Module-1

Classification of HV insulating Media :

The most important material used in high voltage apparatus is the insulation. The principle media of insulation used are Gases/Vacuum, Liquid and Solid or a combination of these (Composite). The dielectric strength of an insulating material is defined as the maximum dielectric stress which the material can withstand. It is also the voltage at which the current starts increasing to very high values. The electric breakdown strength of insulating materials depends on the following parameters

1) Pressure 2) Temperature 3) Humidity
4) Field Configurations 5) Nature of applied voltage
6) Imperfection in dielectric materials
7) Materials of electrodes
8) Surface conditions of electrodes etc

Properties of Important Insulating Media :

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

i) High dielectric strength
ii) Thermal and chemical stability
iii) Non-inflammability
iv) High thermal conductivity : This assists cooling of current carrying conductors immersed in the gas and also assists the arc-extinction process.
v) Arc extinguishing ability : It should have a low dissociation temperature, a short thermal time constant and should not produce conducting products such as carbon during arcing.

Desirable Properties of solid dielectrics

The main requirements of the solid insulating materials used for power apparatus are

1) High Insulation resistance
2) High dielectric strength and low dielectric loss
3) Good mechanical properties
4) It should not be affected by chemical around it.
5) It should be non-hygroscopic because the dielectric strength of any material goes very much down with moisture content.

Examples: PVC, Polythene, Impregnated paper, mica, glass, Ceramics, Epoxy resins, Vulcanized rubber.

If the solid insulating material is truly homogeneous and is free from imperfections, its breakdown stress will be as high as 10MV/cm.

Desirable Properties of Liquid dielectrics

The most important properties of liquid dielectric are

1) High dielectric strength
2) High dielectric Constant
3) Good thermal conductivity
4) Good thermal Stability
5) High flash point
6) Free from moisture and impurities.

The most important factors which affect the dielectric strength of oil are the, presence of water droplets and the fibrous impurities. The presence of even 0.01% water in oil brings down the dielectric strength to 20% of the dry oil value and the presence of fibrous impurities brings down the dielectric strength much sharply.

Desirable Properties of a Gaseous Dielectrics/Insulators

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A gaseous insulating medium regains its dielectric strength quickly after the arc current has been interrupted. Therefore, gaseous insulators are attractive in high voltage applications. However, a gas to be selected for such application should satisfy certain requirements, such as:

a) High dielectric strength
b) Chemical stability, chemical inertness & non-toxicity
c) Low liquefaction temperature so that the gas can be used at high pressure. Act of melting
d) Thermal stability
e) Good thermal conductivity particularly when the gas also serves as a cooling medium
f) Non-inflammability & no chance of explosion.
h) Easy availability at low cost making it economically viable

Air as an insulator has a great advantage from the point of view of easy availability at almost no cost. Air - both at atmosphere pressure & higher pressure. has been widely used to provide insulation in high voltage transmission lines & high voltage equipment like circuit breakers, cables etc.

In the recent years, attempts to utilize other gases in high voltage equipment (transformers, C.B's, cables, m/cs etc) have led to the investigation and development of gases with particularly high electric strengths, much higher than that of air such as Sulphur hexafluoride (SF_6), nitrogen (N_2), Carbon dioxide (CO_2), freon (CCl_2F_2) etc.

Conduction & Breakdown in Gases

Ionization Processes

A gas in its normal state is almost a perfect insulator. However, when a high voltage is applied b/w the two electrodes immersed in a gaseous medium, the gas becomes a conductor and an electrical breakdown occurs.

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

a) Ionization by collision.
b) photo-ionization &
c) Secondary ionization processes.

Electrical discharges in gases are two types
1) Non-sustaining
2) self - sustaining

Ionization by Collision :

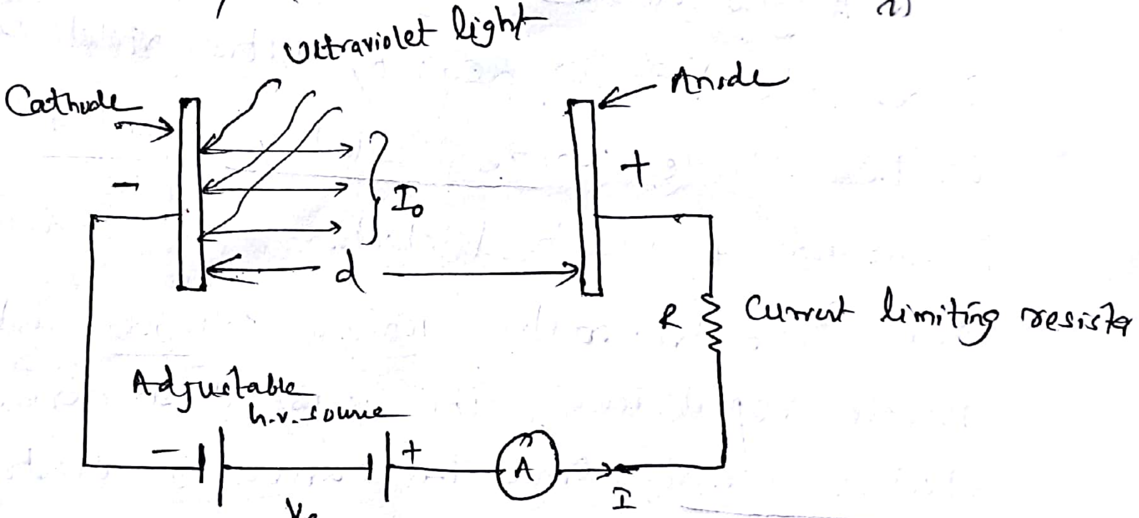


fig ⓐ Arrangement for study of a Townsend discharge

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 & a positive ion. If we consider a low pressure gas column in which an electric field 'E' is applied @ two plane parallel electrodes as shown in fig ⓐ. then any electron starting at the cathode will be accelerated & more & more b/w collisions with other gas molecules during its travel towards the anode. If the energy (E) gained during this travel b/w collisions exceeds the ionization potential, V_i, which is the energy required to remove an electron from its atomic shell, then ionization takes place. This process can be represented as

$$\bar{e} + A \xrightarrow{E > V_i} \bar{e} + A^+ + e^- \quad — ①$$

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

E → Energy Gained
V_i → Ionization Pote[illegible]al

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

* 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

i) Electron emission due to positive ion impact.
ii) Electron emission due to photons
iii) Electron Emission due to metastable & neutral Atoms.

i) 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 the positive ion, namely, the sum of its kinetic energy and the ionization energy, is greater than twice the work function of the metal, then one electron will be ejected and a second electron will neutralise the ion. [The probability of this process is measured as γ_i which is called the Townsend's secondary ionization co-efficient due to positive ions & is defined as the net yield of electrons per incident positive ion. γ_i increases with ion velocity and depends on the kind of gas and electrode material used.]

ii) 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

$$h.\nu \geq \phi \quad - ①$$

where ϕ is the work function of the metallic electrode
h is the Planck's constant
ν is frequency.

The frequency is given by the relationship

$$\nu = \frac{\phi}{h} \quad - ②$$

is known as the threshold frequency.

(ii) Electron emission due to Metastable & 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). Electron can be ejected from the metal surface by the impact of excited (metastable) atoms, provided that their total energy is sufficient to overcome the work function. This process is most easily observed with metastable atoms, because the lifetime of other excited states is too short for them to reach the cathode and cause electron emission, unless they originate very near to the cathode surface.

* Townsend's Current growth equation :

Referring to fig ⓐ let us assume that 'n_0' electrons are emitted from the cathode. when one electron collides with a neutral particle, a positive ion and an electron are formed. This is called an ionizing collision. Let 'α' be the average number of ionizing collisions made by an electron per centimetre travel in the direction of the field (α depends on gas pressure 'p' and E/p, and is called the Townsend's first ionization coefficient). At any distance 'x' from the cathode let the number of electrons be 'n_x'. when these 'n_x' electrons travel a further distance of dx they give rise to ($\alpha n_x dx$) electrons.

At $x=0, \quad n_x = n_0$ —①

Also $\dfrac{dn_x}{dx} = \alpha n_x$ or $n_x = n_0 e^{\alpha x}$ —②

Then, the number of electrons reaching the anode ($x=d$) will be

$$n_d = n_0 e^{\alpha d} \quad —③$$

The number of new electrons created, on the average, by each electron is

$$e^{\alpha d} - 1 = \frac{n_d - n_0}{n_0} \quad —④$$

$e^{\alpha d} = n_d/n_0$

$e^{\alpha d} - 1 = n_d/n_0 - 1$

Therefore, the average current in the gap, which is equal to the number of electrons travelling per second will be

$$I = I_0 e^{\alpha d} \quad \text{—} \; ⑤$$

Where I_0 is the initial current at the cathode.

. Current growth in the presence of secondary processes

When the initial set of electrons reaches the anode the single avalanche process is completed. Since the amplification of electrons ($e^{\alpha d}$) is occurring in the field, the probability of additional new electrons being liberated by other mechanisms increases, and creating further avalanches and are called as secondary electrons. The other mechanisms are

i) The positive ions liberated may have sufficient 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. The secondary ionization coefficient 'γ' is defined 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 the individual co-efficients due to the three different processes i.e. $\gamma = \gamma_1 + \gamma_2 + \gamma_3$. '$\gamma$' is called the Townsend's secondary ionization co-efficient and is a function of the gas pressure p & E/p.

Following Townsend's procedure for current growth,

Let us assume

n_0' = Number of secondary electrons produced due to secondary (γ) processes.

Let n_0'' = Total number of electrons leaving the cathode.

Then $n_0'' = n_0 + n_0'$ — ⑥

The total number of electrons "n" reaching the anode becomes

$$n = n_0'' e^{\alpha d}$$

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

and

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

Eliminating n_0', $n = \dfrac{n_0 e^{\alpha d}}{1 - \gamma [e^{\alpha d} - 1]}$

or

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)} \quad \text{— ⑦}$$

Townsend's Criterion for Breakdown :

Equation ⑦ gives the total average current in a gap before the occurence of breakdown. As the distance between the electrodes 'd' is increased, the denominator of the equation tends to zero, and at some critical distance $d = d_s$.

$$1 - \gamma [e^{\alpha d} - 1] = 0 \quad \text{— ⑧}$$

$d_s \rightarrow$ Sparking distance

For values of $d < d_s$, 'I' is approximately equal to 'I_0' and if the external source for the supply of I_0 is removed, I becomes zero. If $d = d_s$, $I \rightarrow \infty$ and the current will be limited only by the resistance of the power supply and the external circuit. This condition is called Townsend's breakdown criterion and can be written as $\gamma [e^{\alpha d} - 1] = 1$

Normally, $e^{\alpha d}$ is very large, and hence the above equation reduce to $\gamma e^{\alpha d} = 1$ — ⑨

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 the spark breakdown voltage 'V_s' and the corresponding distance 'd_s' is called the sparking distance.

The Townsend mechanism explains the phenomena of breakdown only at low pressure, corresponding to p×d (gas pressure × gap distance) values of 1000 torr-cm and below.

Time Lags for Breakdown

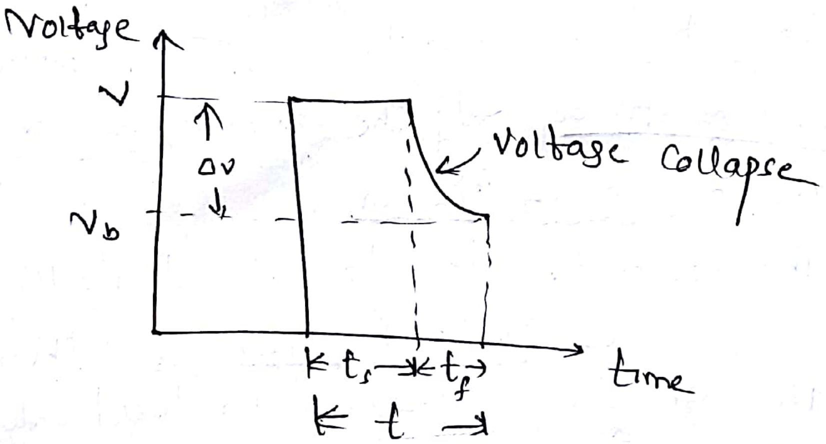


Fig @. Breakdown with a step function voltage pulse

Theoretically the mechanism of spark breakdown is considered as a function of ionization processes under uniform field conditions. 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 occurrence of breakdown itself. This time difference is called as the time lag.

The Townsend criterion for breakdown is satisfied only if at least one electron is present in the gap between the electrodes as in the case of applied d.c or slowly varying (50 Hz a.c) voltages, with rapidly varying voltages of short duration ($\approx 10^{-6}$s), the initiatory electron may not be present in the gap that the breakdown can not occur.

The time which lapses between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called as statistical time lag (t_s) of the gap. After the appearance of the electron, a time 't_f' is required for the ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag (t_f). The total time $t_s + t_f = t$ is called the total time lag as shown in fig ⓐ.

The statistical time lag depends upon the amount of pre-ionization present in the gap. This in turn depends on the size of the gap and the quantity of radiation that produces the primary electron.

The formative time lags depend mostly on the mechanism of the avalanche growth in the gap. In case where the secondary electrons are produced only due to the bombardment of the cathode by the positive ions, the transit time of the positive ion from the anode to cathode will predominately contribute for the formative time lag. The 't_f' is usually much shorter than the 't_s' and therefore the 't_s' can be determined by measuring the total time lag.

Photo ionization

The phenomena 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.

There are several processes by which radiation can be absorbed by atoms or molecules. They are

i) Excitation of the atom to a higher energy state &

ii) Continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionization etc

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 reversible process can be expressed as

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

$\nu \leftarrow$ Frequency (photon of U.V light of suitable freq)

Ionization occurs when

$$\lambda \leq c\,\frac{h}{V_i}$$

where h is the Planck's constant

c is the velocity of light

λ is the wave length of the incident radiation &

V_i is the ionization energy of the atom

(V_i is in electron volts)

Streamer Theory of Breakdown in Gases

Theory.
T - αd = 8-10
S - αd = 18-20

Limitations of Townsend's theory

According to the Townsend theory;

- * Firstly, current growth occurs as a result of ionization process only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap.
- * Secondly, the mechanism predicts time lags of order of 10^{-5} sec, but it was observed to occur at a very short time of 10^{-8} sec.
- * Also the Townsend mechanism predicts a very diffused form of discharge, that actually discharges were found to be filamentary and irregular.

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

Streamer Theory :

Narrow luminous tracks occurring at breakdown are called streamers.

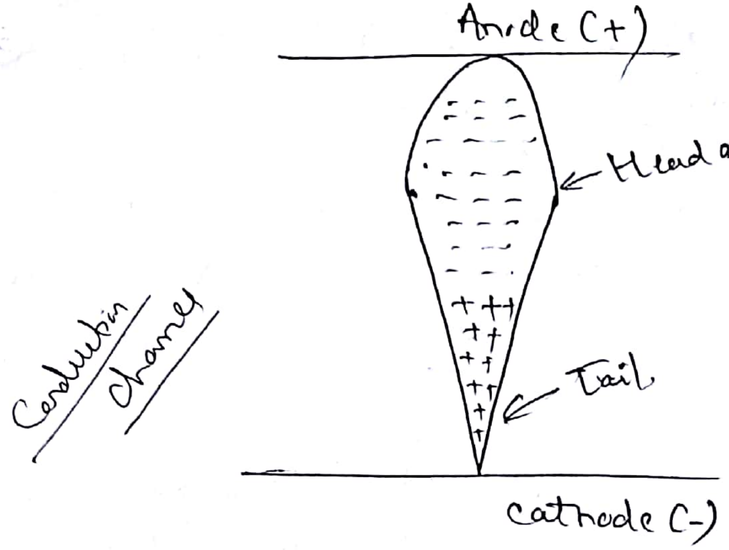
The principal postulates of streamer breakdown theories are as follows :

a) ~~for~~ Formation of an avalanche by an initiating electron by Townsend's 'α' process (primary process)

b) Large local enhancement of the electric field by the ion space charge at the head of the avalanche.

c) Large amount of photo-ionization of gas molecules in the space ahead of the avalanche (secondary process).

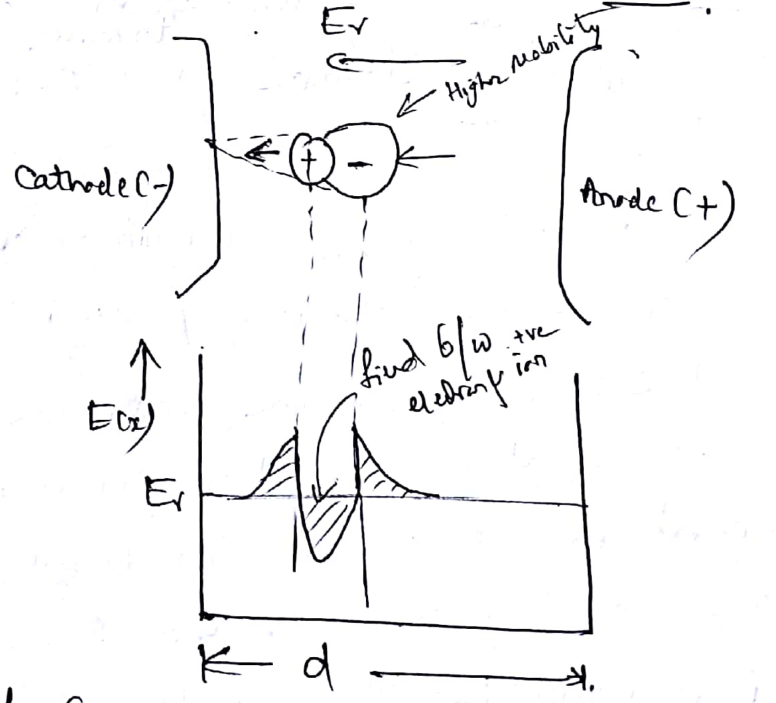
An initiating electron placed in the gap will be accelerated towards the anode and during its travel will cause ionization of gaseous molecules by collision. An avalanche of electrons and positive ions will be created as shown in fig ⓐ.



As soon as the streamer tip approaches cathode, stream of electrons rush from cathode to neutralize the positive space charge in the streamer; the result is a spark breakdown occurs.

Fig ⓐ An avalanche

As the avalanche develops in the gap the electrons being much lighter will have higher mobility (mobility is defined as the average drift velocity per unit electric field). Hence the positive ions will remain almost static, relative to the electrons in the avalanche. The head of the avalanche will therefore, be filled with the fast moving electrons and the positive ions will occupy the tail.



Field distortion ↑

$\uparrow \underline{\alpha d} = 18 \text{ to } 20.$

Er → space charge field (Corrected)

fig ⓑ Field distortion in a gap due to space charge.

For simplicity, the space charge at the head of the avalanche is assumed to be concentrated within a spherical volume with the negative charge ahead of the positive charge as shown in fig ⓑ.

A space charge field E_r will be created. The field behind and ahead of the avalanche is increased by the space charge, and that between the electron and the ion cloud is reduced. The field distortion will increase with the increase in 'αd' (i.e. with more space charge). When 'αd' attains a critical value of 18 to 20, the space charge field is comparable to the external field E_r. An intense ionization and excitation of the gas particles in front of the avalanche head happen later. Excited atoms return to normal state immediately. So, photons are released in the gas ahead of the avalanche head, which in turn generate secondary electrons by the photo-ionization process. These electrons generate further auxiliary avalanches as shown in fig ©. Since photons travel with the velocity of light, this process leads to a rapid development of a conduction Chanel across the gap and develops as a self-propagating streamer. The streamer proceeds across the gap to form a conducting filament of high-ionized gas between the electrodes. the gap, therefore, breakdown.

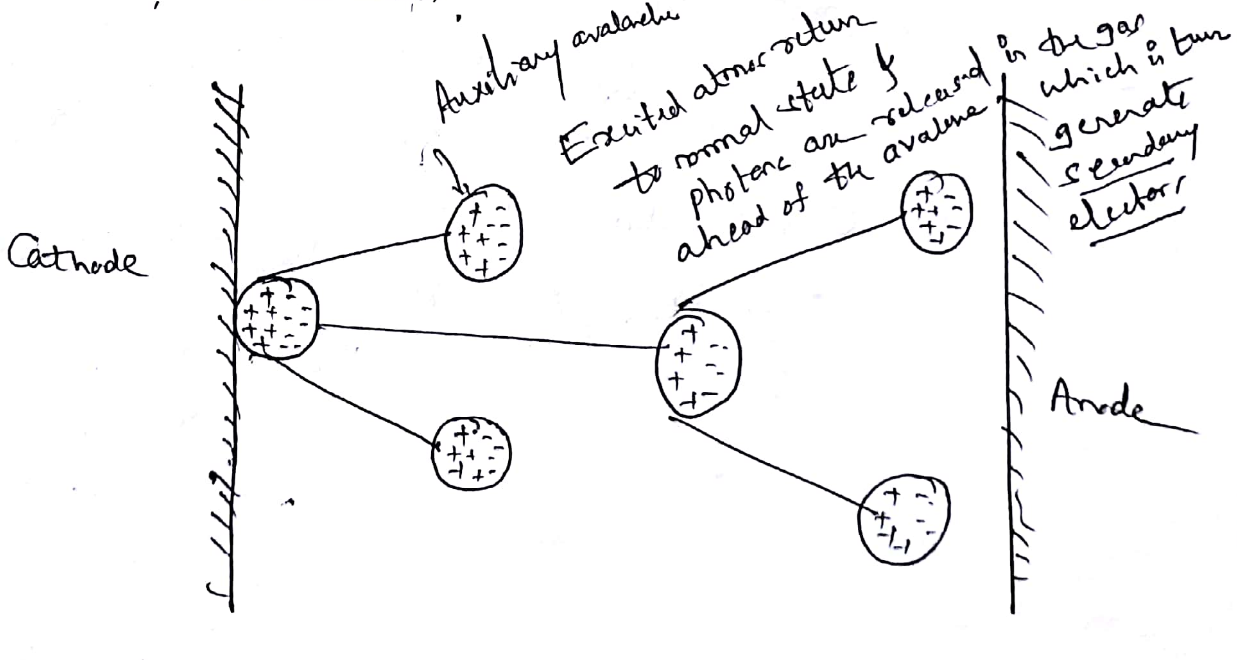


fig © Formation of Secondary avalanches due to Photo-ionization

Ex: In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8} A at 8 KV at a distance of 0.4 cm between the plane electrodes. Keeping the field constant and redu the distance to 0.1 cm results in a current of 5.5×10^{-9} A. Calculate Townsend's primary ioniz co-efficient 'α'

Soln The current at the anode I is given by

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

Where I_0 is the initial current &

d is the gap distance

Given. $d_1 = 0.4$ cm, $d_2 = 0.1$ cm

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

$$I_2 = 5.5 \times 10^{-9} A.$$

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

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

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

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

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Paschen's law

It defines the breakdown voltage for uniform field gaps as a function of gap length and gap pressure.

The breakdown criterion in gases is given as

$$\gamma \left[e^{\alpha d} - 1 \right] = 1 \quad - ①$$

Where the co-efficients α & γ are function of E/p ie

$$\left(\frac{\alpha}{p} \right) = f_1 \left[E/p \right]$$ and

$$\gamma = f_2 \left[E/p \right]$$ Also $E = V/d$

Substituting for 'E' in the expression for α & γ and rewriting eq ① we have

$$f_2 \left[\frac{V}{Pd} \right] \left[e^{\{ Pd \, f_1 (V/Pd) \}} - 1 \right] = 1 \quad - ②$$

This equation shows a relationship between 'V' and 'Pd' and implies that the breakdown voltage varies as the product 'Pd' varies. Knowing the nature of functions f_1 & f_2 we can rewrite eq ① as $\boxed{V = f(Pd)}$ - ③

This equation is known as Paschen's law

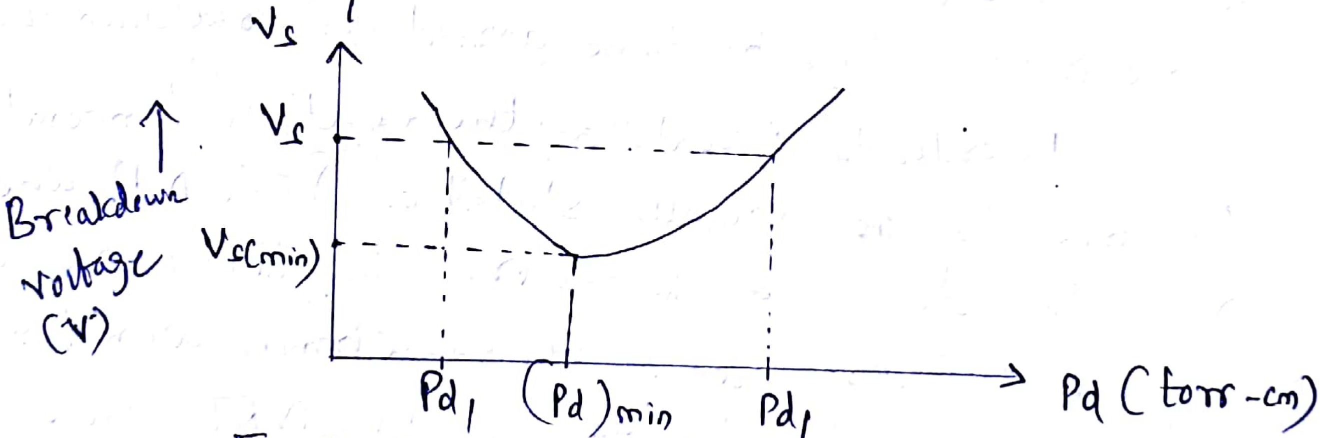


Fig ① Breakdown voltage - Pd curve (Paschen's law)

The Paschen's curve, the relationship between V & Pd is shown in fig ①. It is seen that the relationship b/w V and Pd is not linear and has a minimum value for any gas.

Table ① Minimum breakdown voltages for various gases.

Gas	V_s (min) in volts	Pd at $V_{s\,min}$ (torr-cm)
Air	327	0.567
H_2 (Hydrogen)	273	1.15
CO_2 (Carbon dioxide)	420	0.51
O_2 (Oxygen)	450	0.7
SO_2 (Sulfur dioxide)	457	0.33
Helium	156	4.0

The existence of a minimum sparking potential in Paschen's curve may be explained as follows.

For values $Pd > (Pd)_{min}$ electrons crossing the gap make more frequent collisions with gas molecules than $(Pd)_{min}$, but the energy gained between collisions is lower. Hence to maintain the desired ionization more voltage has to be applied.

For $Pd < (Pd)_{min}$ electron may cross the gap without even making a collision or making only less number of collisions. Hence more voltage has to be applied for breakdown to occur.

In order to account for the effect of temperature Paschen's law is generally stated as $V = f(Nd)$, where 'N' is the density of the gas molecules. This is necessary, because the pressure of the gas changes with temperature according to the gas law $pv = NRT$, where 'v' is the volume of the gas, 'T' is the temperature and 'R' is a constant.

