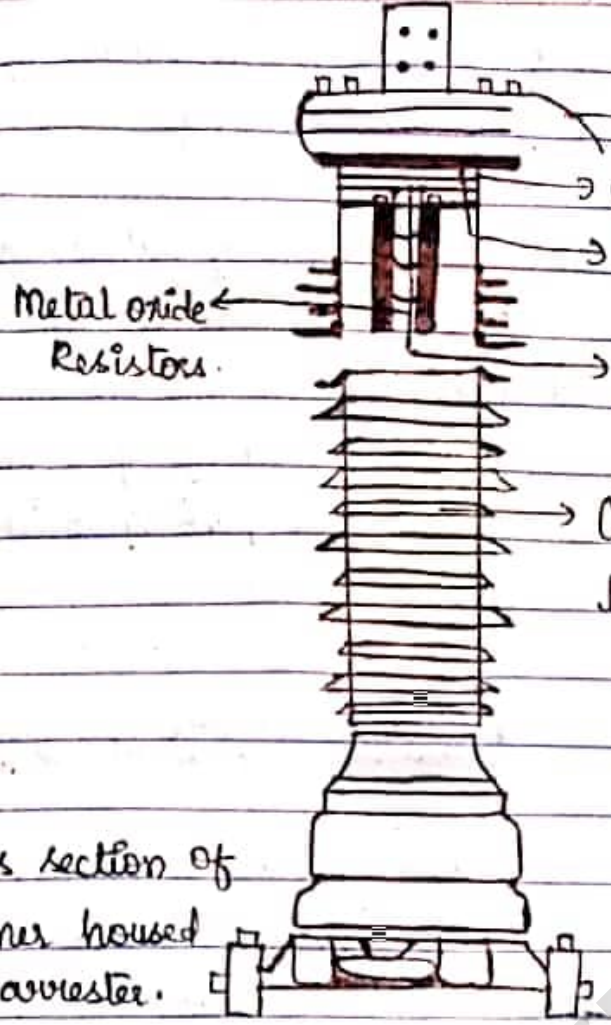
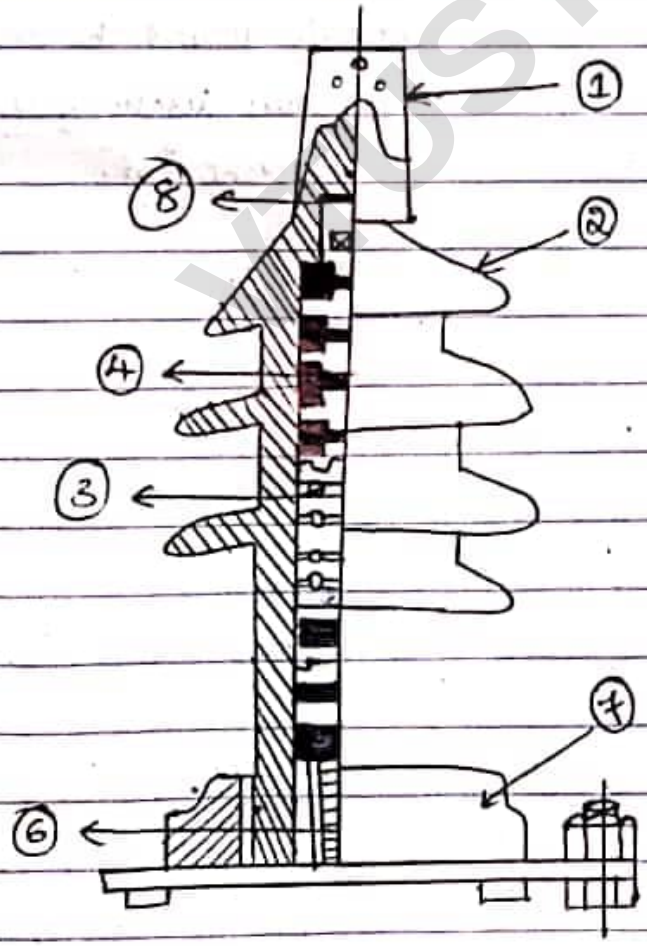


b) Cross section of Polymer housed arrester.

Fig (a). Metal oxide [ZnO] surge arrester in polymer housing.



1) Line end connector.
2) Porcelain housing.
3) Series gap.
4) Non-linear resistance element blocks.
5) Ground connection.
6) Spring.
7) Base.
8) Water-tight sealing.

Fig (b). Non-linear Element Surge arrester.

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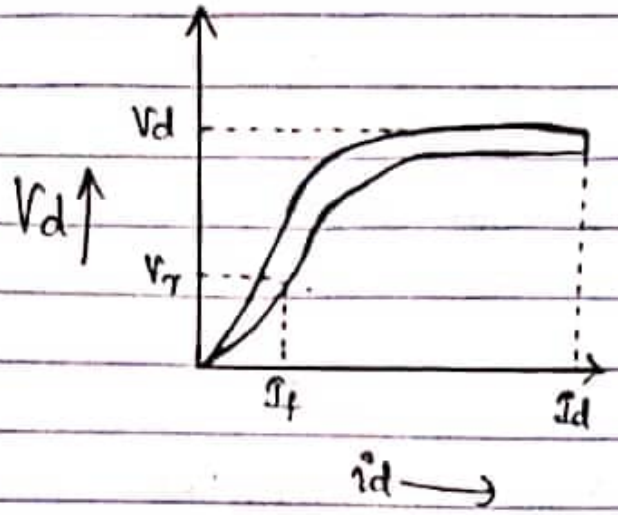
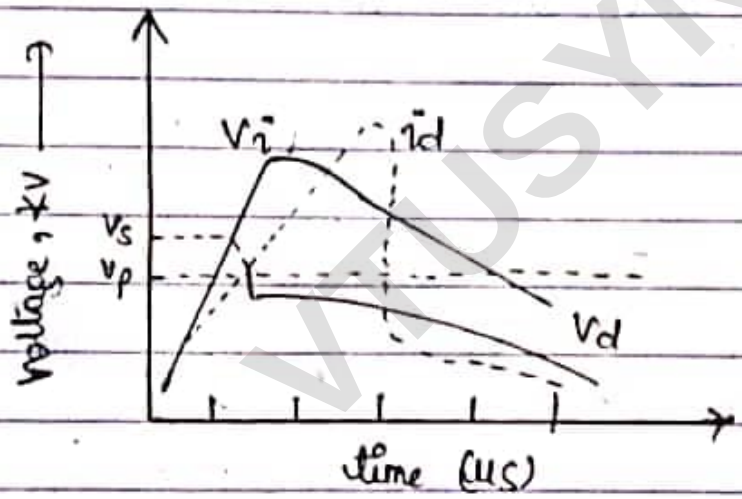


* Volt - ampere characteristics of a non-linear resistor block.

I_f = Power frequency follow-ON current at s/m v/g "V_r".

Vd = Max. v/g across the diverter during discharge of surge current with peak value "I_d".



* Surge - arrester operation.

V_s = Sparkover v/g.

V_p = Protective level.

V_i = Surge v/g.

i_d = Discharge current

Vd = v/g across the diverter when discharging the current "i_d".

Fig ⓒ. Characteristics of a Surge Arrester.

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