Breakdown in Electronegative Gases

It has been recognized that one process that gives high breakdown strength to a gas is the electron attachment in which free electrons get attached to neutral atoms or molecules to form negative ions. Since negative ions like positive ions are too massive to produce ionization due to collisions, attachment presents an effective way of removing electrons which otherwise would have led to current growth and breakdown at low-voltage.

sulphur or carbon

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

oxygen atom or one of halogen atoms or molecules

The most common attachment processes encountered in gases are

S[illegible]$+ e \rightarrow SF_6^-$

i) the direct attachment in which an electron directly attaches to form a negative ion

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

ii) the dissociative attachment in which the gas molecules split into their constituent atoms and the electronegative atom forms a negative ion.

F → Fluorine

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

SF_6 ~~has~~ a halogen gas and is electronegative in nature. The rate of electron attachment is very high in electro~~[illegible]~~negative gases and therefore, the effective value of 'α' becomes smaller. In such cases, a greater electric field stress is required to cause breakdown. Hence electronegative gases have high breakdown strength.

SF_6 has a high dielectric strength, which is about 2.35 times that of air at atmospheric pressure (about 70 kV/cm).

SF_6 is non-toxic & non-inflammable. With such gases, the Townsend current growth equation modified to include ionization and attachment.

An attachment co-efficient (η) is defined, as the no. of attaching collisions made by one electron drifting one centimetre in the direction of the field. Under these conditions, the current reaching the anode, can be written as

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

The Townsend breakdown criterion for attaching gases can also be deduced by equating the denominator in eq to zero

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

This shows that for $\alpha > \eta$, breakdown is always possible irrespective of the values of α, η, & γ

Breakdown in Non-Uniform fields

In non-uniform fields, such as Coaxial cylinders, point-plane and sphere-plane gaps, the applied field varies @ the gap. Similarly, Townsend's first ionization coefficient (α) also varies with the gap. Hence αd in Townsend's criterion, i.e. $\gamma e^{\alpha d} = 1$ is rewritten by replacing 'αd' by $\int_0^d \alpha . dx$. Townsend's criterion for breakdown now becomes $\gamma \left\{ e^{\left[\int_0^d \alpha dx\right]} - 1 \right\} = 1$.

$\frac{\ldots}{(x/p)^{1/2}}$ V/cm

Meek's equation for the radial field at the head of an avalanche when it has crossed a distance 'x' is modified as

$$E_r = \frac{5.27 \times 10^{-7} \alpha_x e^{\left(\int_0^x \alpha dx\right)}}{(x/p)^{1/2}} \text{ V/cm}$$

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 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

Corona discharges

If the electric field is uniform a gradual increase in voltage @ a gap produces a breakdown of the gap in the form of a spark without any preliminary discharges. On the other hand, 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 form of discharge is called a corona discharge (and can be observed as a bluish luminescence). This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into Ozone.

1 Violet glow
2 hissing noise,
3 production of ozone gas.
4 Power loss
5 - R I (noise)

ozone →
allotropic form of oxygen with refreshing odour

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

(phenomenon)
Critical disruptive voltage
→ Minimum V. @ which corona occurs.

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' is

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

Visual critical voltage

Corona glow appears all along the line conductors.

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

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

Where 'm' is the surface irregularity factor which becomes equal to unity for highly polished smooth wires. d is the relative air density correction factor given by

$d = \frac{0.392b}{273+T}$ where 'b' is the atmospheric pressure in torr
T is the temperature in °c

d=1 at 760 torr & 25°c.

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

When the voltage is positive, corona appears as a uniform bluish white sheath over the entire surface of the conductor. On the other hand, when the voltage is negative, the corona will appear like reddish glowing spots distributed along the length of the wire.

The corona inception and breakdown voltages of the sphere - plane arrangement are shown in fig.

From this figure it can be seen that

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

ii) at fairly large spacings (region II), the field is non-uniform, and the breakdown voltage depends both on the sphere diameter & the spacing

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

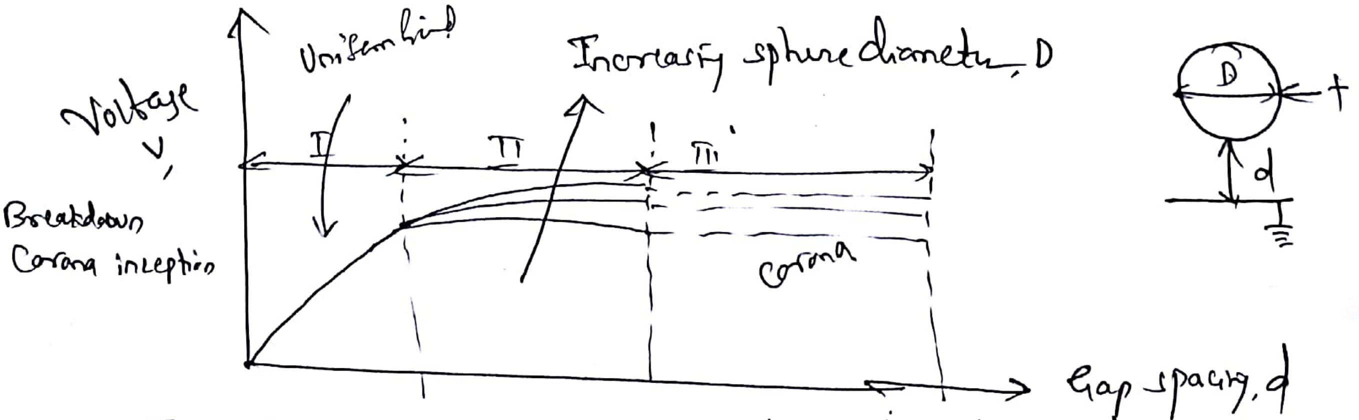


Fig. Breakdown & corona inception characteristics for spheres of different diameter in sphere - plane gap geometry.

Module - 1

Breakdown in Solid Dielectrics

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 & chemical deterioration. Solid dielectrics have higher breakdown strength compared to liquids & gases.

Solid insulating materials, which are generally used in practice, are of two types, the organic materials such as paper, wood & rubber and inorganic materials such as mica, glass & porcelain and synthetic polymers such as perspex, PVC, epoxy resins etc.

The mechanism of breakdown is a complex phenomenon in the case of solids, and varies depending on the time of application of voltages as shown in fig ⓐ.

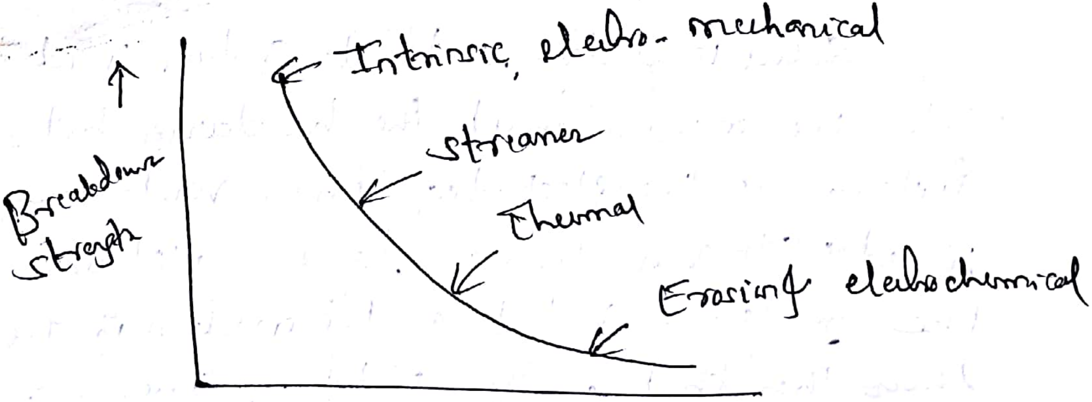


fig ⓐ Variation of breakdown strength with time after application of voltage

The various breakdown mechanisms can be classified as:

1) Breakdown due to internal discharges
2) Thermal breakdown
3) Intrinsic or ionic breakdown
4) Electromechanical breakdown
5) failure due to treeing & tracking
6) Electrochemical breakdown

1) Breakdown due to Internal discharges (also called Partial discharges)

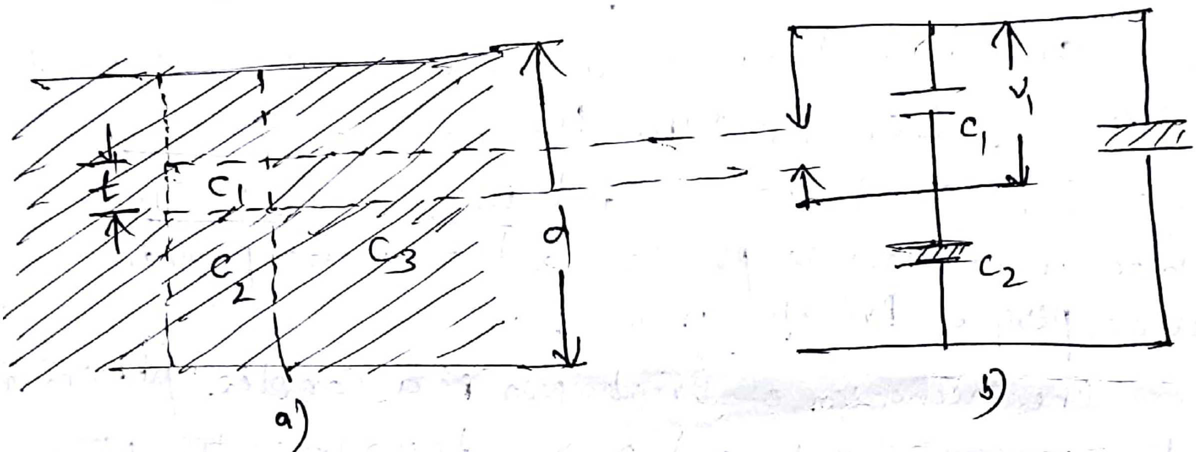


Fig1. Electrical discharge in a cavity and its equivalent circuit

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

Let us consider a dielectric between two conductors as shown in fig1ⓐ. We divide the insulation into three parts, an electrical network of C_1, C_2 & C_3 can be formed as shown in fig 1ⓑ. In this C_1 represents the capacitance of the void or cavity, C_2 is the capacitance of the dielectric which is in series with the void and C_3 is the capacitance of ~~dielectric~~ the rest of the dielectric. When the applied voltage is 'V' the voltage @ the void, 'V_1' is given by

$$V_1 = \frac{Vd_1}{d_1 + \left(\frac{\epsilon_0}{\epsilon_1}\right) d_2}$$

Where d_1 & d_2 are the thickness of the void & the dielectric respectively having permittivities ϵ_0 & ϵ_1.

When a voltage 'V' is applied, V_1 reaches the breakdown strength of the medium in the cavity (V_i) and breakdown occurs. Vi is called the 'discharge inception voltage'. When the applied voltage is ac, breakdown occurs on both the half cycles & the no. of discharges will depend on the applied voltage. The voltage & the discharge current waveforms are shown in fig.

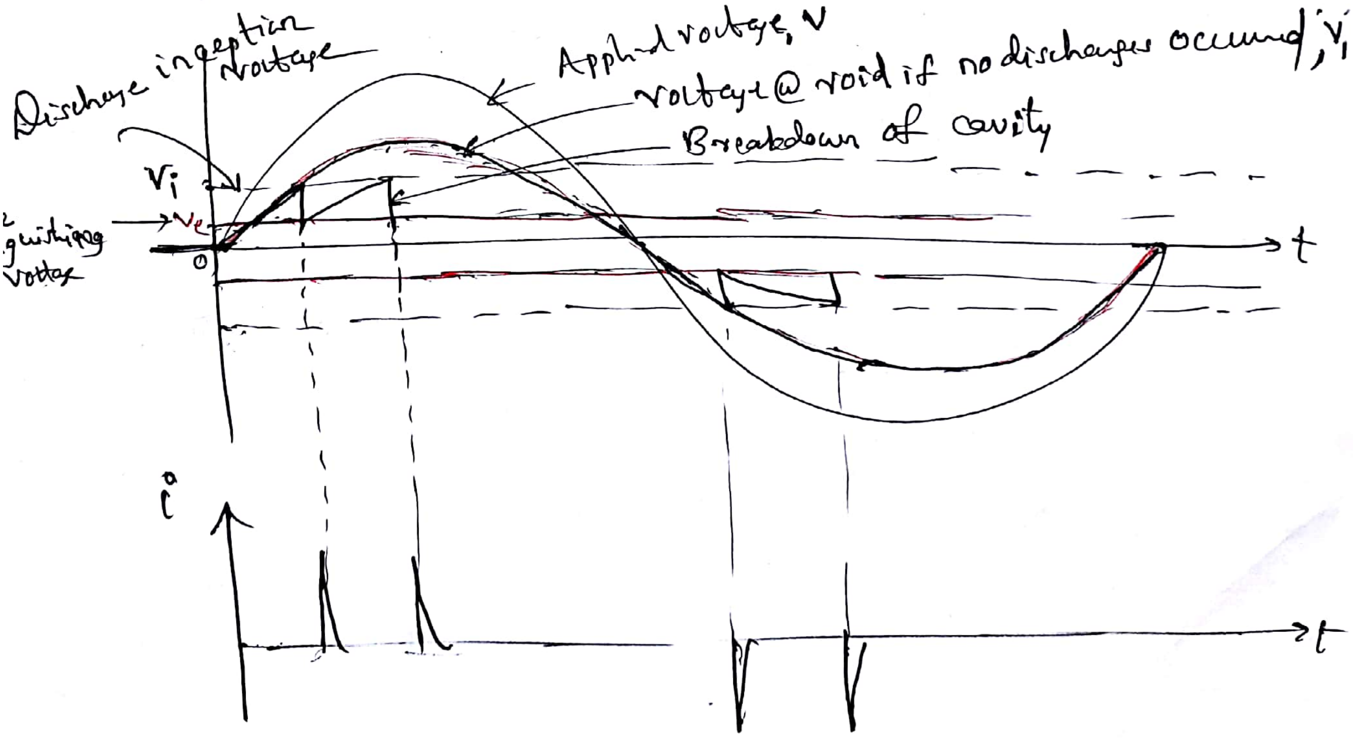
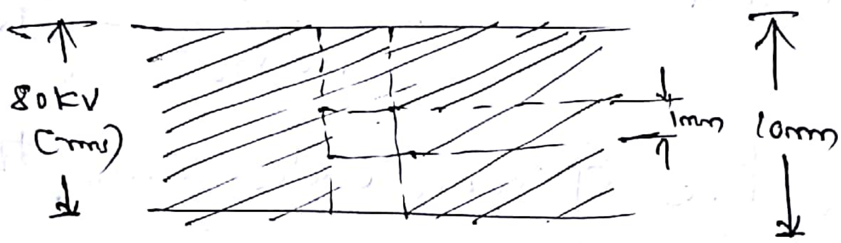


Fig. Sequence of cavity breakdown under alternating voltages.

When the first breakdown @ the cavity occurs the voltage @ it becomes zero. When once the voltage V_1 becomes zero, the spark gets extinguished and again the voltage rises till breakdown occurs again. This process repeats again & again and current pulses as shown, will be obtained both in the positive & negative half cycles.

When the breakdown occurs in the voids, electrons & positive ions are formed. They will have sufficient energy & when they reach the void surfaces they may break the chemical bonds. Also in each discharge there will be some heat dissipated in the cavities and this will carbonize the surface of the voids & will cause erosion of the material. The life of the insulation with internal discharges depends upon the applied voltage and the number of discharges. Breakdown by this process may occur in a few days or may take a few years.

Ex A solid dielectric specimen of dielectric constant of 4 shown in the figure has an internal void of thickness '1' mm. The specimen is 1 cm thick and is subjected to a voltage of 80kV (rms). If the void is filled with air and if the breakdown strength of air can be taken as 30kV (peak)/cm, find the voltage at which an internal discharge can occur.



Sol Voltage that appears @ the void is given as

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\epsilon_0}{\epsilon_1}\right) d_2}$$

Where $d_1 = 1mm$, $d_2 = 9mm$, $\epsilon_0 = 8.89 \times 10^{-12}$ F/m

$$\epsilon_1 = \epsilon_r \epsilon_0 = 4\epsilon_0.$$

$$\therefore V_1 = \frac{V \times 1}{1 + \left(\frac{8.89\times10^{-12}}{4\times 8.89\times10^{-12}}\right)\times 9} = \frac{V}{1+\frac{9}{4}} = \boxed{\frac{4V}{13}}$$

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

$$\therefore V = \frac{13V_1}{4} = \frac{13\times3}{4} = \frac{39}{4} = 9.75\text{ kV (Peak)}$$

The internal discharges appear if the sinusoidal voltage $80\sqrt{2}\sin\omega t$ kV when the voltage reaches a value of 9.75kV.

✓

Ex

Thermal breakdown

A solid specimen of dielectric has a dielectric constant of 4.2 and $\tan\delta = 0.001$ at a freq of 50 Hz. If it is subjected to an alternating field of 50 kV/cm, calculate the heat generated in the specimen due to the dielectric loss.

Soln

Dielectric heat loss at any electric stress E in ac field is $= \dfrac{E^2 f \epsilon_r \tan\delta}{1.8 \times 10^{12}}$ W/cm³

For the specimen under study, the heat loss will be

$$= \frac{50 \times 50 \times 10^{6} \times 50 \times 4.2 \times 0.001}{1.8 \times 10^{12}}$$

$= 0.291$ mW/cm³

Thermal Breakdown

In general, the breakdown voltage of a solid dielectric shoud increase with its thickness. But this is true only upto a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction.

When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material. The current heats up the specimen and the temperature 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 $W_{dc} = E^2 \sigma$ W/cm³ —①

where σ is the conductivity of the specimen.

Under ac fields the heat generated

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

Where f = frequency in Hz

δ = loss angle of the dielectric material

E = rms value

The heat dissipated (W_T) is given by

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

where C_V = specific heat of the specimen

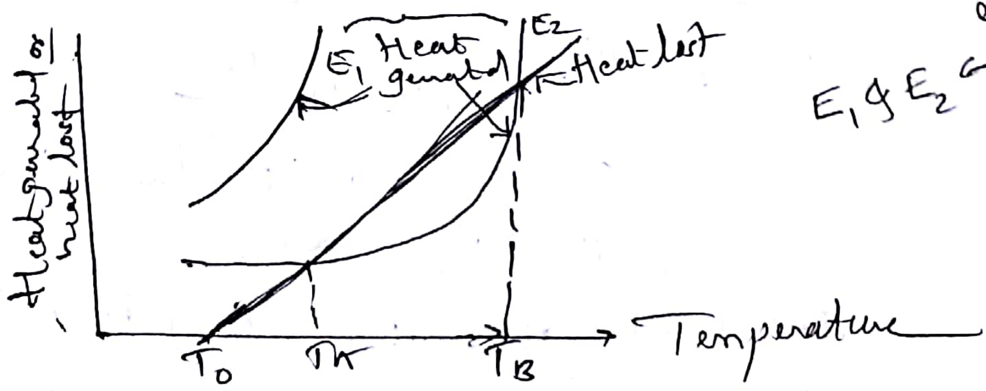
T = Temperature of the specimen

K = Thermal conductivity of the specimen &

t = time over which the heat is dissipated.

Equilibrium is reached when the heat generated (W_{dc} or W_{ac}) becomes equal to the heat dissipated (W_T).

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 a straight line, while the heat generated at fields E_1 & E_2 are shown by separate curves. At fields E_2 breakdown occurs both at temperature 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 and hence the breakdown will not occur.



E_1 & E_2 = electric fields

fig Thermal instability in solid dielectrics

Table Thermal Breakdown stresses in dielectrics

Material.	Maximum thermal breakdown stress in MV/cm	
	dc field	AC field
Muscovite Mica	24	7.18
Rock salt	38	1.4
High grade Porcelain	—	2.8
HV steatite	—	9.8
Quartz - $\perp^{er}$ to axis	1200	—
$\parallel^{el}$ to axis	66	—
Capacitor paper	—	3.4 – 4.4
Polythene	—	3.5
Polystyrene	—	5.0

Table gives the thermal breakdown voltages of various materials under dc & AC fields.

It can be seen from this 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

Electromechanical Breakdown

When solid dielectrics are subjected to high electric fields failure occurs due to electrostatic compressive forces which can exceed the mechanical compressive strength. If the thickness of the specimen is d_0 and is compressed to a thickness 'd' under an applied voltage 'V', then the electrically developed compressive stress is in equilibrium if

Electrically developed compressive stress

$$\epsilon_0 \epsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \quad -①$$

Mech Compressive strength

where Y is the Young's Modulus

From eq ①

$$V^2 = d^2 \left[\frac{2Y}{\epsilon_0 \epsilon_r}\right] \ln\left[\frac{d_0}{d}\right] \quad -②$$

Usually, mechanical instability occurs when

$$\frac{d}{d_0} = 0.6 \quad \text{or} \quad \frac{d_0}{d} = 1.67$$

Substituting this in eq ②, the highest apparent electric stress before breakdown,

$$E_{max} = \frac{V}{d_0} = 0.6 \left[\frac{Y}{\epsilon_0 \epsilon_r}\right]^{1/2} \quad -③$$

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

The pressure exerted when the field reaches about 10^6 V/cm may be several KN/m².

Cavitation & the Bubble theory

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

i) Gas pockets at the surfaces of the electrodes
ii) Electrostatic repulsive forces b/w space charges which may be sufficient to overcome the surface tension
iii) gaseous products due to the dissociation of liquid molecules by electron collisions and
iv) 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. The volume of the bubble remains constant during elongation. Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the minimum value on the Paschen's curve for the gas in the bubble. The breakdown field is given as,

$$E_0 = \frac{1}{(\epsilon_1-\epsilon_2)}\left[\frac{2\pi\sigma(2\epsilon_1+\epsilon_2)}{r}\left\{\frac{\pi}{4}\sqrt{\left(\frac{V_b}{2rE_0}\right)}-1\right\}\right]^{1/2}$$

where σ is the surface tension of the liquid,
ϵ_1 is the permittivity of the liquid
ϵ_2 is the permittivity of the gas bubble
r is the initial radius of the bubble assumed as a sphere and

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

From this equation, it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid.

Breakdown in Pure liquids

Electron breakdown theory

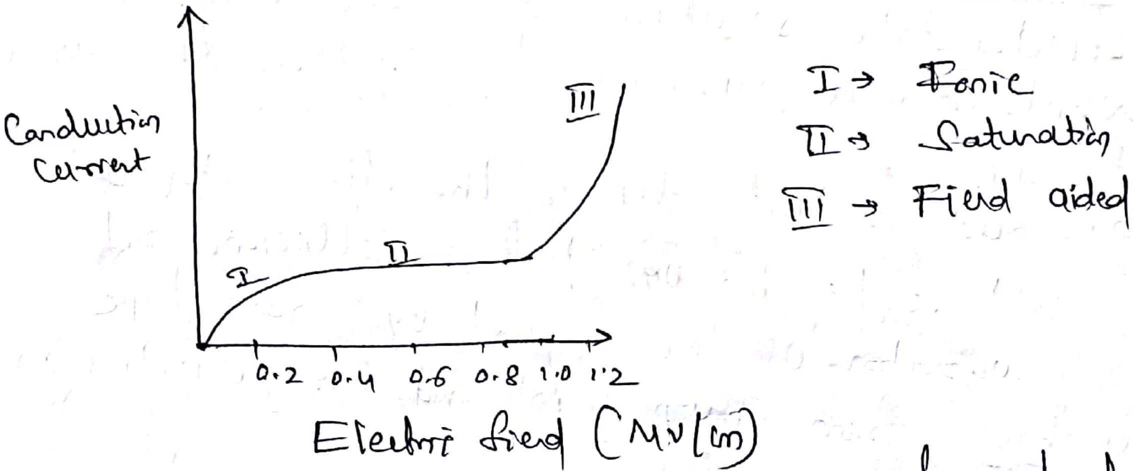


Fig a) Current-field characteristic for a hydrocarbon liquid.

The current-field characteristic curve for a hydrocarbon liquid is shown in fig a). The curve has three distinct regions. At low fields (<1k[illegible]m) the conduction is largely ionic and tends to get dissociated (region I). At intermediate fields this current saturates (region II). At a higher fields, as we approach breakdown, the conduction increases more rapidly and tends to be unstable (region III).

It is believed that this increased current may result from electron emission from the cathode by i) Field emission ii) by field enhanced thermionic (schottky's) emission (effect) iii) possibly by field dissociation of molecules in the liquid.

Electronic Breakdown

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

$$e\lambda E = Ch\nu$$

Where λ is the mean free path

$h\nu$ is the energy of ionization

C is constant

Dielectric strength of pure liquids

Liquid	strength MV/cm
Benzene	1.1
Good oil	1.0 — 4.0
Hexane	1.1 — 1.3
Nitrogen	1.6 — 1.88
oxygen	2-4
Silicon	1.0 — 1.2

Electro Convection Breakdown

When a highly pure insulating liquid is subjected to high voltage, electrical conduction results from charge carriers injected into the the liquid from the electrode surface. The resulting space charge gives rise to Coulombic electrostatic forces which under certain conditions causes hydro dynamic instability, resulting convecting current. As the applied voltage approaches the critical voltage, the motion at first exhibit a structure of hexagonal cells & as the voltage is increased further the motion becomes turbulent. Thus interaction b/w the space charge & the electric field gives rise to forces creating an eddy motion of liquid.

It has been shown that when the voltage applied is near to breakdown value, the speed of the eddy motion is given by $V_e = \sqrt{E_2/\rho}$ where ρ is the density of liquid. In liquids, the ionic drift velocity is given by $V_d = KE$ where K is the mobility of ion.

Module-2

Generation of High Alternating Voltages (HVAC)

HV Transformer or Testing Transformer :

Power frequency single phase stepup testing transformers form the core of high voltage AC test equipment. A testing transformer will have a much lower KVA rating compared to that of a power transformer having the same voltage rating. The testing transformer KVA rating will be a short-term rating, and cooling of the windings will not be a major problem.

Construction of Test Transformers : [Oil Insulated]

Two types of constructions are possible for oil-insulated test transformer.

In the tank-type construction shown in fig ⓐ the core and the windings are enclosed in a metal container, the surface of which provides natural cooling. However with high working voltages, the cost of bushing is high and the space requirement is also high.

In the insulated enclosure transformer type shown in fig ⓑ, the core and the windings are surrounded by an insulated cylinder. Transformer of this kind contain a relatively large quantity of oil and so have large thermal time constants. Heat dissipation through the insulated enclosure is small. But no bushings are required and high voltage electrodes of large radii of curvature can easily be used.

Transformers for generating high AC voltages usually have one end of the high voltage winding earthed. The iron-core is earthed and one terminal of the low voltage winding may also be earthed. The rating of the primary winding is usually 230V and in general will be less than 1 KV.

It should be noted that, difficulties arise in the design of a single coil if voltages of more than 100KV have to be produced. For higher voltages cascading of single unit test transformers is necessary.

Circuit diagram of single unit testing transformer

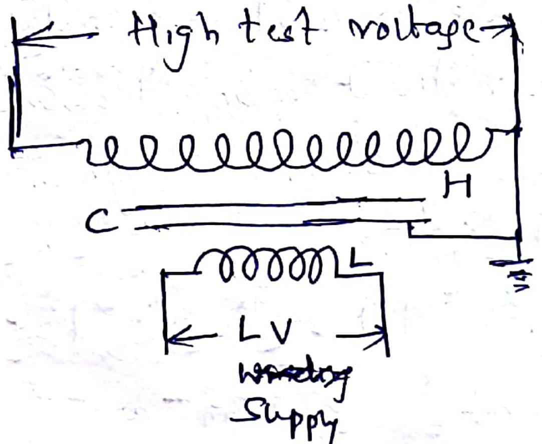
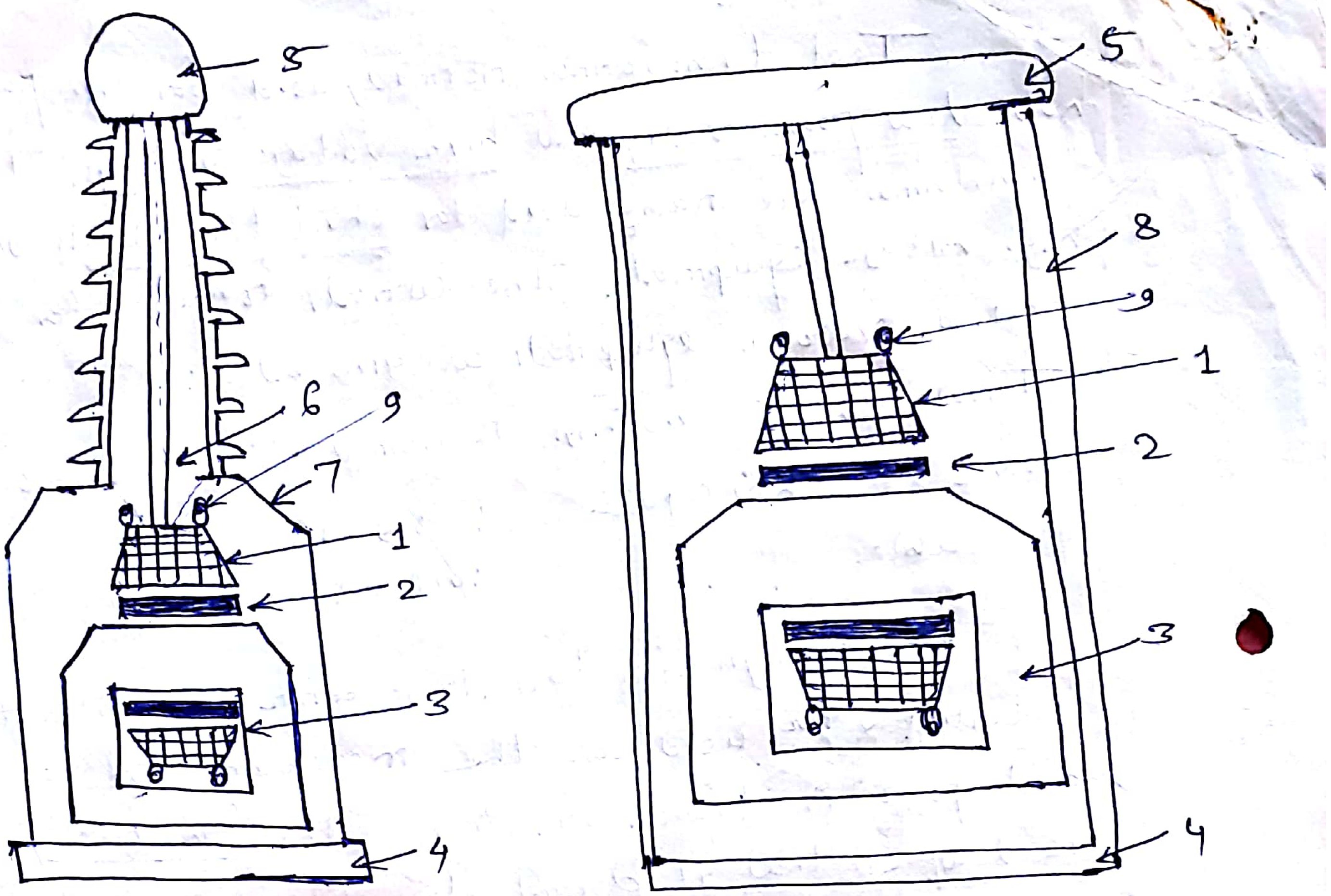


Fig single unit transformer circuit

H – High voltage winding

L – Low voltage winding

C – Iron core.



(a) tank type (b) Insulated enclosure type.

1. High voltage wdg
2. Low voltage wdg
3. Iron core
4. Base.
5. High voltage terminal
6. Bushing
7. Metal tank.
8. Insulated enclosure (cylinder)
9. Field grading shield

Fig. Oil Insulated test transformer

H-V wdg → Trapezoidal shape of cross-section

Single turns are arranged in layer. which are insulated from each other by solid materials (Kraft paper sheets)

Step up x^{mer}

Step down

$$\frac{440V}{11kV} = \frac{10A}{276} = \frac{less}{more}$$

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

turns

$$\frac{80kV}{230V} = \frac{A}{mA} = \frac{more}{less}$$

(step)

Cascaded Transformers

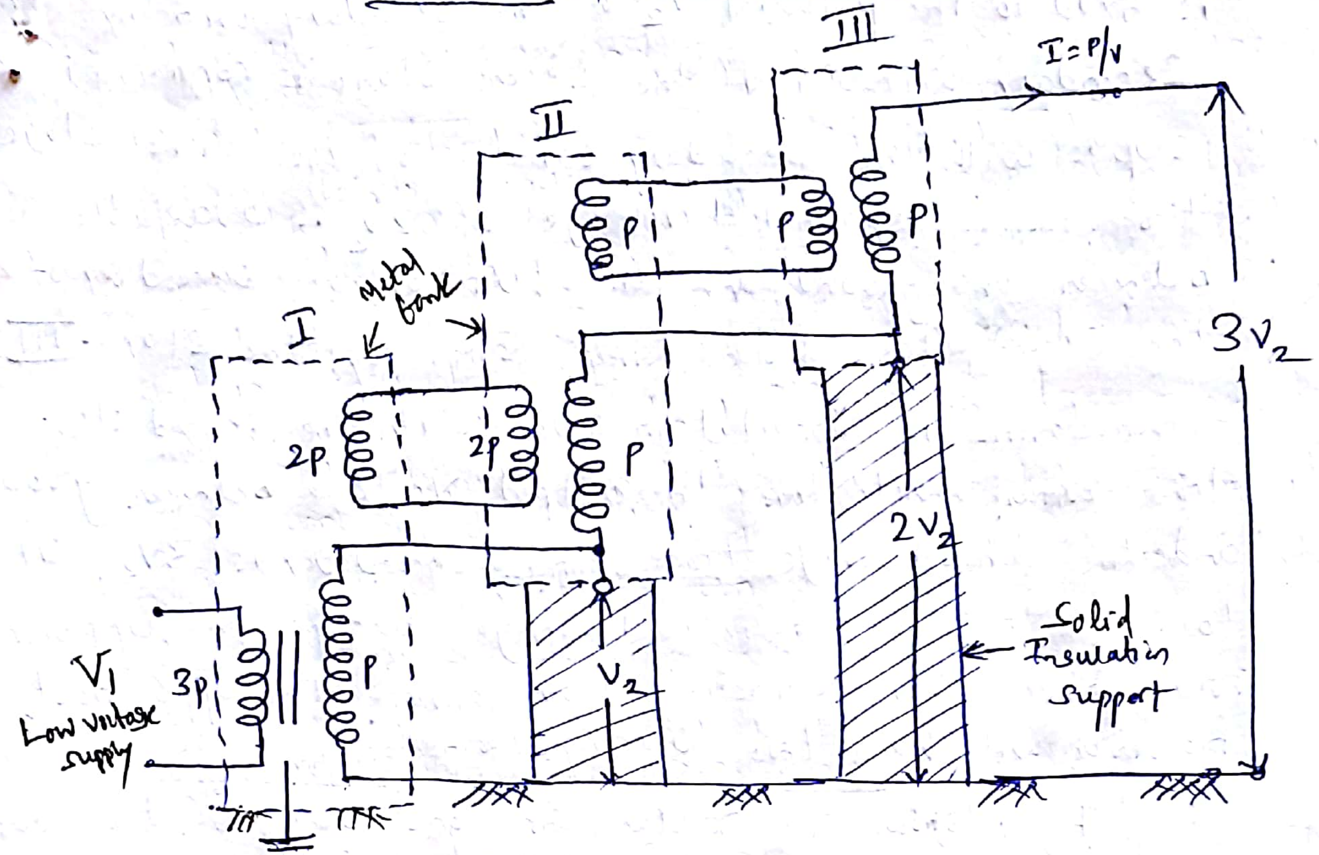


Fig.① Basic 3 stage cascaded transformer

Need for Cascade Connection :

When test voltage requirements are less than about 300kV, a single transformer can be used for testing purposes. For higher voltage requirements, a single unit construction becomes difficult and costly due to insulation problems. Moreover, transportation and errection of large transformers become difficult. These drawbacks are overcome by series connection or cascading of the several identical units of transformer, wherein the high voltage windings of all the units effectively come in series.

Fig ① shows a basic scheme for cascading three transformers. The primary of the first-stage transformer is connected to a low voltage suppy. A voltage is available across the secondary of this transformer. The tertiary (excitation) winding of first stage has the same number of turns as the primary winding and feeds the primary of the second stage transformer. The potential of the tertiary is fixed to the potential V_2 of the secondary winding. The secondary winding of the second stage is connected in series with the secondary winding of the first stage transformer, so that a voltage of $2V_2$ is available between the ground and the terminals of secondary of the second stage transformer. Similarly, the stage-III transformer is connected in series with the second stage transformer. With this the output voltage between ground and the third stage transformer secondary is $3V_2$. It is to be noted that the individual stages except the uppermost must have three winding transformer. The uppermost, however, will be a two winding transformer.

Fig ① shows the metal tank construction of transformer. Here the low voltage terminal of the secondary winding is connected to the tank. The tank of stage-I transformer is earthed. The tanks of stage II & stage III transformer have potentials of V_2 and $2V_2$ respectively above the earth and therefore, these must be insulated from the earth with suitable solid insulation through H.T. bushings the leads from the tertiary winding and the H.V winding are brought out to be connected to the next stage.

The main disadvantage of cascading the transformer is that, the lower stages of the primaries of the transformer are loaded more as compared with upper stages.

Supply to the units can be obtained from a motor-generator set or through an induction regulator for variation of the output voltage. The rating of the primary or the low voltage winding is usually 230 or 400V for small units up to 100 kVA. For larger outputs the rating of the low-voltage winding may be 3.3kV, 6.6kV or 11 kV

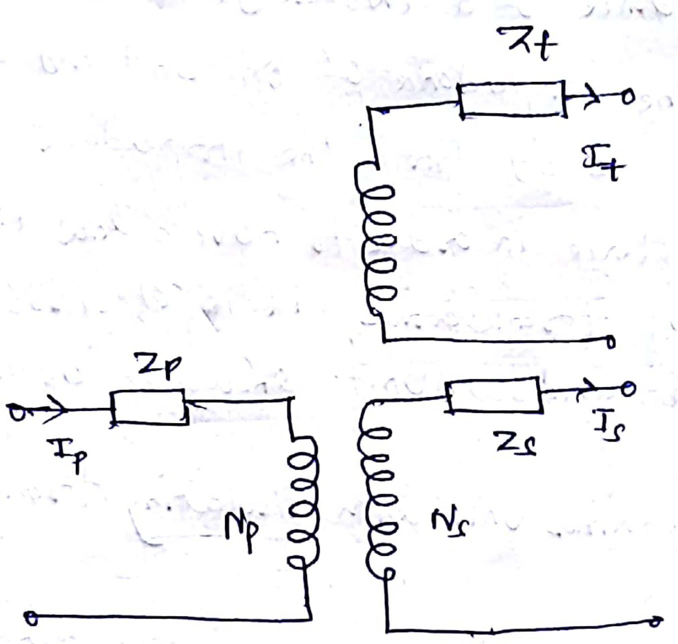


Fig ② Equivalent circuit of one stage

The loading of various windings is indicated by 'p' in fig ①. For the three-stage transformer, the total output VA (volt-ampere) will be 3VI = 3p and therefore each of the secondary winding of the transformer would carry a current of $I = P/V$. The primary winding of stage-III transformer is loaded with 'p' and so also the tertiary winding of second stage transformer. Therefore, the primary of the second stage transformer would be loaded with '2p'. Extending the same logic, it is found that the first stage primary would be loaded with '3p'. Therefore, while designing the primaries and tertiaries of these transformers, this factor must be taken into consideration. Here Z_p, Z_s & Z_t are the impedances associated with each winding. The impedances are shown in series with an ideal 3-winding transformer with corresponding number of turns N_p, N_s & N_t.

The impedance of a two-stage transformer is about 3 to 4 times the impedance of one unit and a three-stage impedance is 8 to 9 times the impedance of one unit transformer. Hence in order to have a low impedance of a cascaded transformer, it is desirable that the impedance of individual units should be as small as possible.

Cascade transformer unit with Isolating transformers for excitation

Fig ② shows a second scheme for providing the excitation to the second and the third stages.
Isolating transformers I_{s_1}, I_{s_2} and I_{s_3} are 1:1 ratio transformers insulated to their respective tank potentials and are meant for supplying the excitation for the second and the third stages at their tank potentials. Power supply to the isolating transformer is also feed from the same ac input. This scheme is expensive and requires more space. The advantage of this scheme is that the natural cooling is sufficient and the transformers are light and compact. Transportation and assembly is easy. Also, the construction is identical for isolating transformer and the high-voltage cascade units. Three phase connection in delta or star is possible for three units.

Testing transformers of ratings upto 10 MVA in cascade connection ~~connection~~ to give high voltages upto 2.25 MV are available for both indoor and outdoor applications. Modern test transformers are built to withstand transients during the flashover of the test object.

T_1, T_2, T_3 → Cascade transformer units

$I_{s_1}, I_{s_2}, I_{s_3}$ → Isolation transformer units

C_1, C_2, C_3 → Capacitance voltage divider for high voltage measurement after I, II & III stages

V_1, V_2, V_3 → For metering after I, II & III stages

1. Primary (LV) wdg
2. HV winding
3. Excitation winding

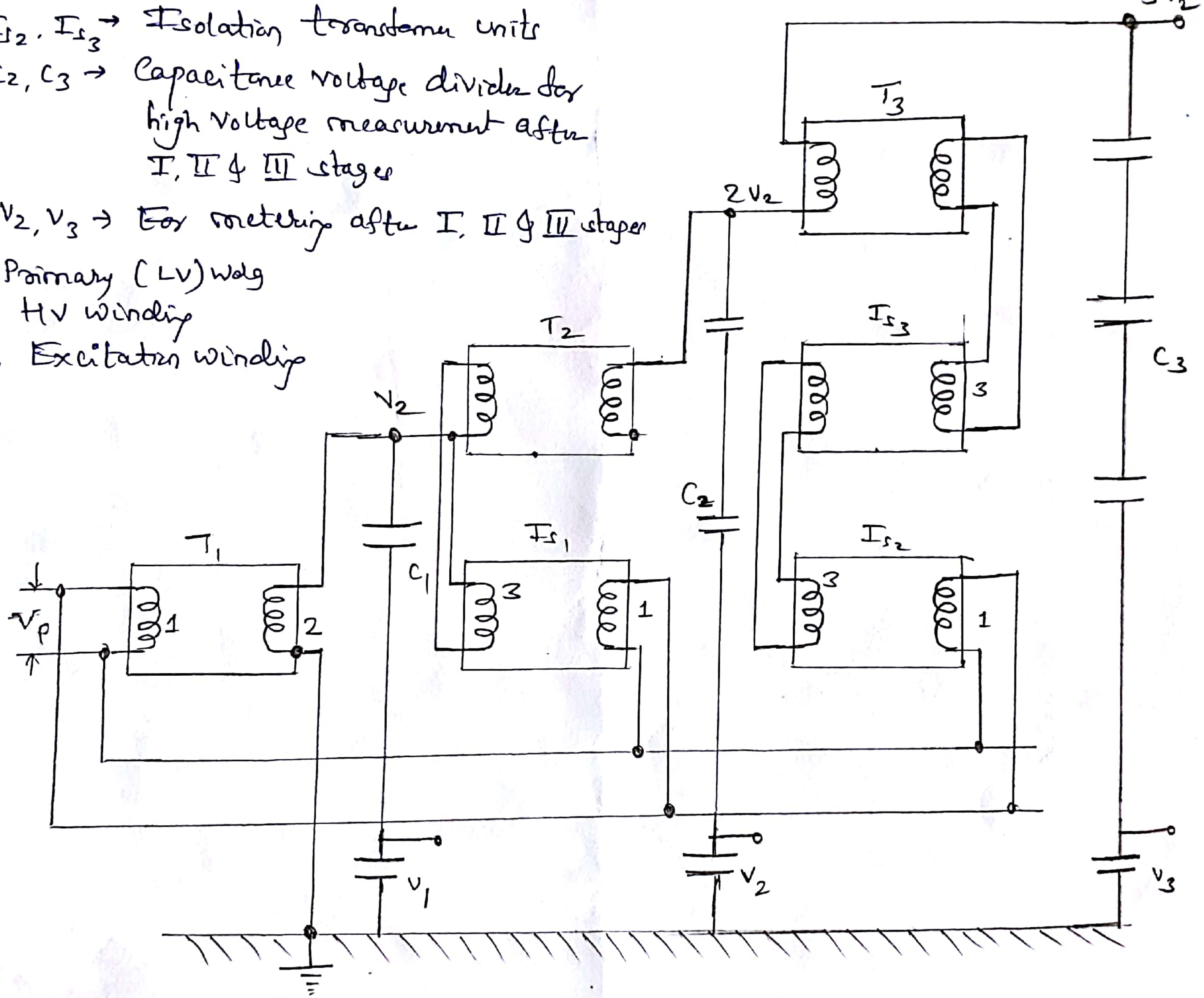


Fig ③ Cascade transformer Unit with Isolating transformers for excitation

Resonant Transformers

Series resonant circuit

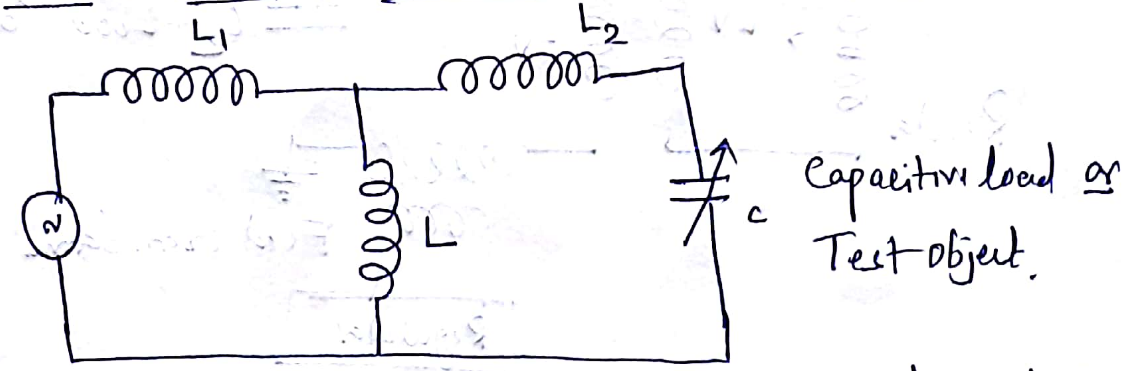


Fig ⓐ Equivalent circuit of singlestage loaded test transformer.

The equivalent circuit of a singlestage test transformer along with its capacitive load is shown in fig ⓐ Here L_1 represents the inductance of the voltage regulator and the transformer primary, L is exciting inductance of the transformer, L_2 the inductance of the transformer secondary and C the capacitance of the load.

Usually the load capacitance is variable and it is possible that for certain loading, resonance may occur in the circuit suddenly and the current will then only be limited by the resistance of the circuit and the voltage across the test specimen/object may goup as high as 20 to 40 times the desired value.

With series resonance, the resonance is controlled at fundamental frequency and hence no unwanted resonance occurs. The development of series resonance circuit for testing purpose has been very widely used in cable industry as they faced resonance problem with test transformer while testing short lengths of cables.

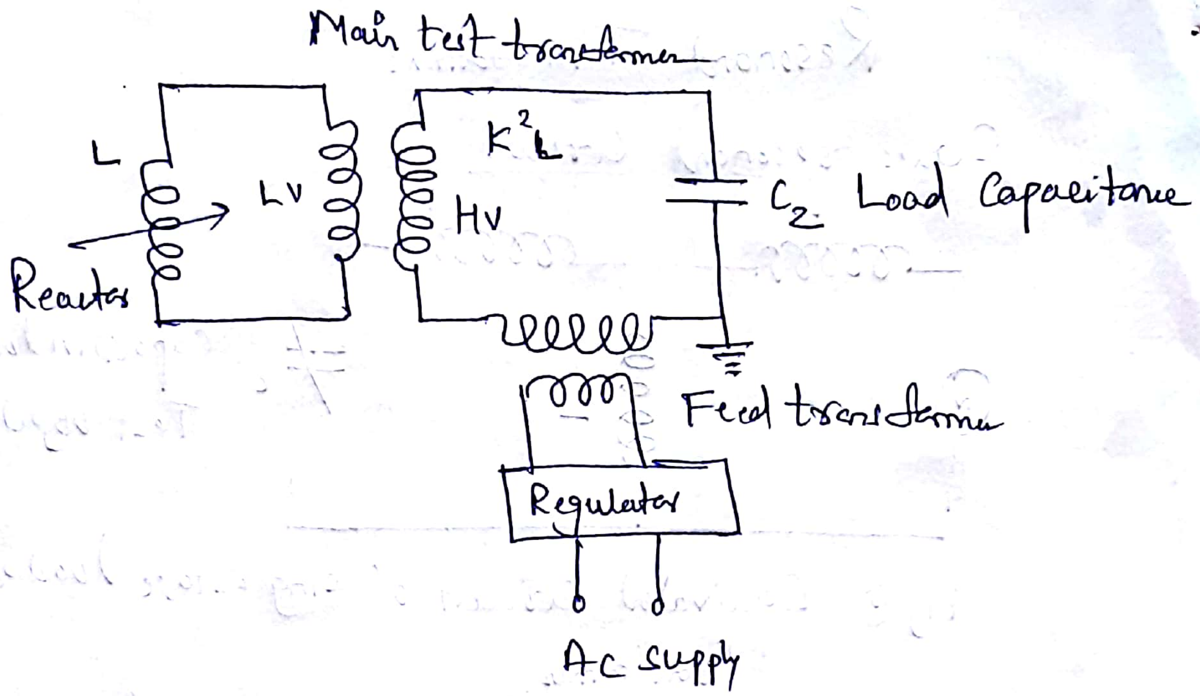


Fig ⓑ Single reactor series resonance circuit

In the initial stages, it was difficult to manufacture continuously variable high voltage and high value reactor to be used in the series circuit and therefore, indirect methods to achieve this objective were employed. Fig ⓑ shows a continuously variable reactor connected in the low voltage winding of the step up transformer whose secondary is rated for the full test voltage. C_2 represents the load capacitance.

If K is the transformation ratio and L is the inductance on the low voltage side of the transformer, then it is reflected with K^2L value on the secondary side (load side) of the transformer. For certain setting of the reactor, the inductive reactance may equal the capacitive reactance of the circuit, hence resonance will take place. Thus the reactive power requirement of the supply becomes zero and it has to supply only the losses of the circuit. However the transformer has to carry the full load current on the high voltage. This is a dis-advantage of the method. The inductors are designed for high quality factor $Q = \frac{\omega L}{R}$. The feed transformer, therefore injects the losses of the circuit.

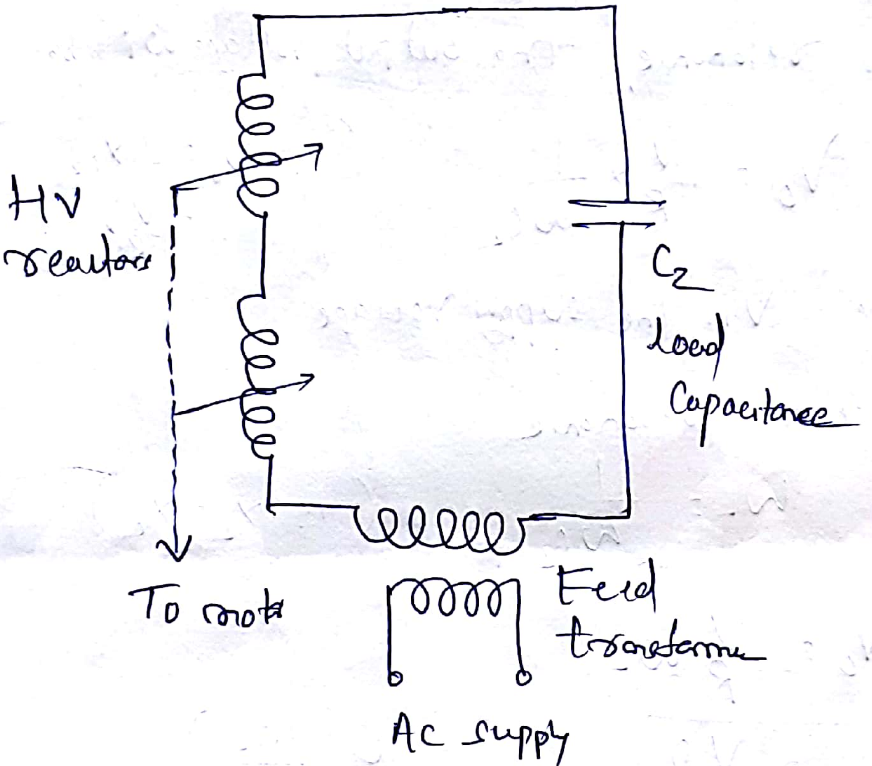


Fig ⓒ Series resonance circuit With Variable HV reactors

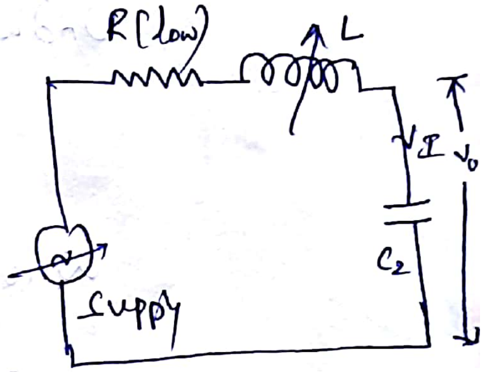


Fig ⓓ Equivalent ckt of fig ⓒ

It has now been possible to manufacture high voltage continuously variable reactors 300 kV per unit using a new technique with split iron core. With this the testing stepup transformer can be eliminated as shown in fig ⓒ. The inductance of these inductors can be varied over a wide range depending upon the capacitance of the load to produce resonance.

Fig ⓓ represents an equivalent circuit for series resonance circuit. Here 'R' is usually of low value. After the resonance condition is achieved, the o/p voltage can be increased by increasing the input voltage. The feed transformer are rated for nominal current ratings of the reactor.

Under resonance, the output voltage will be

$$V_0 = \frac{V}{R} \times \frac{1}{\omega C_2} \qquad \left(\because V_0 = I X_{C2} = \frac{V}{R} \times \frac{1}{\omega C_2}\right)$$

Where V is the supply voltage

Since at resonance

$$\omega L = \frac{1}{\omega C_2} \qquad (\text{i.e } X_L = X_C)$$

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

$$\boxed{V_0 = VQ} \qquad \left(\because Q = \frac{\omega L}{R}\right)$$

Where Q is the quality ~~factor~~ factor of the inductor which usually varies between 40 & 80. This means that with Q=40, the output voltage is 40 times the supply voltage. It also means that the reactive power requirements of the load capacitance in KVA is 40 times the power to be produced by the feed transformer in kW. This results in a relatively small power rating for the feed transformer.

Advantages of Series resonance circuit

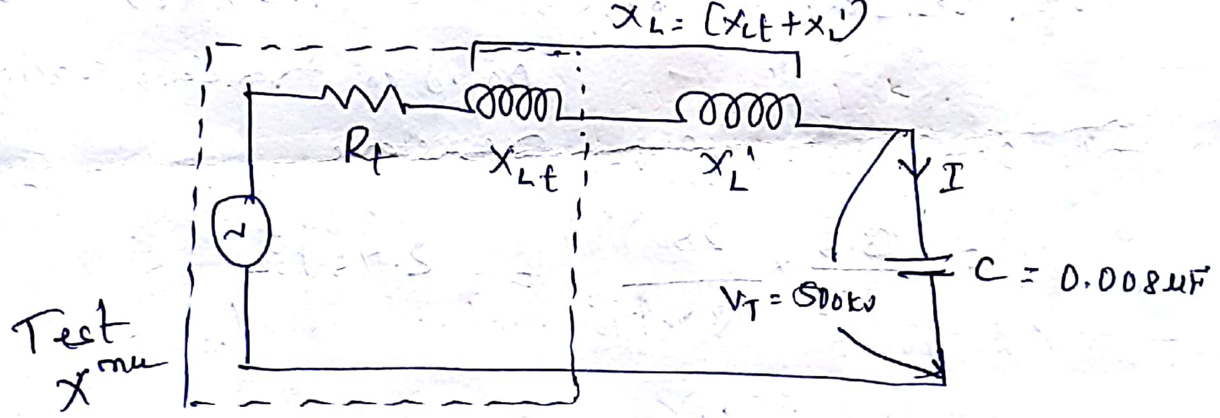
1) It gives an output of pure sine wave
2) Power requirements from the source are less (5 to 10% of total KVA required)
3) No high power arcing and heavy current surges occur if the test object fails, as resonance ceases at the failure of the test object.
4) Cascading is also possible for very high voltages
5) Simple and Compact test arrangement
6) No repeated flashovers occur in case of partial failures of the test object and insulation recovery.
7) The series resonance circuit supresses harmonics and interference to a large extent.

Disadvantages

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

Ex 1. A 250 kVA 230V|250 kV testing transformer having resistance and leakage reactance of 1.5% and 6% resp^{ly}, is to be used as resonant transformer at 50Hz to test a piece of cable at 500 kV. Neglecting the dielectric loss of the cable, determine the series inductance required if the load capacitance is 0.008 μF. What will be the input voltage and power to be fed to the transformer if the inductor coil is assumed to have 2% resistance based on the rating of the transformer? Neglect magnetizing current and core losses of the transformer.

Soln Given data Rating of test x^{mer} 250 kVA, 230V/250 kV $f = 50Hz$



At resonance $X_L = X_C$

$$(X_{Lt} + X_L') = X_C$$

Cable reactance $X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 50 \times 0.008 \times 10^{-6}}$

$$\boxed{\therefore X_C = 397.9 k\Omega}$$

Leakage reactance of the transformer

$$X_{Lt} = \frac{6}{100} \times \frac{(\text{Base kV})^2}{\text{Base MVA}} = \frac{6}{100} \times \frac{(250)^2}{250 \times 10^{-3}} = 15 k\Omega$$

referred to HT side

Since at resonance $X_L = X_C$

So an additional inductive reactance needs to be connected in series is $X_L' = X_L - X_{LT}$ $(\because X_L = X_C)$

$= 397.9 - 15$

$\boxed{X_L' = 382.9 k\Omega}$

$X_L' = 2\pi f L'$

$\therefore$ Inductance of the reacter $L' = \frac{382.9}{2\pi \times 50} = 1218.8 H$

To have a voltage of 500 kV @ the cable insulation, the secondary current required is $I = V/X_C = \frac{500\times10^3}{397.9\times10^3} = 1.25A$

So under resonance, Secondary voltage $= 1.25 \times$ Total resistance of the ckt

$(V_S = IR)$

Total resistance of the circuit $= (1.5\% + 2\%) = 3.5\%$

based on transformer rating

So, ohmic value of the resistance

$$= \frac{3.5}{100} \times \frac{(250)^2}{250\times10^{-3}} = 8.75 k\Omega$$

$\therefore$ Secondary voltage $= 1.25 \times 8.75 \times 10^3$

$V_s = 10.94 kV$

$230V : x :: 250kV : 10.94$

Primary input voltage V_p $= \frac{10.94\times10^3}{250\times10^3} \times 230 = 10.06V$

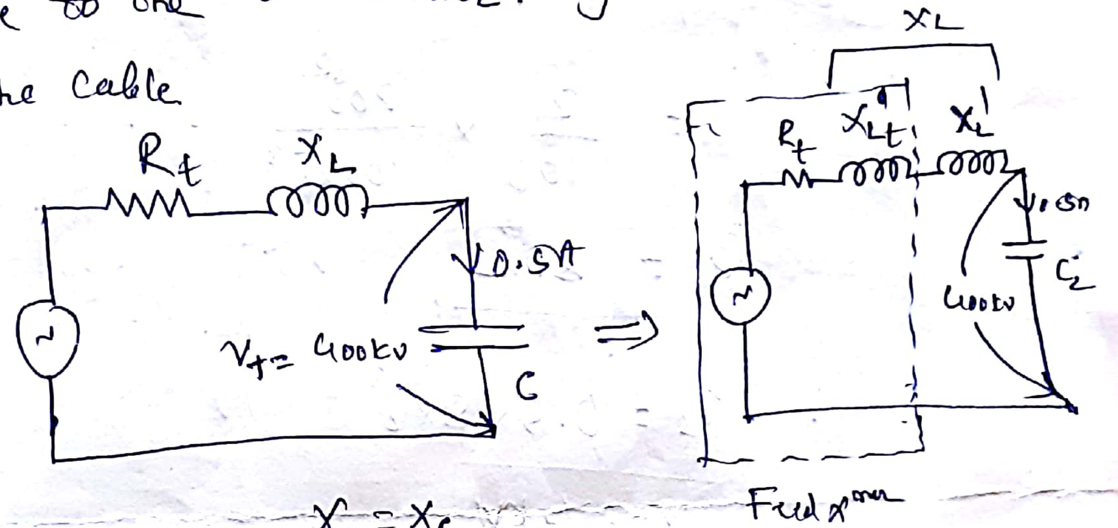
Input Power = Power dissipated in the resistance $P = I^2R$

$= (1.25)^2 \times 8.75\times10^3$

$\boxed{P_i = 13.67 kW}$

Ex 2: A 100KVA 250V | 200KV feed transformer has resistance and reactance of 1% and 5% respectively. this transformer is used to test a cable at 400KV, 50HZ. The cable takes a charging current of 0.5A at 400KV. Determine the series inductance required. Assume 1% resistance of the inductor. Also determine input voltage to the transformer. Neglect dielectric loss of the cable.

Soln



For resonance $X_L = X_C$

$$(X_{Lt} + X_L') = X_C$$

Leakage reactance of the x^mer $= \frac{5}{100} \times \frac{(200)^2}{100\times10^{-3}}$

$$\boxed{X_{Lt} = 20k\Omega}$$

V_t = Voltage @ test specimen (object)

Cable reactance $X_c = \frac{V_t}{I} = \frac{400}{0.5} = 800\,k\Omega$

So additional inductive reactance needs to be connected $X_L' = X_L - X_{Lt}$.

$= 800 - 20$ (∵ $X_L = X_c$ & $X_c = 800k\Omega$)

$$\boxed{X_L' = 780k\Omega}$$

Inductance of the reactor $L' = \frac{X_L'}{2\pi f} = \frac{780\times10^3}{2\pi\times50} = 2484H$

$X_L' = 2\pi f L'$

$$\boxed{L' = 2484}$$

Under resonance

Secondary voltage = IR

$V_s = IR$

Total resistance of the ckt = $(1\% + 1\%) = 2\%$

Based on X^{mer} rating

$$= \frac{2}{100} \times \frac{200^2}{100 \times 10^{-3}}$$

$$\boxed{R = 8k\Omega}$$

$\therefore V_s = 0.5 \times 8 \times 10^3$

$$\boxed{V_s = 4kV}$$

$\therefore$ Primary voltage $V_p = \frac{250 \times 4 \times 10^3}{200 \times 10^3}$

200kV

250v: 4kV

x:

$$\boxed{V_p = 5V}$$

Input Power $P_i = I^2 R$

$= (0.5)^2 \times 8 \times 10^3$

$$\boxed{P_i = 2kW}$$

Generation of High frequency A.C high Voltages.

[Tesla coil or High frequency resonant Transformer]

High frequency high voltages are required for rectifier d.c power supplies. Also for testing electrical apparatus for switching surges, high frequency high voltage damped oscillations are needed which need high voltage high frequency transformers.

The advantages of these high frequency transformers are

1) the absence of iron core in transformer and hence saving in cost and size
2) Pure sine wave output.
3) Slow buildup of voltage over a few cycles and hence no damage due to switching surges.
4) Uniform distribution of voltage across the winding coils due to subdivision of coil stack into a number of units.

The commonly used high frequency resonant transformer is the Tesla coil, which is a doubly tuned resonant circuit as shown in fig ⓐ

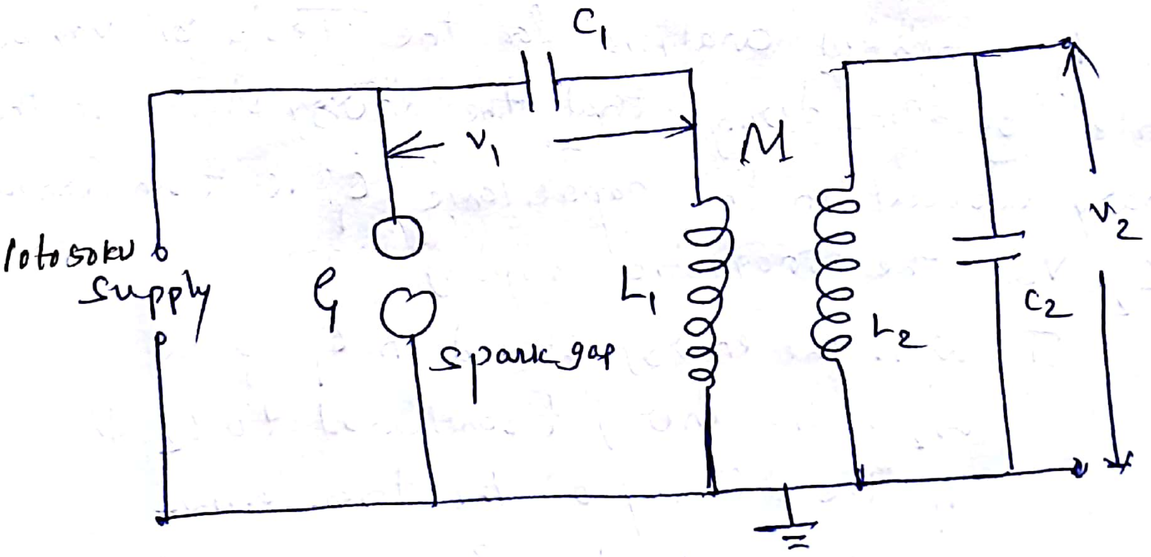


Fig ⓐ Tesla coil - Equivalent circuit.

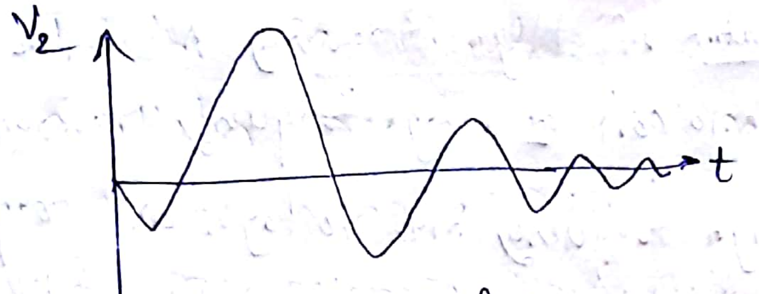


Fig ⑤ Output Waveform

The primary voltage rating is 10kV and the secondary may be rated to as high as 500 to 1000 kV. the primary is fed from a dc or AC supply, through the condenser C_1. A sparkgap 'G' connected across the primary is triggered at the desired voltage V_1 which induces a high self-excitation in the secondary. The primary and secondary windings (L_1+L_2) are wound on an insulated former with no core (air-cored) and are immersed in oil. The windings are tuned to a frequency of 10 to 100 kHz by means of the condensers C_1 and C_2.

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

A simplified analysis for the Tesla coil may be presented by considering that the energy stored in the primary circuit in the capacitance C_1 is transferred to C_2 via the magnetic coupling.

If W_1 is the energy stored in C_1 &
W_2 is the energy transferred to C_2 &
'η' the efficiency of the transformer

Then $W_1 = \frac{1}{2}\eta C_1 V_1^2 = \frac{1}{2} C_2 V_2^2$ for which

$$V_2 = V_1\sqrt{\eta\, C_1/C_2}$$

If the co-efficient of coupling 'K' is large the oscillation frequency is less, and for large values of the winding resistances and 'K', the waveform may become a unidirectional impulse.

Module 2 Generation of High DC voltages

Generation of high dc voltages is mainly required in research work in the areas of applied physics. Sometimes, high direct voltages are needed in insulation tests on cables and capacitors. Normally, for the generation of d.c voltages upto 100kV, rectifiers are used.

Voltage Doubler Circuits :

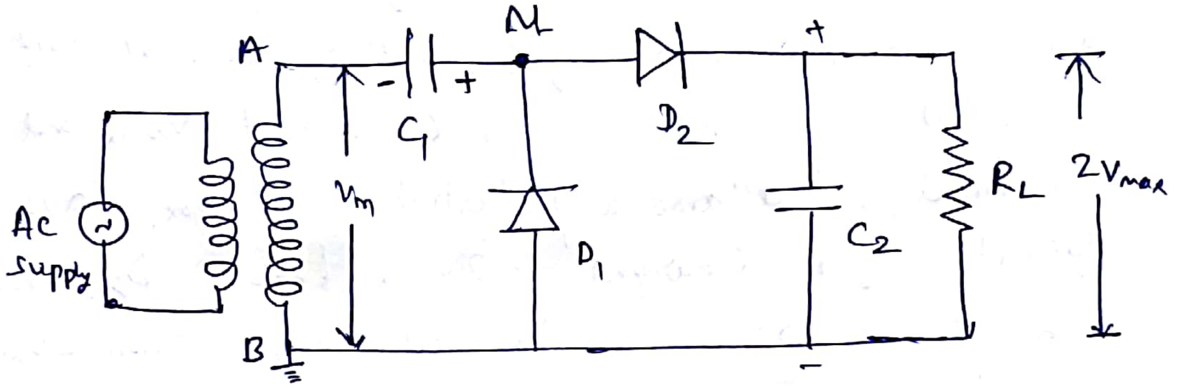


Fig ⓐ Greinacher voltage doubler circuit.

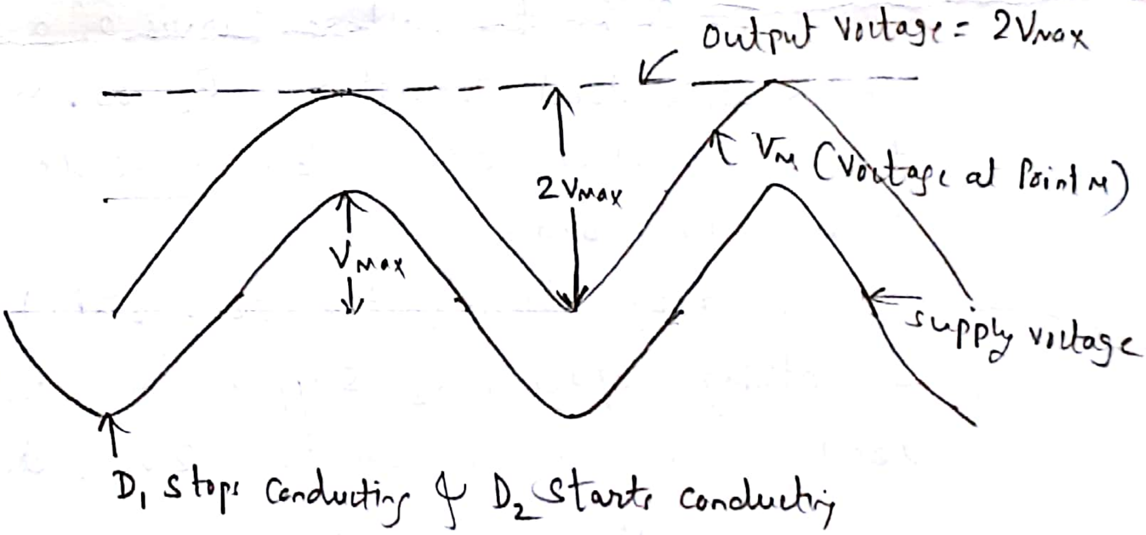
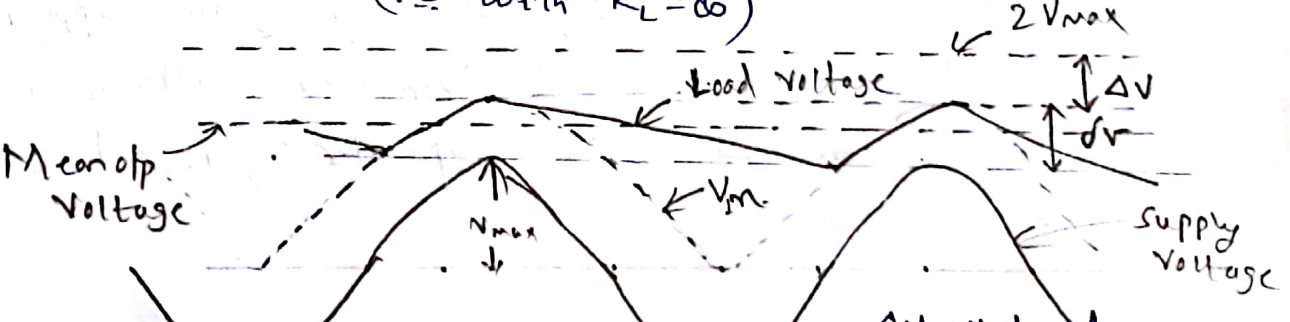


Fig ⓑ Voltage curve of the doubler circuit under no-load (i.e with $R_L = \infty$)



$\Delta V \rightarrow$ Voltage drop
$\delta V \rightarrow$ Magnitude of ripple Voltage

Fig ⓒ Voltage curves for a loaded voltage doubler circuit

Both fullwave and halfwave rectifier circuits produce a dc voltage less than the Ac maximum voltage. When higher d.c voltages are needed a voltage doubler or cascaded rectifier double circuits are used. One of the most popular double circuit due to Greinacher is shown in fig ⓐ

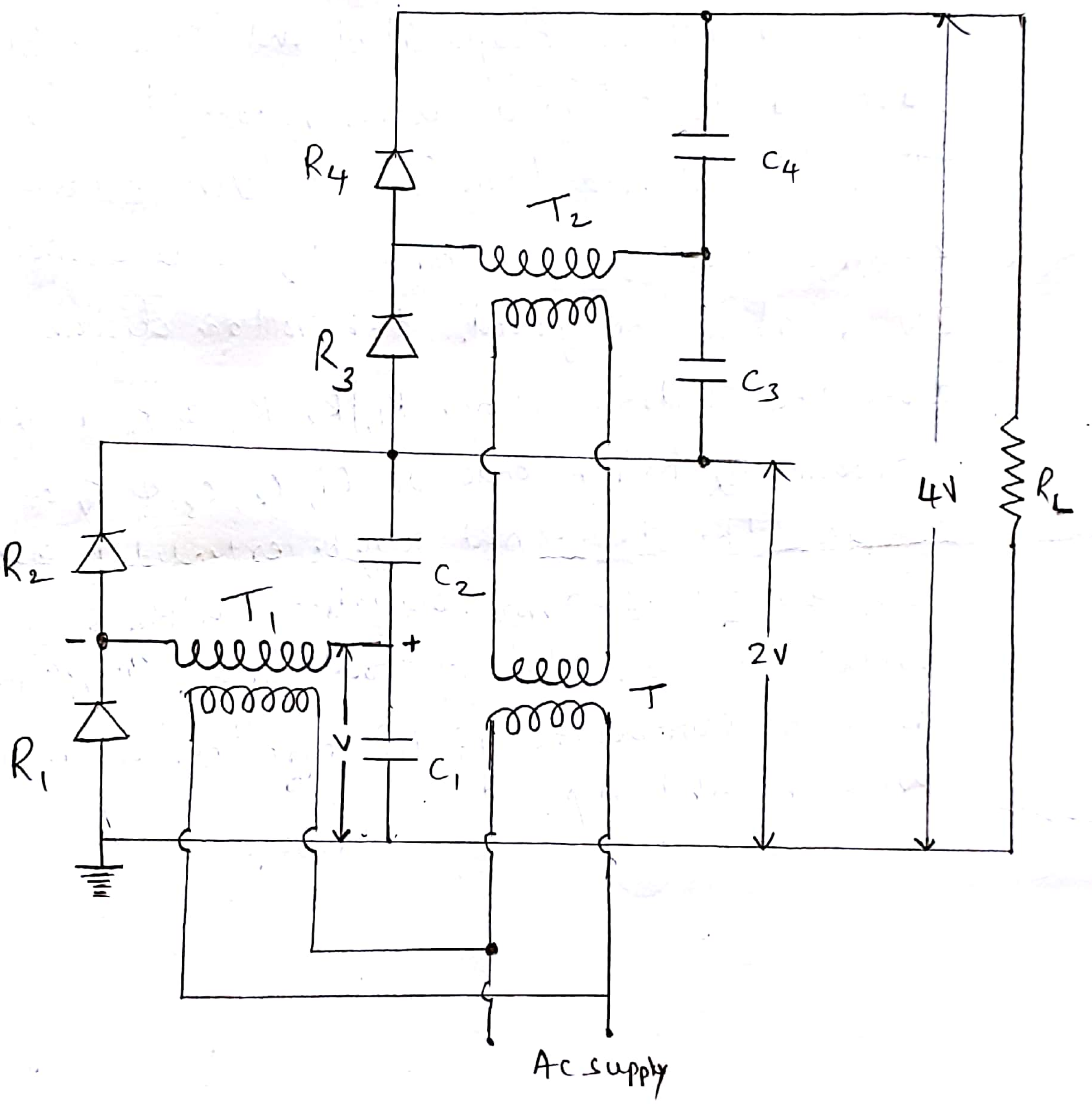
Suppose 'B' is more positive with respect to 'A' and the diode D_1 conducts thus charging the capacitor C_1 to Vmax with polarity as shown in fig ⓐ. During the next half cycle terminal 'A' of the capacitor C_1 rises to Vmax and hence terminal 'M' attains a potential of 2Vmax. Thus, the capacitor C_2 is charged to 2Vmax through D_2. Normally the voltage across the load will be less than 2Vmax depending upon the time constant of the circuit C_2R_L

In fig ⓑ the voltage curves of a doubler circuit shown with load resistance $R_L = \infty$, when $R_L \neq \infty$, the mean output voltage Vout will be less than 2Vmax due to two reasons

Firstly, during the non-conduction period the smoothing capacitor C_2 supplies the load current and the load voltage will be less than 2Vmax due to ripple.

Secondly, during each cycle the capacitor C_1 restores the charges lost by C_2 in supplying the load as a result of which Vm never attains a potential of 2Vmax and so the capacitor C_2 is not charged to 2Vmax at all.

Cascaded Voltage Doubler



T_1, T_2 → High voltage Transformers

R_1, R_2, R_3, R_4 → Rectifiers

C_1, C_2, C_3, C_4 → Capacitors

R_L → Load resistance

T → Isolating transformer

Cascaded voltage doublers are used when larger output voltages are needed without changing the input transformer voltage level.

The rectifier R_1 & R_2 with transformer T_1 & Condensers C_1 & C_2 produce an output voltage of 2V. This circuit is duplicated and connected in series or cascaded to obtain a further voltage doubling to 4V. T' is an isolating transformer to give an insulation for $2V_{max}$ since the transformer T_2 is at a potential of $2V_{max}$ above the ground. The voltage distribution along the rectifier string R_1, R_2, R_3 & R_4 is made uniform by having Condensers C_1, C_2, C_3 & C_4 of equal values. The arrangement may be extended to give 6V, 8V and so on by repeating further stages. With suitable isolating transformers. The arrangement becomes cumbersome If the more than 4V is needed with cascaded steps.

Cock croft - Walton Voltage Multiplier

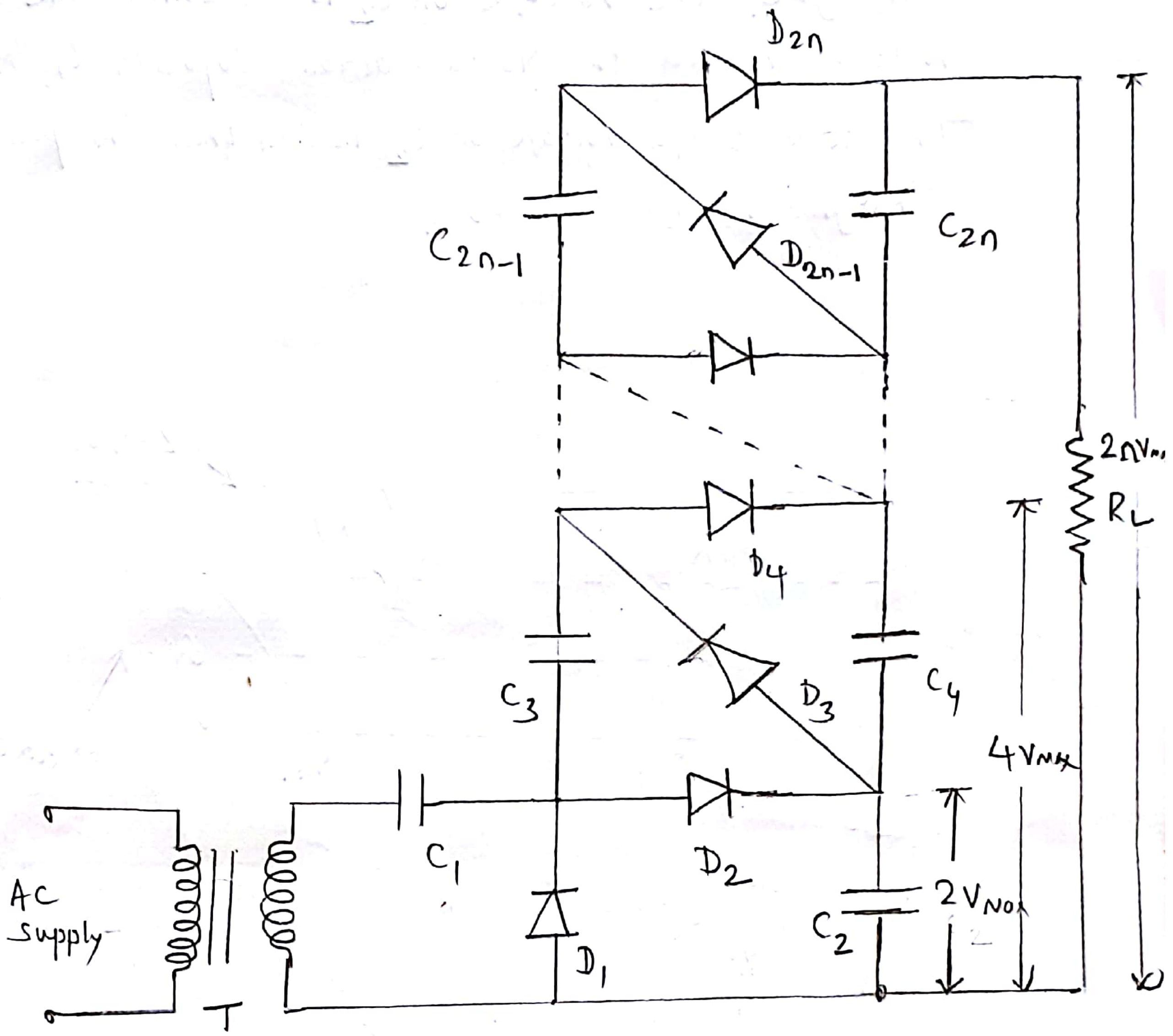


Fig ⓐ Cock croft - Walton Voltage multiplier.

Voltage multiplier circuit using the Crockcroft-Walton principle is shown in fig ⓐ. The first stage i.e D_1, D_2, C_1, C_2 and the transformer 'T' are identical as in the voltage doubler. For higher output voltage of 4, 6, --- 2n of the input voltage 'V', the circuit is repeated with cascade or series connection. Thus, the capacitor C_4 is charged to $4V_{max}$ and C_{2n} to $2nV_{max}$ above the earth potential. But the voltage across any individual capacitor or rectifier is only $2V_{max}$. The rectifiers D_1, D_3 --- D_{2n-1} shown in fig ⓐ operate and conduct during the negative half cycles while rectifiers D_2, D_4 --- D_{2n} Conduct during the positive half cycles. The voltage on C_2 is the sum of the input Ac voltage, Vac and the voltage across capacitor C_1, V_{C1}.

The mean output voltage on C_2 is less than the positive peak charging voltage ($V_{ac} + V_{C1}$).

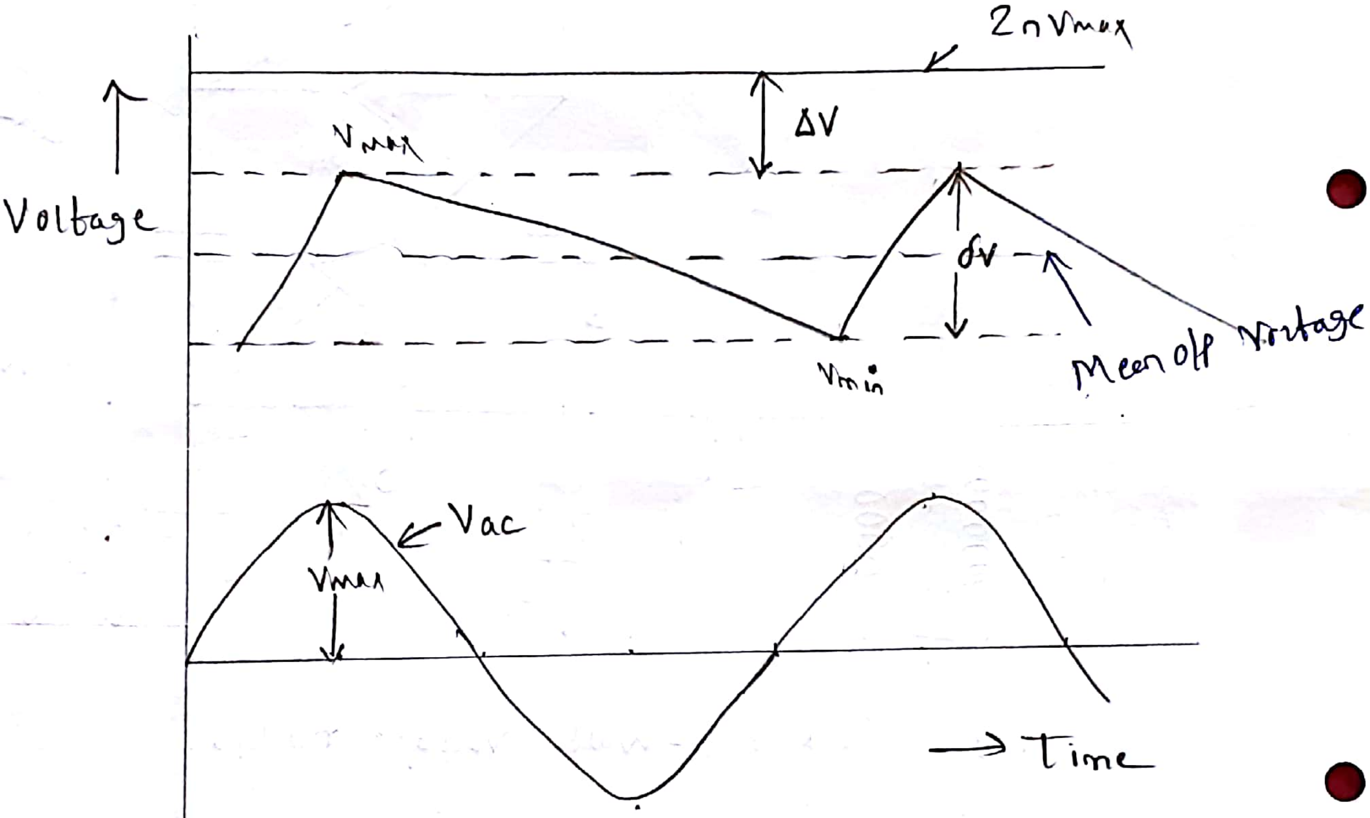


Fig ⓑ Ripple voltage 'δV' and the Voltage drop 'ΔV' in a Cockcroft-walton Voltage Multiplier circuit.

Expression for ripple voltage in multiplier circuit (δV)

With load, the output voltage of the multiplier circuit is less than $2nV_{max}$ where 'n' is the number of stages.

Let f = supply frequency
q = charge transferred in each cycle
I_1 = Load current from rectifier
t_1 = Conduction period of rectifiers
t_2 = Non-conduction period of rectifiers &
δV = Ripple voltage (Peak to Peak)

Referring to voltage doubler circuit, when load current I_1 supplied from condenser C_2 to load R_L during the non-conducting period, the charge transferred per cycle from the condenser C_2 to the load during the non-conduction period t_2 is 'q' and related as

$$I_1 = \frac{dq}{dt} = \frac{q}{t_2} \quad \boxed{q = I_1 t_2} \rightarrow ① \quad \text{since } t_1 << t_2 \ \& \ t_1 + t_2 = \frac{1}{f}$$

$$\therefore t_2 = \frac{1}{f}$$

Also $q = C_2 \delta V$ — ② Equating eqs ① & ②

$$I_1 t_2 = C_2 \delta V$$

Hence ripple $\delta V = \frac{I_1 t_2}{C_2} = \frac{I_1}{f C_2}$

At the same time a charge 'q' is transferred from C_1 to C_2 during each cycle equal to $I_1 / f C_2$

Thus the total voltage drop that occurs $= \frac{I_1}{fC_1} + \frac{2I_1}{fC_2}$

Hence Regulation = Mean voltage drop from $2V_{max}$

$$= \frac{I_1}{f}\left[\frac{1}{C_1} + \frac{2}{C_2}\right] \quad — ③$$

∴ The mean output voltage $= 2V_{max} - \frac{I_1}{f}\left[\frac{1}{C_1} + \frac{2}{C_2}\right]$ —④

For the multiplier circuit, on <u>no load</u>, the voltages between stages are raised by $2V_{max}$ giving an output voltage of $2nV_{max}$ for 'n' stages.

Referring to CWVM circuit, to find an expression for the total ripple voltage, assume that all capacitors C_1, C_2 --- C_{2n} be equal to C. Let 'q' be the charge transferred from C_{2n} to the load per cycle.

Then the ripple at the capacitor <u>C_{2n}</u> will be I_1/fc

Simultaneously, C_{2n-2} transfers a charge q to the load & to C_{2n-1}. Hence, the ripple at the capacitor <u>C_{2n-2}</u> is $\frac{2I_1}{fc}$

Similarly, C_{2n-4} transfers a charge q to the load, to C_{2n-3} & to C_{2n-2}. Therefore, the ripple at capacitor C_{2n-4} is $\frac{3I_1}{fc}$

Proceeding in the same way, the ripple at C_2 will be $\frac{nI_1}{fc}$

Hence for 'n' stages the total ripple (Peak to Peak) will be

$$\delta V_{total} = \frac{I_1}{fc}\left[1+2+3+ --- +n\right] = \frac{I_1}{fc}\,\frac{n(n+1)}{2} \quad -⑤$$

and the average ripple $= \frac{\delta V_{total}}{2} = \frac{I_1\, n(n+1)}{4fc}$ —⑥

The major contribution to the ripple is from the lowest or ground end capacitors, C_1, C_2, C_3, C_4 etc. Ripple can be reduced if the capacitance of these capacitors is increased proportionately i.e C_1, C_2 are made nC, C_3, C_4 are made (n-1)c and so on so that the total ripple will be equal to $\frac{nI_1}{fc}$.

<u>Note</u>: 'n' capacitors here mean n/2 stages only since two capacitors from each stage or a doubler unit.

Regulation or voltage drop on load

In addition to the ripple δV there is a voltage drop ΔV, which is the difference between the theoretical noload and the on load voltage

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

Expression for optimum number of stages for maximum o/p voltage for a given load current, supply frequency and input voltage

For an n-stage voltage multiplier circuit, the voltage drop

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

Assuming that the capacitor $C_1 = 2C$ as this capacitor has to withstand half the voltage across any other capacitor, ΔV decreases by an amount $\frac{n^2 I}{2fc}$

$$\text{so } \Delta V = \frac{I}{fc}\left[\frac{2}{3}n^3 - \frac{n}{6}\right]$$

Moreover assuming $n > 4$, $\frac{n}{6}$ will be much smaller than $\frac{2n^3}{3}$ and hence may be neglected. With these two assumptions

$$\Delta V \simeq \frac{I}{fc} \cdot \frac{2n^3}{3}$$

Therefore output voltage $V_0 \simeq 2nV_{max} - \Delta V$

$$\simeq 2nV_{max} - \frac{I}{fc}\frac{2}{3}n^3$$

For Maximum V_0, $\frac{dV_0}{dn} = 0$

$$\frac{dV_0}{dn} = 2V_{max} - \frac{I}{fc}\frac{2}{\cancel{3}} \times \cancel{3}n^2$$

$$\frac{dV_0}{dn} = 2V_{max} - \frac{2I}{fc}n^2$$

$$\cancel{2}V_{max} = \frac{\cancel{2}I}{fc}n^2 \quad \therefore n_{optimum} = \sqrt{\frac{V_{max}fc}{I}}$$

Provided i) $C_1 = 2C$ ii) $n > 4$.

Ex: A Cockcroft - Walton type voltage multiplier has eight stages with capacitances, all equal to 0.05 μF. the supply transformer

July 2015. Secondary voltage is 125 kV at a frequency of 150 HZ. If the

Jan 2016 load current to be supplied is 5mA find a) the percentage ripple b) the regulation c) the optimum No. of stages for minimum regulation or voltage drop.

Soln a) Calculation of percentage ripple :

$I = 5mA, \; f = 150 HZ$

$C = 0.05 \mu F$

No. of stages = 8.

The ripple voltage $\delta v = \frac{I}{fc} \frac{n(n+1)}{2}$

Here $n = 16$ (No. of Capacitors)

$$\therefore \delta v = \frac{5 \times 10^{-3}}{150 \times 0.03 \times 10^{-6}} \times \frac{16 \times 17}{2} = 90.7 kV$$

$$\% \text{ ripple} = \frac{\delta v}{2n V_{max}} \times 100 = \frac{90.7 \times 100}{2 \times 125 \times 8} = 4.53\%$$

b) Calculation of Regulation :

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

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

$$\Delta V = 248 kV$$

$$\% \text{ regulation} \left[\frac{\Delta V}{2n V_{max}}\right] \times 100 \quad \frac{248}{2 \times 8 \times 125} = 12.4\%$$

c) Calculation of optimum Number of stages

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

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

$$= 13.69$$

$$N_{optimum} \simeq 14 \text{ stages}$$

Ex: Determine the ripple voltage and regulation of a 10 stage Cockcroft - Walton type dc voltage multiplier circuit having a stage capacitance = 0.01 μF, supply voltage = 100 kV at a frequency of 400 Hz and a load current = 10 mA. 18.

Soln: Calculation of Percentage ripple

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

stage capacitance (C_1+C_2)

Given $I = 10mA$ $f = 400 Hz$ $C = 0.01\mu F$ No. of stages = 10

Here $n = 10$

$$\therefore \delta V = \frac{10 \times 10^{-3}}{400 \times 0.01 \times 10^{-6}} \times \frac{10(10+1)}{2} = 137.5 KV$$

$$\% \text{ ripple} = \frac{\delta V}{2nV_{max}} \times 100 = \frac{137.5}{2 \times 10 \times 100} \times 100 = 6.875\%$$

Calculation of Regulation:

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

$$= \frac{10 \times 10^{-3}}{400 \times 0.01 \times 10^{-6}}\left[\frac{2}{3}10^3 + \frac{10^2}{2} - \frac{10}{6}\right]$$

$$= 715 KV$$

$$\% \text{ regulation} \left[\frac{V}{2nV_{max}} \times 100\right] = \frac{715}{2 \times 10 \times 100} \times 100$$

$$\% \text{ regn} = 35.75\%$$

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~~Unit-II~~ Module-2

Generation of Impulse Voltages

Electrical transmission and distribution systems are subjected to transient overvoltages, amplitudes of which may exceed the peak value of the normal system voltage by a large amount. These transient overvoltages are due to two reasons i) lightning strokes ii) switching.

Overvoltages due to lightning are called external overvoltages and are independent of system voltages. Switching overvoltages are internal overvoltages caused by switching operations of circuit breakers and are always related to system operating voltage.

Definition of Impulse voltage

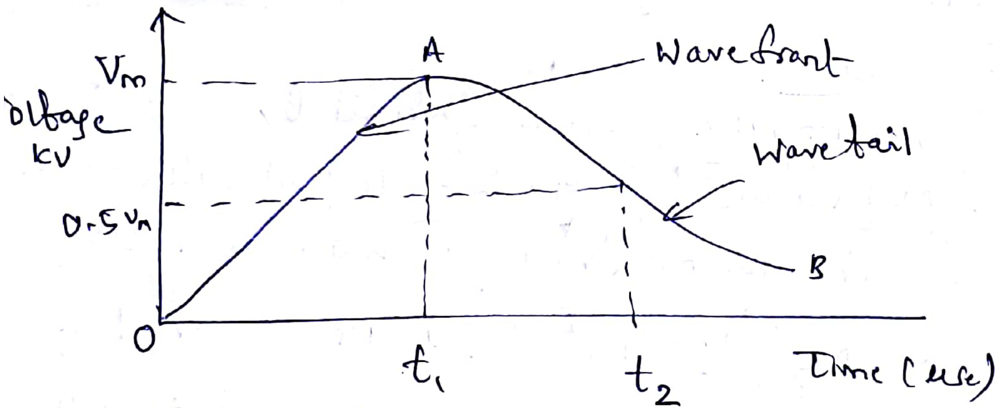


Fig ⓐ. An impulse voltage wave shape

An impulse voltage is unidirectional voltage which rises more or less rapidly to a maximum value without appreciable oscillations and then decays slowly to zero. The maximum value of the impulse voltage is called the peak value of the impulse and the impulse voltage is specified by this value. In fig ⓐ, the waveshape of an impulse voltage is shown. The curve OAB in this figure represents the voltage-time characteristic of a typical curve

i) **Wave front** :

The wavefront of a impulse voltage is the rising portion of the voltage-time characteristic (Portion OA in fig (a)). The duration of the wavefront is the total time occupied by the impulse voltage while rising from zero to peak value. This time is known as time to peak value and denoted by t_1 expressed in microseconds.

ii) **Wave tail** :

The wavetail of an impulse voltage is the falling portion of the voltage-time characteristic (Portion AB in fig (a)). The time to half-value of the wave-tail of an impulse voltage is the total time occupied by the impulse voltage in rising to peak value and falling therefrom to half the peak value of the impulse. This is denoted by t_2 expressed in microseconds.

iii) **Specification** :

An impulse wave is specified by

i) its peak value ii) the time to peak value in μsec & iii) the time to half peak value on wavetail in μsec.

For example 1000 kV 1/50 μs impulse voltage has a peak value of 1000 kV which is attained in 1 μseconds and 500 kV on the wave-tail is reached after 50 μseconds.

iv) **Standard impulse** waveshapes

For lightning impulses the standard waveshapes are

a) 1.2/50 μs (Indian Standard) $t_1 = 1.2\mu s \pm 30\%$, $t_2 = 50\mu s \pm 20\%$

b) 1/50 μs (British ")

c) 1.5/40 μs (American ")

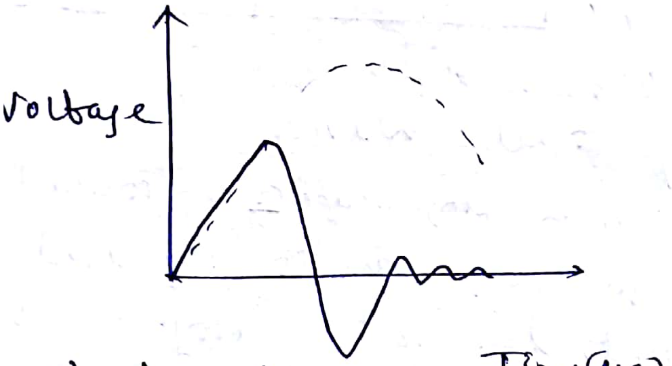
For switching impulses

$t_1 = 250\mu s \pm 20\%$, $t_2 = 2500\mu s \pm 60\%$.

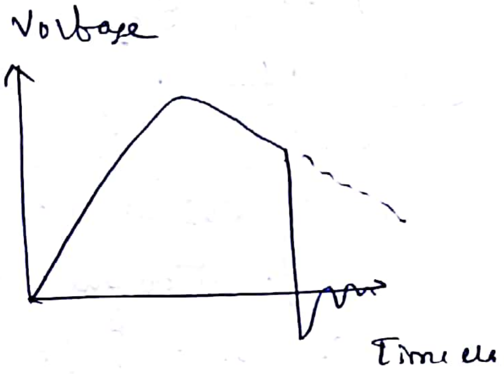
Switching impulse:

A switching overvoltage is a short-duration transient voltage produced in electric transmission and distribution systems due to sudden opening or closing of circuit breakers or a switch or due to arcing in a fault.

Chopped Impulse waves



i) chopped on wave front



ii) Chopped on wave-tail

If an impulse voltage develops without causing flashover or puncture of an insulating medium, it is called a full impulse voltage; if flashover or puncture occurs, thus causing a ~~[illegible]~~ sudden collapse of the impulse voltage, it is called a chopped impulse voltage. Chopping may take place either on the wavefront or on the wave tail.

ngle Stage Impulse generator

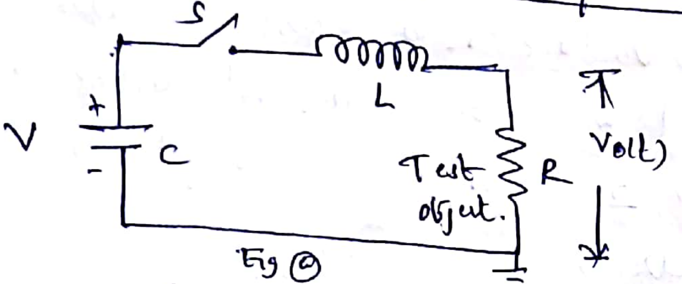


Fig ⓐ

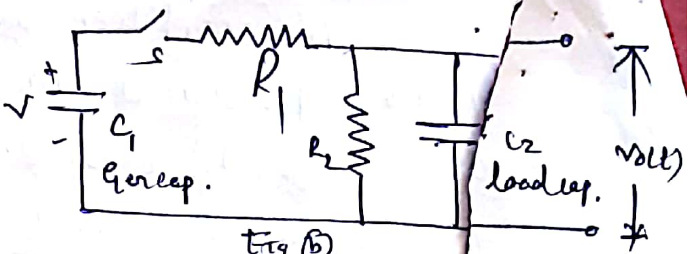


Fig ⓑ

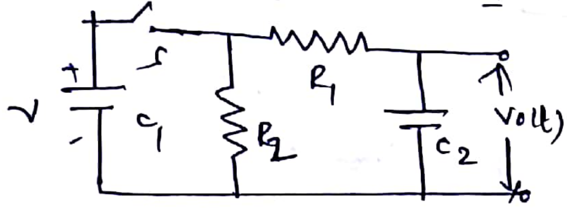


Fig ⓒ

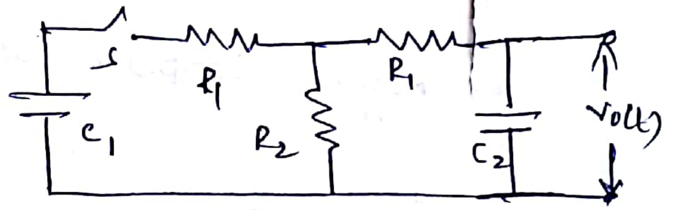


Fig ⓓ

Fig ①. Circuits for producing impulse waves.

Impulse generator can be singlestage or of multistage construction. The single-stage circuits are mainly used for the generation of relatively low-voltage impulses required for testing of dielectric sheets or non-linear resistance discs for surge diverters.

$\alpha \Rightarrow$ wave tail time

$\beta \Rightarrow$ wave front time

A double exponential waveform of the type $V = V_0 \left[e^{(-\alpha t)} - e^{(\beta t)} \right]$ may be produced in the laboratory with a combination of a series R-L-C circuit under over damped conditions or by the combination of two R-C circuits. Different equivalent circuits that produce impulse wave are given in figs ⓐ to ⓓ. out of these circuits, circuit shown in fig ⓐ is limited to model generators only and commercial generator employ circuits shown in figs ⓑ to ⓓ.

A capacitor (C_1 or C) charged to a particular d-c voltage is suddenly discharged into the waveshaping network (L-R or $R_1 R_2 C_2$ or other combination) by closing the switch S. The discharge voltage $V(t)$ gives the desired double exponential waveshape.

Fig.1 ⓐ, nalysis of Impulse generator circuit of series R-L-C type

The wave front and the wavetail times are controlled by changing the values of R & L simultaneously with a given generator capacitance C; choosing a suitable value for L, β or the wave-front time is determined and α or the wave-tail time is controlled by the value of R in the circuit.

The advantage of this circuit is its simplicity. But the waveshape control is not flexible and independent. Another disadvantage is that the basic circuit is altered when a test object which will be mainly capacitive in nature is connected across the output. Hence, the waveshape gets changed with the change of test object.

Other Impulse generator circuits :

The most commonly used configuration for impulse generators are the circuits shown in figs ⓑ & ⓒ. The advantages of these circuits are that the wavefront and wavetail times are independently controlled by changing either R_1 or R_2 seperately. Secondly, the test objects which are mainly capacitive in nature form part of C_2.

The equivalent circuit given in fig ⓓ is a combination of the configurations of fig ⓑ & ⓒ. The resistance R_1 is made into two parts and kept on either side of R_2 to give greater flexibility for the circuit.

Waveshape control

Generally for a given impulse generator of fig ⓑ or ⓒ the generator capacitance C_1 & load capacitance C_2 will be fixed depending on the design of the generator and the test object. Here the desired waveshape is obtained by controlling R_1 & R_2.

The following approximate formulae used to calculate the wavefront and wavetail times.

Wavefront time → $t_1 = 3 R_1 \frac{C_1 C_2}{C_1 + C_2} = 3 R_1 C_e$

C_1 charges the load capacitance C_2. The time taken for charging is approximately three times the time constants of the circuit

If R_1 is in ohms & C_e in microfarads then t_1 is obtained in microseconds.

wave tail time $t_2 = 0.7 (R_1 + R_2) (C_1 + C_2)$

With the approximate formulae, the wavefront & wave tail times can be estimated to within ± 20%. for the standard impulse waves.

Multistage Impulse Generator – Marx Circuit

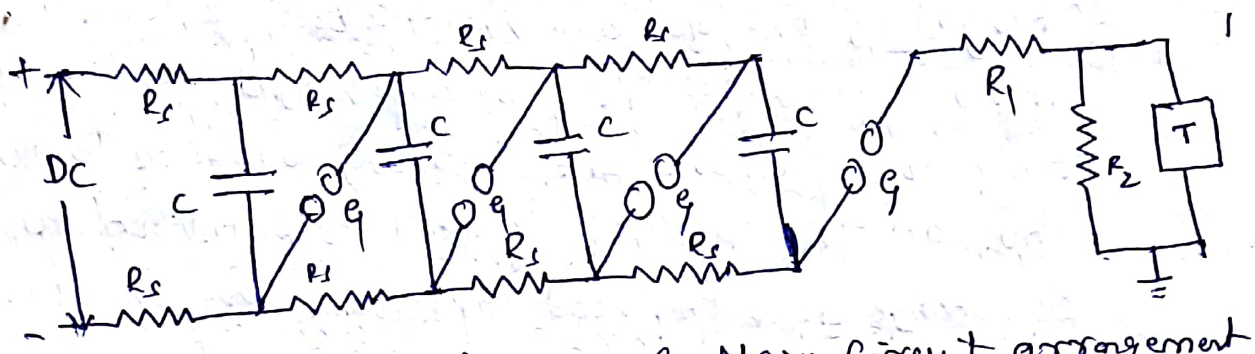


Fig ⓐ schematic diagram of Marx-Circuit arrangement for multistage impulse generator.

C - Capacitance of the generator R_s - Charging resistors

G - Sparkgap R_1, R_2 - Waveshaping resistors

T - Test object.

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

The schematic diagram of Marx circuit is as shown in fig ⓐ. Usually the charging resistance R_s is chosen to limit the charging current to about 50 to 100mA, and the generator capacitance 'C' is chosen such that the product CR_s is about 10s to 1 min. The gap spacing is chosen such that the breakdown voltage of the gap 'G' is greater than the charging voltage 'V'. Thus, all the capacitances are charged to the voltage 'V' in about 1 minute. When the impulse generator is to be discharged, the gaps 'G' are made to sparkover simultaneously by some external means. Thus all the capacitors 'C' get connected in series and discharge into the load capacitance or the test object. The discharge time constant CR_1/n (for n stages) will be very small (μsec), compared to the charging time constant CR_s which will be few seconds. Hence, no discharge takesplace through the charging ~~capacitors~~ resistors R_s.

Modified Marx Circuit :

In the Marx circuit of fig ⓐ, the impulse wave shaping circuit is connected externally to the capacitor unit. In Fig ⓑ, the modified Marx circuit is shown, wherein the resistances R_1 & R_2 are incorporated inside the unit. R_1 is divided into 'n' parts equal to R_1/n and put in series with the gap 'G'. R_2 is also divided into 'n' parts and arranged across each capacitor unit after the gap 'G'. This arrangement saves space and also the cost is reduced. But, in case the waveshape is to be varied widely, the variation becomes difficult. The additional advantages gained by distributing R_1 and R_2 inside the unit are that the control resistors are smaller in size and the efficiency (V_0/nV) is high.

Modified Marx Circuit :

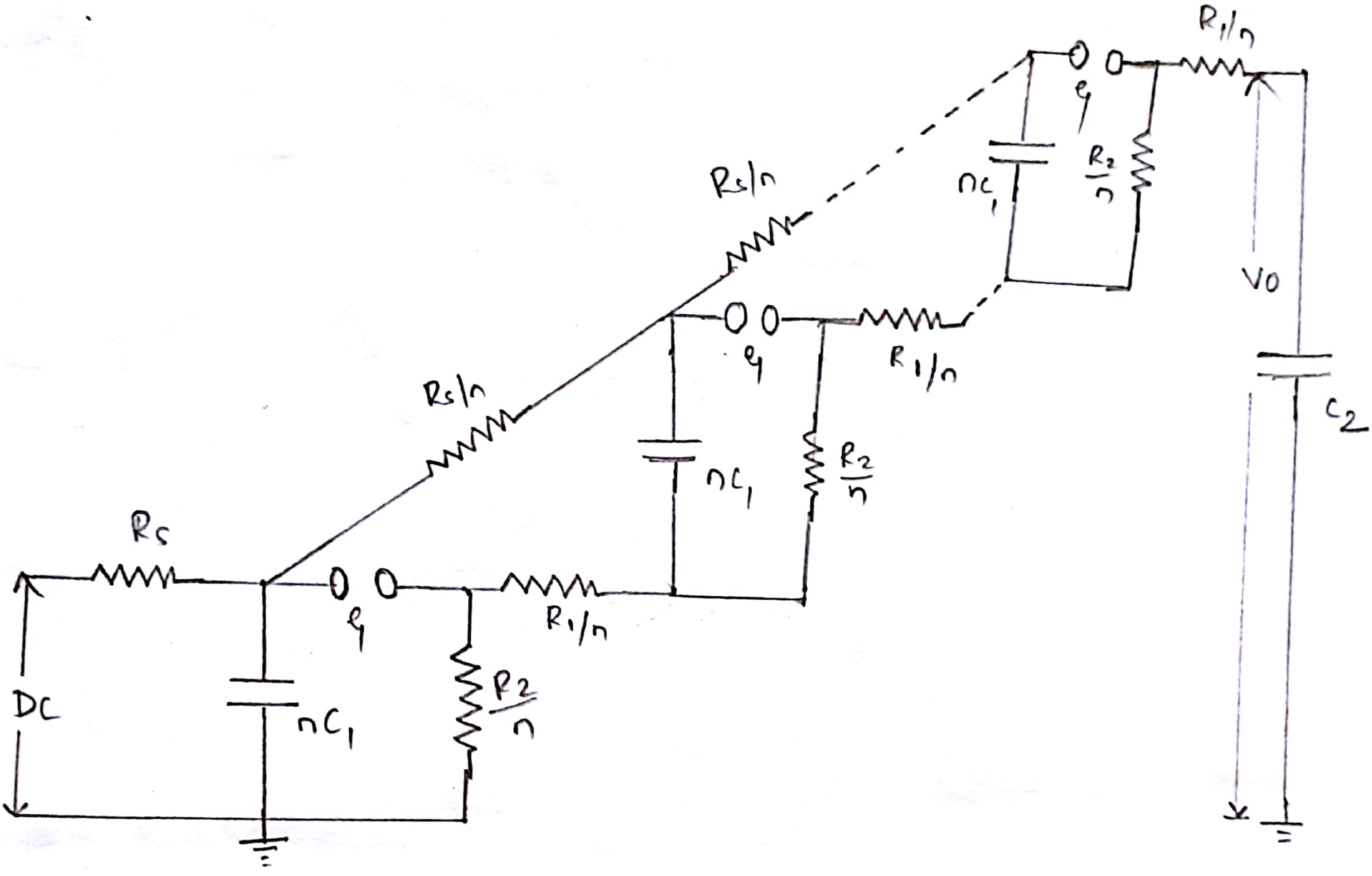


Fig ⓑ Multistage impulse generator incorporating the series and wave tail resistances within the generator

Components of Multistage Impulse Generator

A Multistage impulse Generator requires several Components for flexibility and for the production of the desired waveshape. These may be grouped as follows

1) D.C Charging set. → Capable of giving a variable DC voltage of either polarity to charge the generator capacitors to the req. value

2) Charging resisters → Non-inductive high value resistors of about 10 to 100 KΩ. Each resistor will be designed to have a 50 to 100 KV Max. voltage

3) Generator Capacitors → Designed for several charging & discharging operations.
On dead short circuit, the cap. will be capable of giving 10 KA of current

4) Spark Gaps → Spheres or hemispheres of 10 to 25 cm diameter. Sometime spherical ended cylinders with a central support may be used

5) Wave shaping resisters & Capacitors →
Non-inductive wound type
Capable of discharging impulse current of 1000 A or more
50 to 100 KV maximum operating voltage
Capacitor may be of Compressed gas or Oil filled with 1 to 10 μF Capacitance

6) Voltage divider -

Capacitor or resistor type and an CRO with recording arrangement for measurement of the voltage @ the test object.

Spheregap for calibration purposes

7) Triggering system

Trigger sparkgap to cause spark breakdown

The height of a 4.8 MV unit may be around 30m

To ~~Make~~ make unit compact, a compressed gas such as N_2 or SF_6 may be used as the insulation

Impulse generators are needed to generate very fast transients having time duration of 0.5/5 or 0.1/1 us waves for testing Gas insulated Systems (GIS), that are coming up nowadays. The energy needed for testing of this type of equipment is small (less than 30KJ) and the load capacitance is usually less than 500pF.

Rating of Impulse Generators

Impulse generators are rated by

i) the number of stages

ii) the nominal o/p voltages &

iii) the gross energy stored (in charging capacitance C_s)

The nominal o/p voltage V, is the charging voltage multiplied by the number of stages.

The nominal energy stored is given by $\frac{1}{2} C_s V^2$.

The C_s/C_b ratio should be about 5-10 and therefore a generator energy storage rating of an impulse generator at the same nominal output voltage implies that the generator is capable of testing insulators of high capacitance values.

An eight-stage 1400kV, 12 kW-s impulse generator has the following particulars.

Dc charging voltage = $1400/8 = 175$kV

~~Charging~~ discharge capacitance $C_s = \frac{12\times10^3\times2}{(1400\times10^3)^2} = 0.01224\,\mu F$

Stage capacitance $C_1 = 8C_s = 0.0976\,\mu F$.

A 16 stage impulse generator having a stage capacitance of 0.28μF and a maximum charging voltage of ~~0.28μF~~ 300 KV will have an energy rating of 192 kw-sec. The height of generator will be about 15mt. & will occupy a floor area of about 3.25 × 3 mt. The waveform of either polarity can be obtained by suitably charging and charging unit polarity.

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✓ 8

Ex:: An 8-stage impulse generator has 1.2μF capacitors rated for 167 kV. what is its maximum discharge energy? If it has to produce a 1/50 μs waveform across a load capacitor of 15,000 PF. Find the values of the wave front & wave tail resistances.

Sol: Energy rating $= \frac{1}{2} CV^2$

$= \frac{1}{2} \times 8 \times 1.2\times10^{-6} \times (167\times10^{3})^2$

$= 133.86$ KJ

W.K.T $t_1 = 3R_1 \frac{C_1 C_2}{C_1+C_2}$

$C_1 = \frac{1.2\times10^{-6}}{8} = 0.15\mu F$

$C_2 = 15000pF$
$= 0.015\mu F$

$\therefore R_1 = t_1 \frac{C_1+C_2}{C_1C_2} \times \frac{1}{3}$

$= 1\times10^{-6} \times \frac{0.15\times10^{-6} + 0.015\times10^{-6}}{0.15\times10^{-6} \times 0.015\times10^{-6}} \times \frac{1}{3}$

$R_1 = 24.4\Omega$.

W.K.T $t_2 = 0.7(R_1+R_2)(C_1+C_2)$.

$50\times10^{-6} = 0.7(24.4+R_2)(0.15\times10^{-6} + 0.015\times10^{-6})$

$\therefore R_2 = 409.6\,\Omega$

Ex: An impulse generator has 12 capacitors of 0.12 μF and 200 kV rating. The wave front and wave-tail resistances are 1.25 kΩ & 4 kΩ respectively. If the load capacitance including that of the test object is 1000pF, find the wave front and wave tail times.

Sol: Generator Capacitance $C_1 = \frac{0.12}{12} = 0.01 \mu F$.

$C_2 = 1000 pF = 0.001 \mu F$.

Wave front time $t_1 = 3R_1 \frac{C_1 C_2}{C_1 + C_2}$

$$\therefore t_1 = 3 \times 1.25 \times 10^{3} \times \frac{0.01 \times 10^{-6} \times 0.001 \times 10^{-6}}{0.01 \times 10^{-6} + 0.001 \times 10^{-6}}$$

$t_1 = 3.41 \mu sec$

Wave tail time $t_2 = 0.7 (R_1 + R_2)(C_1 + C_2)$

$= 0.7 (1250 + 4000)(0.01 \times 10^{-6} + 0.001 \times 10^{-6})$

$= 40.42 \mu sec$

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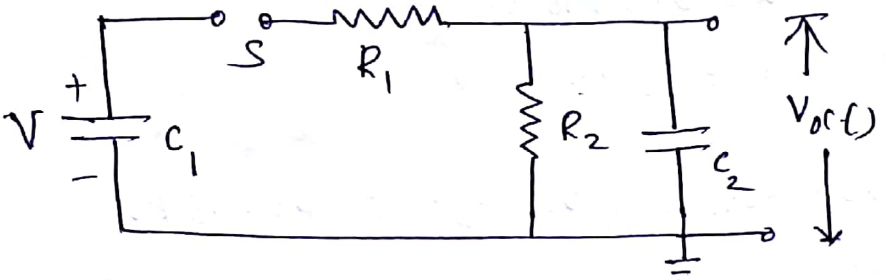
Ex: An impulse generator has eight stages with each condenser rated for 0.16 μF and 125 kV. The load capacitor available is 1000 pF. Find the series resistance and the damping resistance needed to produce 1.2/50 μs impulse wave. What is the maximum output voltage of the generator if the charging voltage is 120 kV?

Jan 2006.
Jan 2015

Soln Assume the equivalent circuit of the impulse generator to be as shown in fig.



C_1, the generator capacitance $= \frac{0.16}{8} = 0.02\mu F$

C_2, the load capacitance $= 0.001\mu F$

t_1, time to front $= 1.2\mu s$

$$t_1 = 3 R_1 \frac{C_1 C_2}{C_1 + C_2}$$

$$\therefore R_1 = t_1 \frac{C_1 + C_2}{C_1 C_2} \times \frac{1}{3}$$

$$= 1.2\times10^{-6} \frac{0.021\times10^{-6}}{0.02\times0.001\times10^{-12}} \times \frac{1}{3} = 420\Omega$$

t_2, time to tail $= 0.7 (R_1 + R_2)(C_1 + C_2)$

$$t_2 = 50\times10^{-6}$$

$$0.7 (420 + R_2)(0.021\times10^{-6}) = 50\times10^{-6}$$

$$\therefore R_2 = 2981\Omega$$

The dc charging voltage for eight stages is

$$V = 8\times120 = 960 \text{ kV}.$$

The maximum output voltage is

$$\frac{V}{R_1 C_2(\alpha-\beta)}\left(e^{-\alpha t} - e^{-\beta t}\right)$$

where $\alpha = \frac{1}{R_1 C_2}$ $\beta = \frac{1}{R_2 C_1}$ & V is the dc Charging voltage.

Substituting for R_1, C_1 & $R_2 C_2$

$\alpha = 0.7936 \times 10^{6}$

$\beta = 0.02335 \times 10^{6}$

∴ maximum o/p voltage = 932.6 kV

Typical values of C_2 (Cap. of test object).

Equipment	C_2
1) Line insulators	A few tens of pF
2) Bushing	200 - 500pF
3) Power transformers	
a) < 1 MVA	a) 1000pF
b) > 1 MVA	b) 1000 - 10,000pF.
4) Underground Cables	
a) Impregnated paper insulated	a) 200 - 250pF / mt length
b) Gaseous insulated.	b) 50-75 pF / mt. length

Tripping or Triggering of Impulse Generator by Three Electrode Gap Arrangement

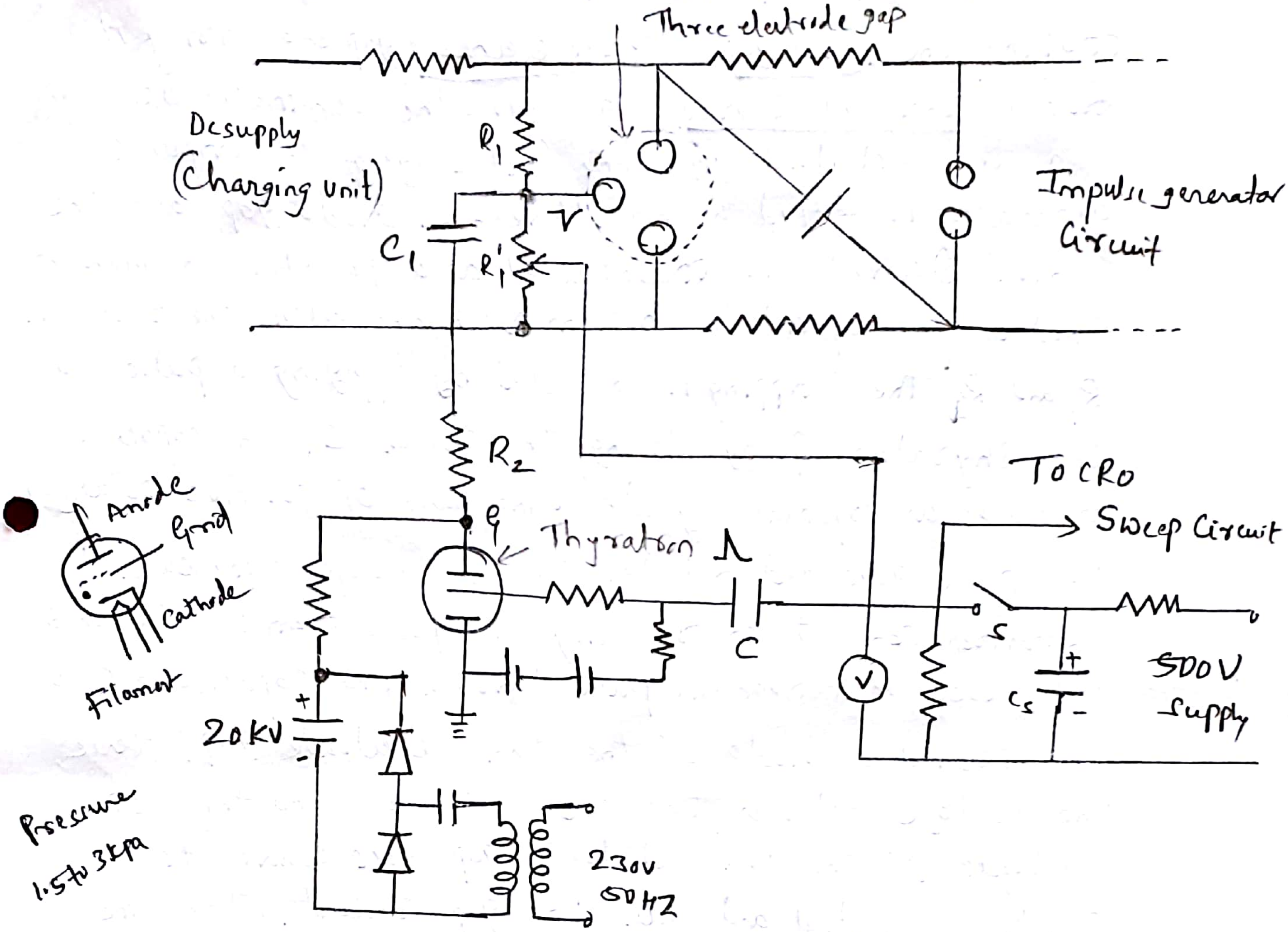


Fig ① Tripping of an impulse Generator with a three electrode gap.

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

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

A simple method of controlled tripping consists of making the first gap a three electrode gap and firing it from a controlled source. Fig ① gives the schematic arrangement of a three-electrode gap. The first stage of the impulse generator is fitted with a three-electrode gap, and the central electrode is maintained at a potential in between that of the top and the bottom electrodes with the resistors R_1 and R_2. The tripping is initiated by applying a pulse to the thyratron "G" by closing the switch 'S'. The capacitor 'C' produces an exponentially decaying pulse of positive polarity. The pulse goes and initiates the oscilloscope time base. The thyratron conducts on receiving the pulse from the switch 'S' and produces a negative pulse through the capacitance C_1 at the central electrode of the three electrode gap. Hence, the voltage between the central electrode and the top electrode of the three electrode gap goes above its sparking potential and thus the gap conducts. The time lag required for the thyratron firing and breakdown of the three electrode gap ensures that the sweep circuit of the oscilloscope begins before the start of the impulse generator voltage. The resistance R_2 ensures decoupling of voltage oscillations produced at the spark gap entering the oscilloscope through the common trip circuit.

Mercury vapour, neon, hydrogen

The first commercial appearance 1928

* A thyratron is a type of gas filled tube used as a high power electrical switch and controlled rectifier

1960 - Thyristors

Thyratron can handle much greater currents
Electron multiplication occurs when the gas becomes ionized, producing a discharge

Trigatron gap and tripping circuit!

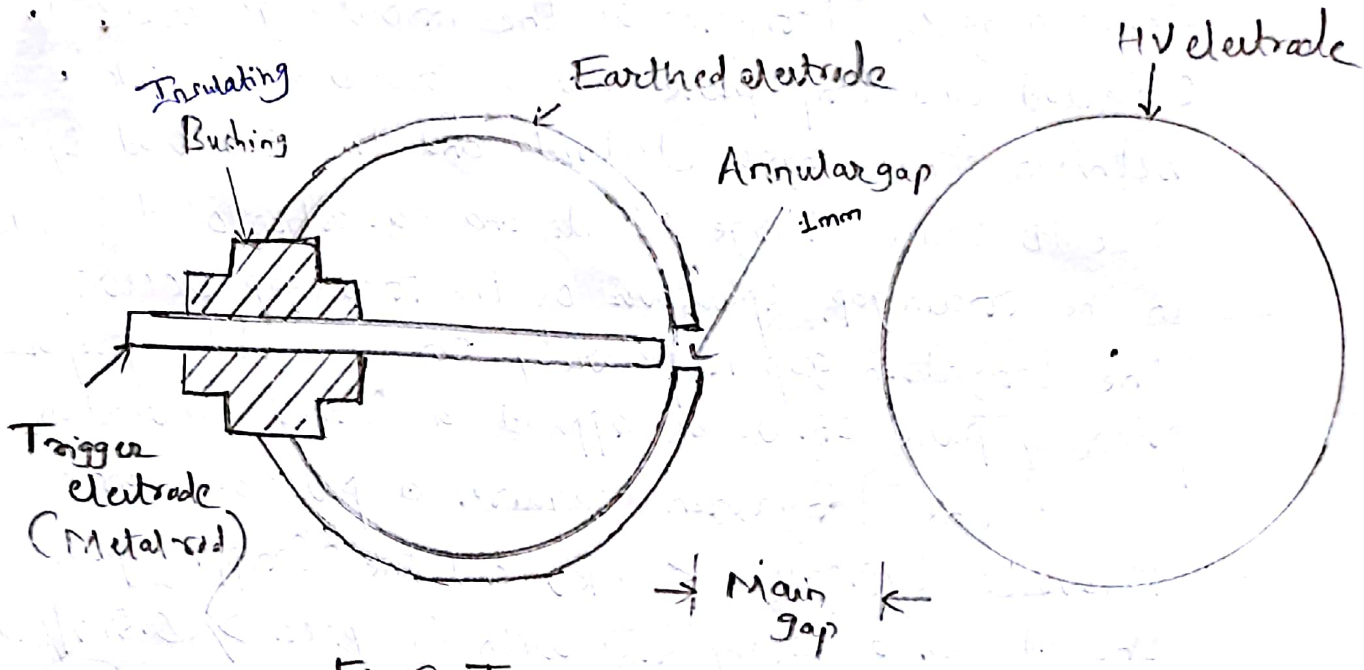


Fig ① Trigatron gap

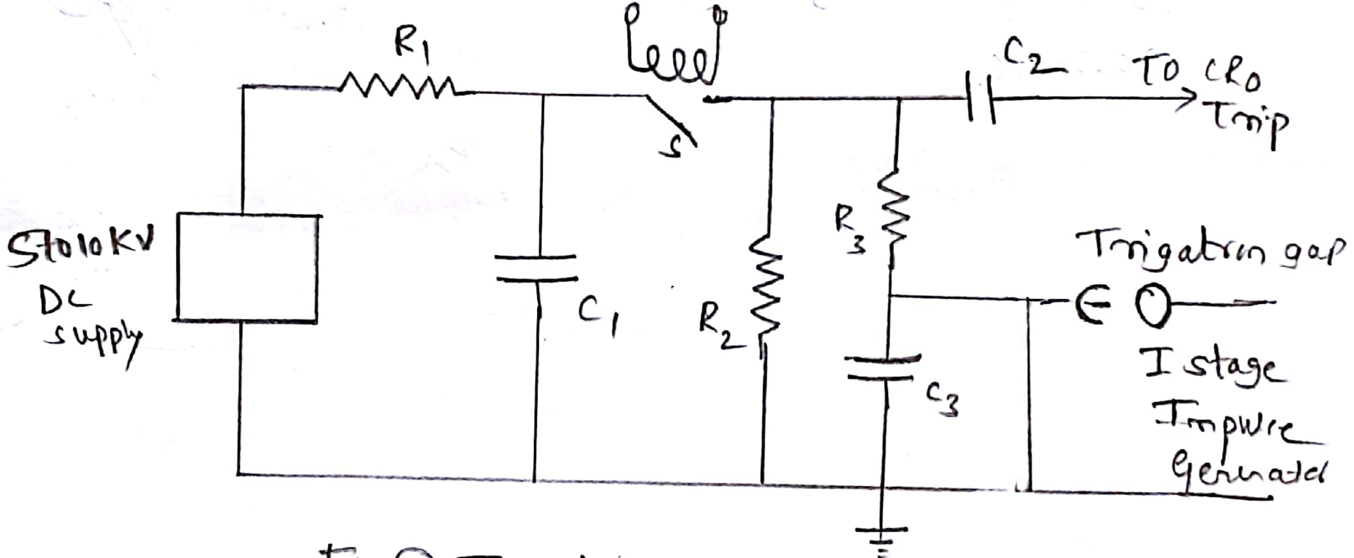


Fig ② Trigatron gap and tripping circuit.

The three electrode gap requires larger space and an elaborate construction. Nowadays a trigatron gap shown in fig ① is used, and this requires much smaller voltage for operation compared to the three-electrode gap.

A trigatron gap consists of a high-voltage spherical electrode of suitable size, an earthed main electrode of spherical shape, and a trigger electrode through the main electrode. The trigger electrode is a metal rod with an annular clearance of about 1 mm fitted into the main electrode through a bushing

The trigatron is connected to a pulse circuit as shown in fig ②. Tripping of the impulse generator is effected by a trip pulse which produces a spark between the trigger electrode and the earthed sphere. Due to space charge effects and distortion of the field in the main gap, sparkover of the main gap occurs. The trigatron gap is polarity sensitive and a proper polarity pulse should be applied for correct operation.

The trigatron requires a pulse of some kilovolts typically ≤ 10kV and the tripping pulse should have a steep front with steepness ≥ 0.5kV/nsec to keep the jitter of the breakdown as small as possible.

Generation of Switching Surges :

Nowadays, in extra high voltage transmission lines & power systems, switching surge is an important factor that affects the design of insulation. All transmission lines rated for 220KV and above, incorporate switching surge spark overvoltage for their insulation levels. A switching surge is a short duration transient voltage produced in the system due to a sudden opening or closing of a switch or circuit breaker or due to an arcing at a fault in the system.

Standard switching impulse voltage is defined, both by the Indian standards and the IEC, as 250/2500 μs wave with the same tolerances for time to front and time to tail i.e time to front of (250 ± 50)μs and time to half value of (2500 ± 500)μs. Other switching impulse voltage waves commonly used for testing the lightning arresters are 250/1500 μs with a tolerance of ± 500 μs in time to half value.

Several circuits have been adopted for producing switching surges. They are grouped as

i) Impulse generator circuit modified to give larger duration waveshapes.

ii) Power transformer or testing transformer excited by dc voltages giving oscillatory waves and these include Tesla coils.

Generation of switching surges using modified Impulse generator circuit :

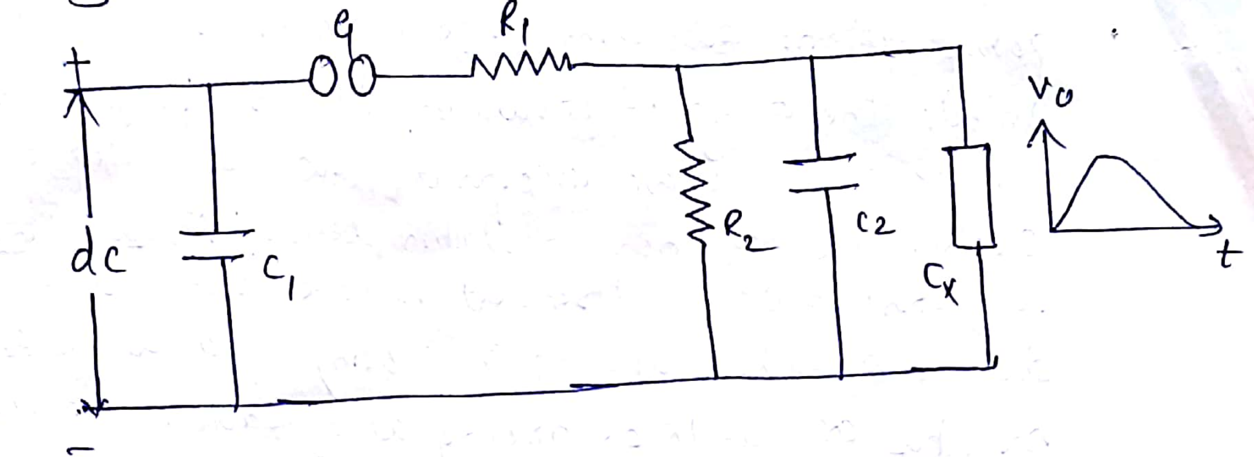


Fig ⓐ

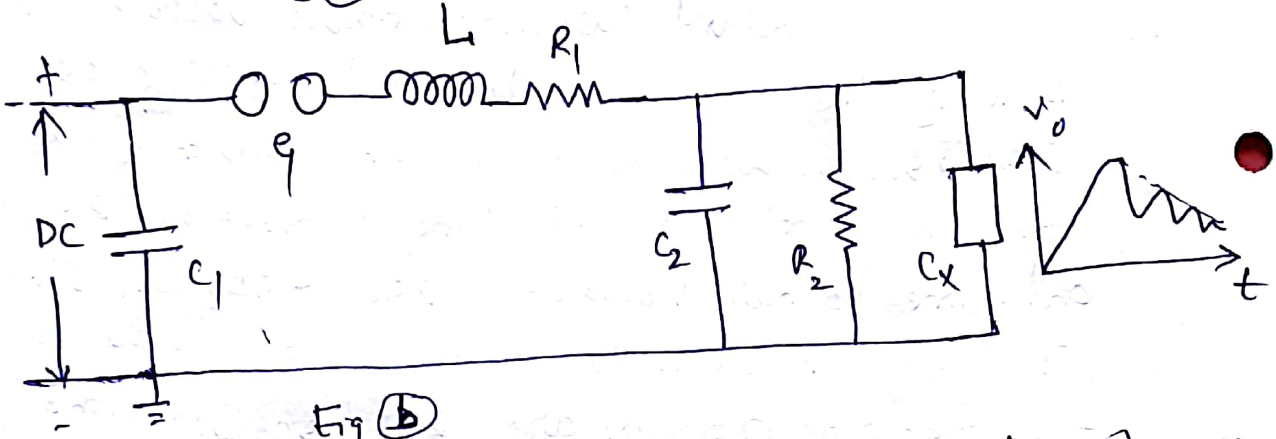


Fig ⓑ

Fig ① Circuits for producing switching surges. Also, shown are the output waveshapes across the load Cx.

Fig ① 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 and R_2 for producing waveshapes of long duration, such as 100/1000 µs or 400/4000 µs will range from 1 to 5 kΩ and 5 to 20 kΩ respectively. Thus R_1 is about 20 to 30% of R_2. The efficiency of generator gets considerably reduced to about 50% or even less. Moreover, the values 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 fig 1ⓑ produces unidirectional damped oscillations. With the use of inductor L, the value of R_1 is considerably reduced and the efficiency of the generator increases. The damped oscillations may have a frequency of 1 to 10 KHz depending on the circuit parameters. Usually, the maximum value of the switching surge obtained is 250 to 300kV with an impulse generator having a nominal rating of 1000 KV and 25 KJ.

* Generation of switching surges using the testing transformer

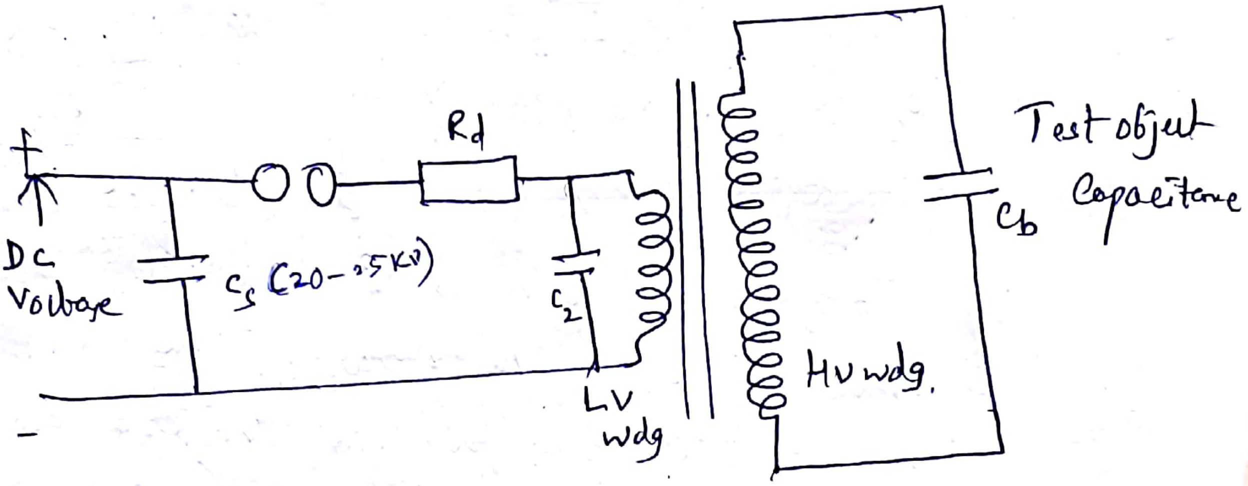


Fig ② Circuit for generation of switching overvoltages using the testing transformer.

Fig ② shows one circuit to generate switching overvoltages. An initially charged capacitor C_s (20-25kV) discharges into the RC circuit (R_d & C_2) and the low voltage winding of the transformer. The series inductance of the transformer L_s forms a series resonant circuit in combination with C_s and load capacitance C_b. R_d and C_2 are used to control the wave shape.

Neglecting losses with the circuit, the voltage

across C_b takes the form of $(1-\cos\omega t)$ function.
So, the time period T is given by

$$T = \frac{1}{f_r},$$

Where fr the frequency of oscillation

$$f_r = \frac{1}{2\pi\sqrt{L_s C}}.$$

Where C = Combined capacitance of C_s and C_b referred to the low voltage side (C_b')

$$= \frac{C_s C_b'}{C_s + C_b'}$$

So, the time to peak value

t_1 is given by $t_1 = \frac{T}{2} = \pi\sqrt{L_s C}$

In general, low values of t_1 are difficult to achieve as L_s is quite large. There will be transient oscillations within the transformer windings and the transformer insulation should be capable of withstanding high voltages.

Module-3

Measurement of High Direct Current Voltages (HVDC)

High Ohmic series resistance with Microammeter:

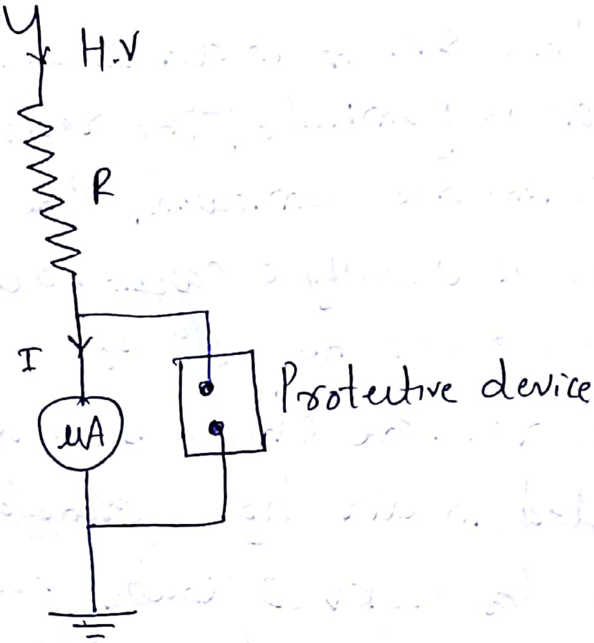


Fig ① Series resistance micrometer

High dc Voltages are usually measured by connecting a very high resistance (few hundreds of megaohms) in series with a microammeter as shown in fig ①. Only the current I flowing through the large calibrated resistance 'R' is measured by the moving coil microammeter. the voltage of the source is given by V = IR

The voltage drop in the meter is negligible, as the impedance of the meter is only few ohms compared to few hundred megaohms of the series resistance R. A protective device like a paper gap, a neon glow tube, or a zener diode with a suitable series resistance is connected across the meter as a protection against high voltages in case the series resistance 'R' fails or flashes over. The ohmic value of the series resistance 'R' is chosen such that a current of one to ten microampers is allowed for full scale deflection. The resistance is constructed.

The resistance is constructed from a large No. of wire wound resistors in series. The voltage drop in each resistor element is chosen to avoid surface flashover and discharges. A value of less than 5kV/cm in air or less than 20kV/cm in good oil is permissible. The resistor chain is provided with corona free terminations. The material for resistive elements is usually a carbon-alloy with temperature co-efficient less than $10^{-4}/°C$

A resistance chain built with carbon resistors located in air tight transformer oil filled P.V.C tube for 100KV operating had very good temperature stability.

The limitations in the series resistance design are

1) Power dissipation & source loading
2) Temp. effects & long time stability
3) Voltage dependence of resistive elements
4) Sensitivity to mech. stresses.

Generating Voltmeter or Rotary Voltmeter or Variable Capacitor electrostatic voltage generator.

High voltage measuring devices employ generating principle when source loading is prohibited or when direct connection to the high voltage source is to be avoided.

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

2.5-3.5 The device is driven by an external synchronous or
3-10 constant speed motor and doesnot absorb power from the voltage measuring source/device.

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 voltage 'V' the current through the capacitor

$$i = \frac{dq}{dt} = \frac{d[CV]}{dt} = C\frac{dv}{dt} + V\frac{dc}{dt} \quad -①$$

For DC voltages $\frac{dv}{dt} = 0$ Hence $\boxed{i = \frac{dq}{dt} = V\frac{dc}{dt}}$ ②

If the capacitance 'C' varies b/w the limits C_0 & $(C_0 + C_m)$ sinusoidally as $C = C_0 + C_m \sin\omega t$

Capacitance of generating voltmeter

The current is $i = i_m \cos\omega t$ where $i_m = V C_m \omega$

← Due to capacitor current

$\left[i = \frac{V}{X_c} = \frac{V}{1/\omega C} = V\omega C \right]$ leads by 90°.

i_m is the peak value of the current.

The rms value of the current is given by

$$\boxed{i_{rms} = \frac{V C_m \omega}{\sqrt{2}}}$$

Angular speed of the drive.

For a constant angular frequency 'w', the current is is proportional to the applied voltage 'v'. Usually, the generated current is rectified and measured by a moving coil meter. Generating voltmeter can be used for AC voltage measurements also provided the angular frequency 'w' is the same or equal to half that of the supply frequency.

Construction

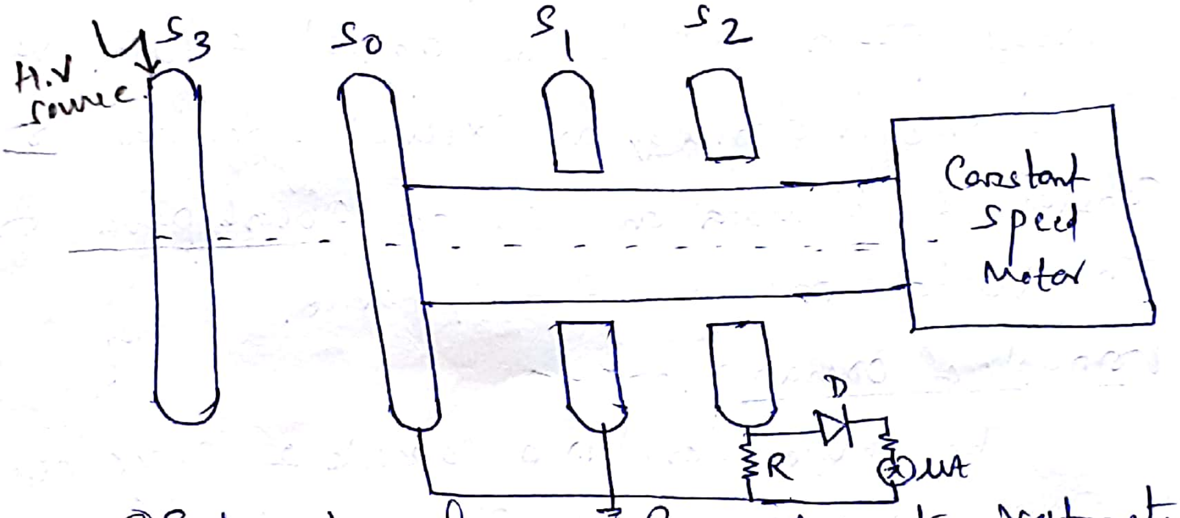
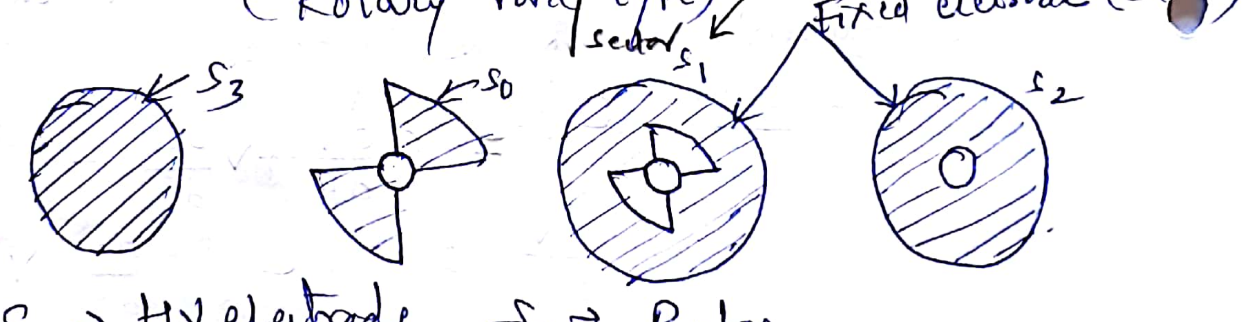


Fig ① Schematic diagram of a generating voltmeter (Rotary vane type)



$S_3 \rightarrow$ HV electrode $S_0 \rightarrow$ Rotor.

- * The rotor vanes of S_0 periodically cover and uncover the portion of static sensing electrode S_2. Hence the cap. b/w S_2 & S_3 undergoes a periodic change
- * Rotor vanes of S_0 cause periodic change in capacitance b/w insulated disc S_2 and hv electrode, S_3
- * Shape and No. of vanes of S_0 & S_1 are so designed that they produce sinusoidal variation in the capacitance.

Generating voltmeter employ rotating sectors or vanes for variation of capacitance. Fig① shows a schematic diagram of a generating voltmeter. The high voltage source is connected to a disc electrode S_3 which is kept at a fixed distance on the axis of the other low voltage electrodes S_0, S_1 & S_2. The rotor 'S_0' 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/w the insulated disc 'S_2' and the h.v electrode S_3. The shape and no. of the vanes of S_0 & S_1 are so designed that they produce sinusoidal variation in the capacitance. The generated a.c current through the resistor 'R' is rectified and measured by a moving coil instrument. An amplifier is needed, if the shunt capacitance is large or longer leads are used for connection to rectifier and meter. The instrument is calibrated using a potential divider or spheregap. The meter scale is linear and its range can be extended by extrapolation. Typical calibration curve of a generating voltmeter (rotating vane type) is shown in fig ②.

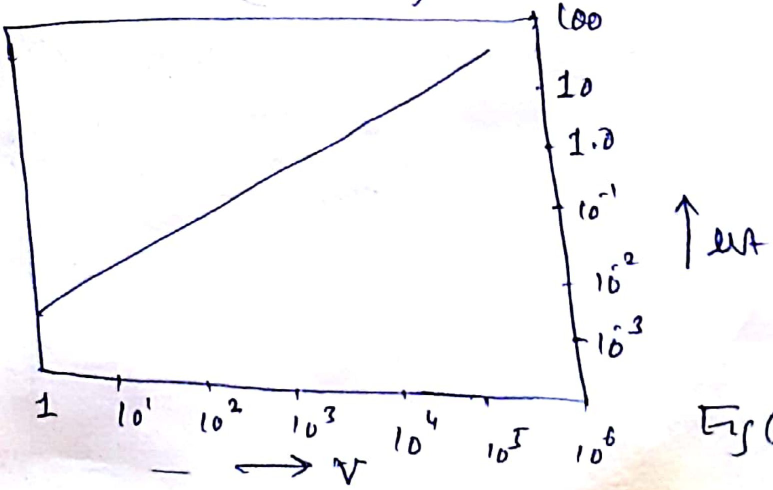


Fig ② Calibration curve

Advantages of Generating Voltmeter.

i) No-source loading by the meter

ii) No-direct connection to high voltage electrode

iii) Scale is linear and extension of range is easy and

iv) A very convenient instrument for electrostatic devices such as Van de Graaff generator and particle accelerator

Limitations of G.V

i) They require Calibration

ii) Careful construction is needed and is a cumbersome instrument requiring an auxiliary device

iii) Disturbance in position and mounting of the electrodes make the calibration invalid.

* This device can be used for measuring AC voltages provided the speed of a drive-motor is half the frequency of the voltage to be measured. thus a four-pole synchronous motor with 1500 rpm is suitable for 50 HZ.

Ex: A generating voltmeter has to be designed so that it can have a range from 20 to 200 kV d.c. If the indicating meter reads a minimum current of 2 µA and Maximum current of 25 µA, what should the capacitance of the generating voltmeter be ?

Dec 2010
Dec 2012
Jan 2017
May 2017

Soln Assume that the driving motor has a synchronous speed of 1500 rpm. $I_{rms} = \frac{V C_m W}{\sqrt{2}}$

Where V = Applied voltage
C_m = Capacitance of the meter
W = Angular speed of the drive $\frac{2\pi N}{60}$ rad/sec

Substituting

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

C_m = 0.9 pF

At 200 kV.

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

= 20 µA

The capacitance of the meter should be 0.9 pF.
The meter will indicate 20 kV at a current of 2 µA & 200 kV at a current of 20 µA.

Ex: A generating voltmeter is required to measure voltage b/w 15 kV to 250 kV. If the indicating meter reads a minimum current of 2 μA and maximum of 35 μA. Determine the capacitance of the generating voltmeter. Assume that the speed of the driving synchronous motor is 1500 rpm

Sol:
$$I_{rms} = \frac{V C_m \omega}{\sqrt{2}}$$

$$2 \times 10^{-6} = \frac{15 \times 10^{3}}{\sqrt{2}} C_m \times \frac{2\pi \times 1500}{60}$$

$$C_m = 1.2 pF$$

At 250 kV, the current indicated will be

$$I_{rms} = \frac{250 \times 10^{3} \times 1.2 \times 10^{-12}}{\sqrt{2}} \times \frac{2\pi \times 1500}{60} = 33.3 \mu A.$$

Ex: A generating voltmeter is to read 250 kV with an indicating meter having a range of (0-20) μA calibrated accordingly. Calculate the capacitance of the generating voltmeter when the driving motor rotates at a constant speed of 1500 rpm.

Soln

$$I_{rms} = \frac{V C_m \omega}{\sqrt{2}}$$

$$20 \times 10^{-6} = \frac{250 \times 1000 \times C_m \times}{\sqrt{2}} \frac{2\pi \times 1500}{60}$$

$$C_m = 0.72 \, pF$$

Ex: Calculate the correction factors for atmospheric condition, if the laboratory temp is 37°c, the atmospheric pressure is 750 mm Hg and the wet bulb temp is 27°c.

Soln Air density factor $d = \frac{P}{760}\left(\frac{293}{273+t}\right)$

At $t = 37°c$ $d = \frac{750}{760}\left(\frac{293}{273+37}\right)$

$= 0.9327$

<u>Ref table</u> Air density correction factor

$k = 0.9362$

12, 16, 26, 31,

5, 8, 19, 36, 38,

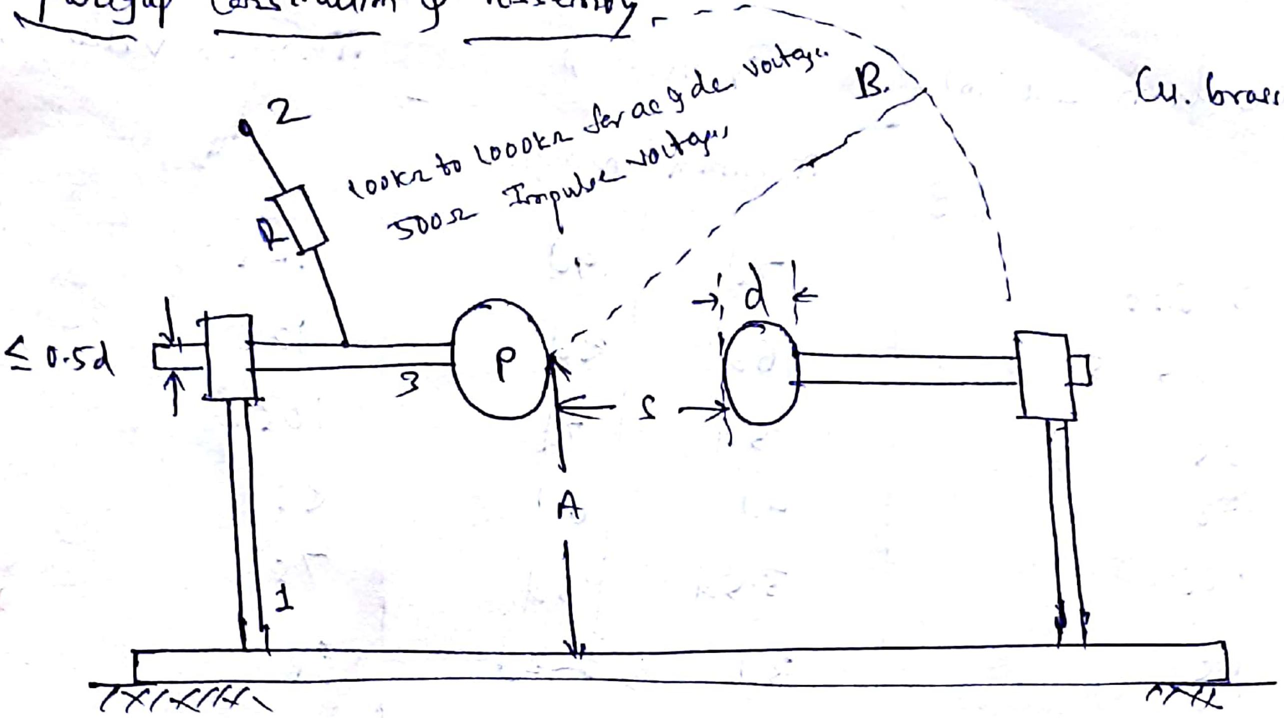
Spheregap for Voltage measurement

Spheregap for HVDC, HVAC & Impulse Voltage measurement,

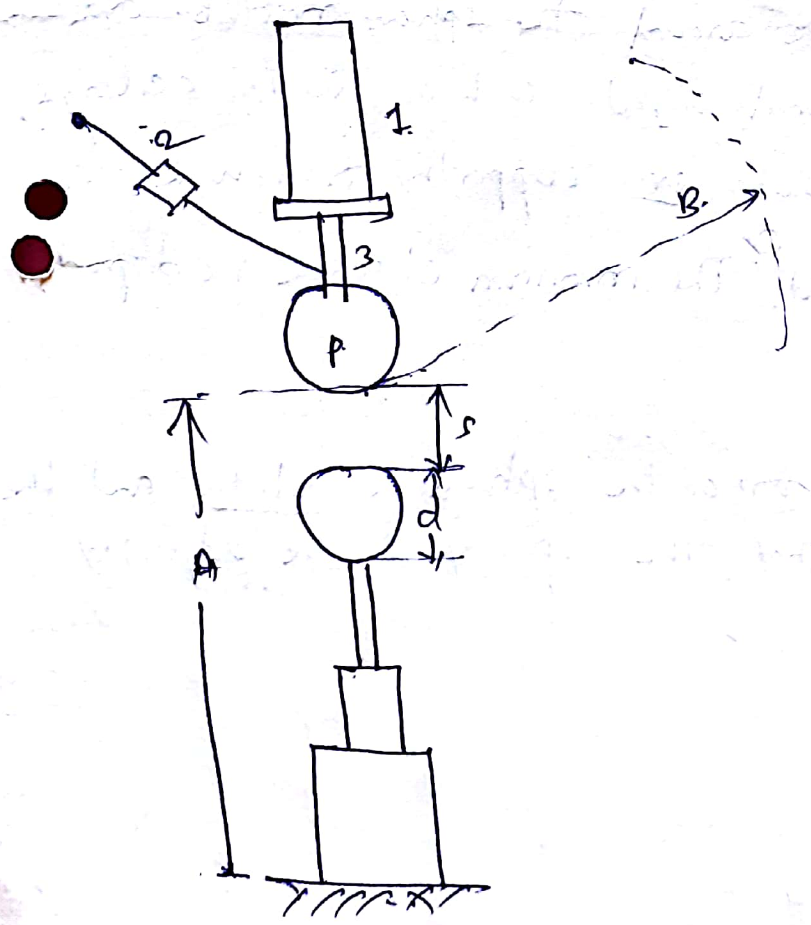
⑥

Spheregap Construction & Assembly

Cu. brass & Al.



a) Horizontal arrangement [This arrangement is usually preferred for sphere diameter d < 50cm]



1 → Insulating support

2 – High voltage Connection with series resistor

3 → sphere shank

P → sparking point

d → Diameter of sphere

S → Spacing

A → Height of sparking point P above the ground plane

B → Radius of the Clearance from external structures

Spherometer

b) Vertical arrangement [with larger spheres the vertical arrangement is chosen]

Tabl ①. Clearance for sphere gaps

Sphere diameter d (cm)	Value of A		Minimum value of B
	Minimum	Maxium	
2, 5, 6.25	7d	9d	14s
10, 12.5, 15	6d	8d	12s
25	5d	7d	10s
50	4d	6d	8s
100	3.5d	5d	7s
150	3d	4d	6s
200	3d	4d	6s

* A minimum clearance around the spheres must be available within which no external objects such as walls, ceilings, tr. tanks, impulse generators or supporting framework for the spheres are allowed. The minimum clearance is depend on the gap spacing.

* In both the arrangements one of the spheres is static and the other is movable so that the spacing can be adjusted.

gap **Spark gaps for measurement of high d.c. a.c and impulse Voltages (Peak values)** ⑦

A uniform field sparkgap will always have a sparkover voltage within a known tolerence under constant atmospheric conditions. Hence a spark gap can be used for measurement of the peak value of the voltage, if the gap distance is known. A sparkover voltage of 30kV (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 configuration. Normally, only sphere gaps are used for voltage measurements. In certain cases, uniform field gaps & rod gaps are used, but their accuracy is less. The sparkgap breakdown, especially the spheregap breakdown, is independent of the voltage waveform & hence is highly suitable for all types of waveforms from dc to impulse voltages of short rise times (rise time ≥ 0.5 us). sphere gaps can be used for radio freq a.c. voltage peak measurement also upto 1 MHz

Spheregap Measurements

Sphere gaps can be arranged either
i) Vertically with lower sphere grounded or
ii) horizontally with both spheres connected to source voltage or one sphere grounded.

In horizontal configuration, it is generally arrayed such that both spheres are symmetrically at high voltage above the ground. The two spheres used are identical in size & shape.

The voltage to be measured is applied b/w the two spheres and the distance or spacing 'S' b/w them
20 gives a measure of the sparkover voltage.

A series resistance is usually connected b/w the source and the sphere gap to

i) limit the breakdown current and

ii) to suppress unwanted oscillations in the source voltage when breakdown occurs. (In case of impulse voltages).

The value of series resistance may vary from 100 to 1000 kΩ for ac or dc voltages and not more than 500 Ω in the case of impulse voltages

In the case of a.c peak value and d.c voltage measurements, the applied voltage is uniformly increased until sparkover occurs in the gap. Generally, a mean of about five breakdown values is taken when they agree to within ±3%.

50% flashover voltage
This is the voltage which has a probability of 50% flashover when applied to a test object

In the case of impulse voltages, to obtain 50% flashover voltage, two voltage limits, differing by not more than 2% are set such that on application of lower limit value either 2 or 4 flashovers take place & on application of upper limit value 6 or 8 flashovers take place respectively. The mean of these two limits is taken as 50% flashover voltage.

Sphere gap construction and Assembly

Sphere gap are made with two metal spheres of identical diameters 'D' with their shanks, operating gear, and insulator supports. Spheres are generally made of copper, brass or aluminium. The standard diameters for the spheres are 2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150 & 200 cm. The spacing is so designed and chosen such that flashover occurs near to sparking point P. The spheres should be so made that their surfaces are smooth & their curvatures as uniform as possible (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% of the nominal value.)

The surface of the sphere should be free from dust grease or any other coating. If excessive pitting occurs due to repeated spark over, they should be smoothned.

Irradiation of sphere gap is needed when measurements of Illumination voltages less than 50 kV are made with spheregaps of 10cm diameter or less. The irradiation may be obtained from a quartz tube mercury vapour lamp of 40W rating.

Impulse voltage measurement using spheregap

50% flashover voltage: 100 kV

Two limits not differing by 2%.

applied for 10 times

Upper limit 102 kV

Lower limit 98 kV

On application of lower limit voltage 2 or 4 flashover takes place

upper limit 6 or 8 "

Mean of these two limits is taken as 50% flashover voltage

Factors Influencing the Sparkover voltage of Sphere gaps OR

Factors affecting the Measurements

1) Atmospheric conditions and humidity
2) Nearby earthed objects
3) Irradiation
4) Polarity and rise time of voltage waveforms
5) Influence of dust particles.

1) Effect of atmospheric conditions

The sparkover voltage of a sparkgap depends on the air density which varies with the changes in both temperature and pressure. If sparkover voltage is V' under test conditions of Temp & Pressure T & P and if spark voltage Voltage is V_0 under std. temp T = 20°C & P = 760 Torr and T = 20°C, P = 760 Torr

Then $V = KV_0$

$V \mid T_L \,\&\, P_L$ ↳ Lab or Test condition

$V_0 \mid T_S\, P_S$ ← std. Condition.

K → Function of Air density factor d

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

The relationship b/w d & k

Relation b/w Correction factor k & Air density factor d

d	0.7	0.75	0.8	0.9	0.95	1.0	1.05	1.10	1.15
k	0.72	0.77	0.82	0.91	0.95	1.0	1.05	1.09	1.12

The sparkover voltage increases with humidity.

For normal humidity 8 gm/m³ to 15 gm/m³ → 2 to 3%.

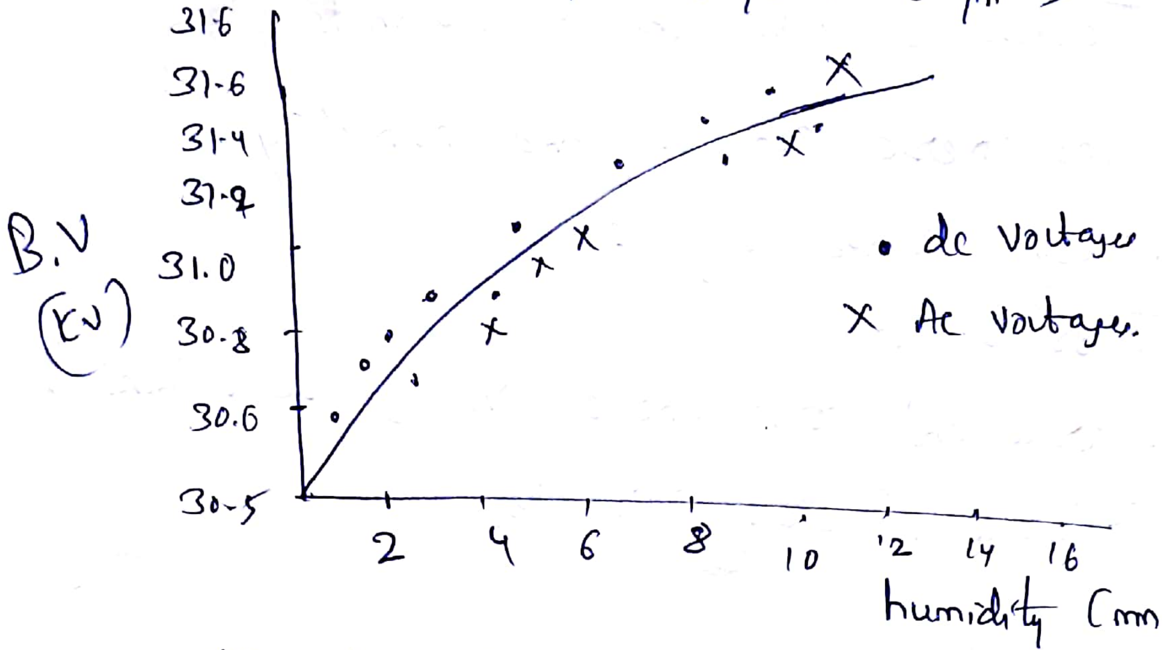


Fig Influence of humidity on dc and ac breakdown voltages (25cm dia sphere gap, 1cm spacing)

Increase in sparkover voltage is less than 3% and variation b/w AC & DC breakdown voltages is negligible (< 0.5%)

Hence it can be seen that

i) The A.C breakdown voltage is slightly less than dc voltage

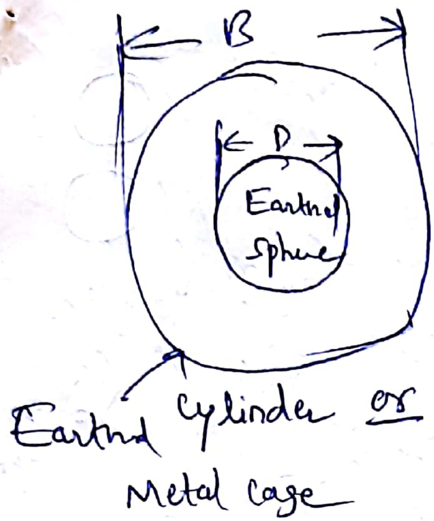
ii) The breakdown voltage increases with the partial pressure of water vapour

iii) the humidity effect increases with the size of spheres & is largest for uniform field electrodes

iv) Voltage change for a given humidity change increases with gap length

Note: As the change in sparkover voltage with humidity is within 3%, no correction is normally given for humidit

Effect of nearby earthed objects



Investigated by enclosing the earthed sphere inside an earthed cylinder
It was observed that the sparkover voltage is reduced.

The reduction was observed to be

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

Where ΔV = %age reduction in the breakdown voltage

B = Diameter of earthed enclosing cylind

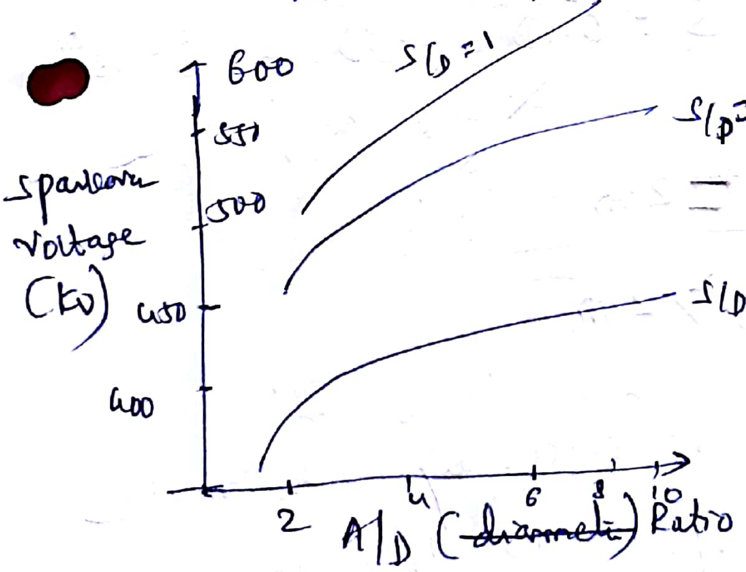
D = Dia. of the sphere

S = spacing

M & C are constants depending on the ratio S/D.

$\Delta V < 2\%$ for $S/D \leq 0.5$ & $B/D \geq 0.8$

$\Delta V = 3\%$ for $S/D \simeq 1$ & $B/D \geq 1.0$



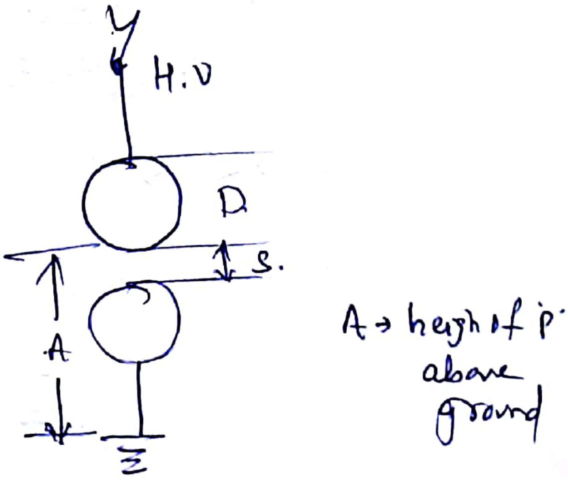
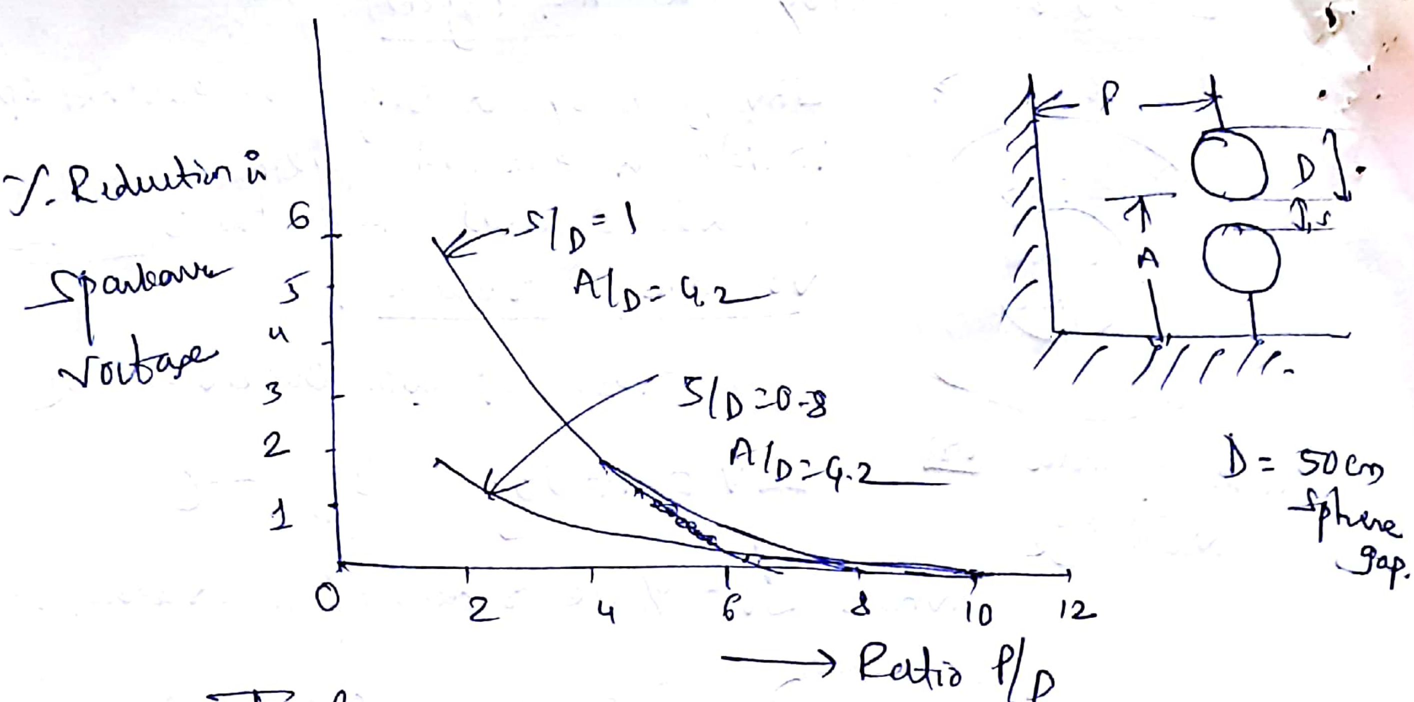


Fig. Breakdown voltage as a function of A/D

It is observed that the voltage increases with increase in the ratio A/D



Influence of ground planes on sparkover voltage.

iii) Effect of Irradiation (Illumination)

Availability of initiating electrons

Illumination of spheregaps with Ultra-violet or X-rays helps easy ionization in gaps.

The effect of irradiation is more for small gap spacings.

$\Delta V = 20\%$ for $S = 0.1D$ to $0.3D$ for $D = 1.3$ cm
(with DC voltages)

0.13cm 0.39cm

$\Delta V < 5\%$ for $S \geq 2$cm

$\Delta V = 1.5\%$ for $S \geq 2$cm.

Hence irradiation is necessary for smaller spheregaps of gap spacing less that 1cm for obtaining consistent values.

iv) Effect of polarity and waveform

Sparkover voltages for +ve & -ve polarity impulses are different.

* For spheregaps of D = 6.25 to 25 cm,

The difference b/w +ve & -ve dc voltages is < 1%.

\# For smaller spheregap D ≤ 2 cm → 8% for 1/50 μs

For wavefront < 0.5 μs & wave tail < 5 μs.

Breakdown voltages are not consistent and hence the use of spheregap is not recommended for voltage measurement in such cases.

v) Influence of dust particles

When a dust particle is floating b/w the gap this results into erratic breakdown in electrode configuration.

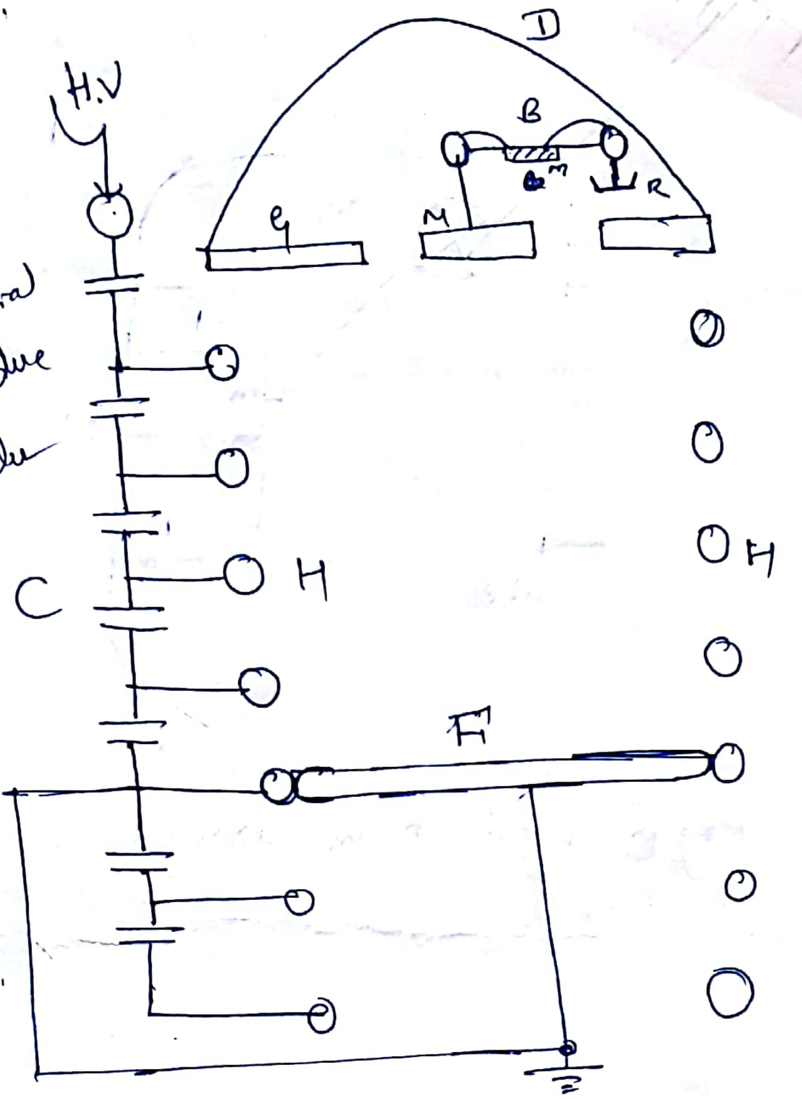
Under DC voltages erratic breakdown occurs for voltages as low as 80% of the nominal breakdown voltages. This is a major problem with HVDC measurement with spheregap.

Electrostatic Voltmeter

1000 KV (max)

Spring control

Coverbal meter
spring control



Uniform potential distribution due to 'C' divider

Limitation of the gap distance is safe working stress (V/d) allowed

Air → 5kV/cm
Vacuum & → 100kV/cm
compressed gas

$C = 5$ to $50\,pF$
High Insulation resistance
$R > 10^{13}\,\Omega$
High I/p Impedance

~~f~~ = 1MHz

Accuracy
AC → ± 0.25%
DC → ± 0.1%

fig ⓐ Electrostatic voltmeter

$C = \frac{\epsilon A}{d}$

Force of attraction

$F = \frac{1}{2} \epsilon A \frac{V^2}{d^2}$ Newton

$g \neq 0$

M → Moving Electrode

F → Fixed Electrode

G → Guard ring to make field uniform

m → Mirror

H → Guard ~~rings~~ hoops

B → Balance beam

C → capacitance divider

D – Dome

R → balancing weight for controlling the torque

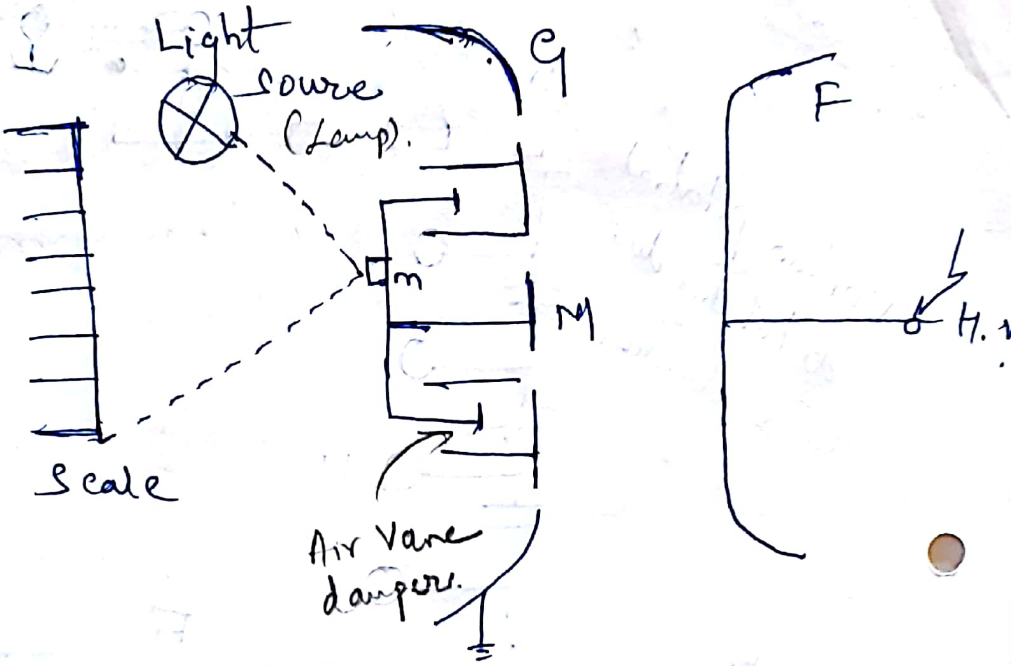


Fig ⓑ Light beam arrangement (Indicating system)

upto 600kV

Dielectric Medium: Air, Compressed air, Nitrogen, SF_6 + vacuum.

Safe working stress

5kV/cm in air.

100kV/cm

Principle. In electrostatic fields, the attractive force b/w the electrodes of a parallel plate Capacitor is given by

$$F = \left|\frac{-\delta W_s}{\delta d}\right| = \left|\frac{\delta}{\delta d}\left(\frac{1}{2}CV^2\right)\right| = \left|\frac{1}{2}V^2\frac{\delta C}{\delta d}\right| = \frac{1}{2}C_0V^2\frac{A}{d2} = \frac{1}{2}\epsilon_0 A\frac{V^2}{d2}\ \text{gm.wt}$$

$$\boxed{F = \frac{1}{2}\epsilon A\frac{V^2}{d^2}\ \text{newton gm-wt}}$$

Force of attraction

Ex

K G Naidu
Ex problem-9
Page no 282
5th edition

An electrostatic Voltmeter has an effective plate diameter of 50 cm with a gap separation of 30 cm. Find the force between the plates when measuring a dc voltage of 100 kV. What is the Maximum Voltage that can be measured if the electric field 'E' is to be not more than 5 kV/cm.

Sol: Given data. $D = 50\text{cm}$ $d = 30\text{cm}$ $V = 100\text{kV}$.
$E = 5\ \text{kV/cm}$

Area of plates $A = \frac{\pi D^2}{4} = \frac{\pi (50)^2}{4} = 625\pi \times 10^{-4}\ \text{m}^2$.

Force of attraction $F = \frac{1}{2}\epsilon \frac{V^2}{d^2} A$. Newton

$$\therefore F = \frac{1}{2} \times 8.84 \times 10^{-12} \times \frac{(100 \times 10^3)^2}{(30 \times 10^{-2})^2} \times 625\pi \times 10^{-4}$$

$F = 0.0965$ Newton

$9.8\ \text{kgf} = 0.0965$

$\text{kgf} = \frac{0.0965}{9.8} = 9.85 \times 10^{-3}$

$\boxed{\text{gm-wt} = 9.85\ \text{gm-wt}}$

W.k.T $E = V/d$.

$\therefore$ Maximum Voltage that can be measured

$V = E \times d = 5 \times 30$ $\text{kV/cm} \times \text{cm}$

$\boxed{V = 150\ \text{kV}}$

Ex! The effective diameter of the moving disc of an electrostatic voltmeter is 15 cm with an electrode separation of 1.5 cm. Find the weight in grams that is necessary to be added to balance the moving plate when measuring a voltage of 50 kV dc. What is the force of attraction b/w the two plates when they are baloneed?

ESV
K J Naidu
Exercise Problem

Sol: Force of attraction

$d = 1.5 cm$
$= 1.5 \times 10^{-2} m$

$$F = \frac{1}{2} \epsilon \frac{V^2}{d^2} A \quad \text{Newton}$$

Area of plate $A = \frac{\pi D^2}{4} = \frac{\pi (15)^2}{4} = 56.25\pi \ cm^2$
$= 56.25\pi \times 10^{-4} m^2$

$$F = \frac{1}{2} \times 8.84 \times 10^{-12} \times \frac{(50 \times 10^3)^2}{(1.5 \times 10^{-2})^2} \times 56.25\pi \times 10^{-4}.$$

$F = 0.8675 N$

$F = 9.8 kgf$

$9.8 \ kgf = 0.8675$

$$kgf = \frac{0.8675}{9.8}$$

$kgf = 0.08852$

Weight in grams $\boxed{g = 88.52 \ gms.}$

Ex: An electrostatic voltmeter has two parallel plates. The movable plate is 10cm in diameter. With 10KV between the plates the pull is 5×10^{-3}N. Determine the change in capacitance for a movement of 1mm of movable plate. ⑫

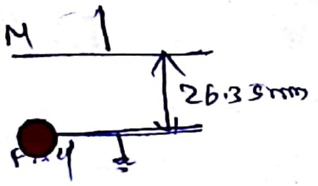
CLW.

Sol: Given data $D = 10cm$ $F = 5\times10^{-3}N.$ $V = 10KV.$

$\therefore$ Area of plate $A = \frac{\pi D^2}{4} = \frac{\pi (10)^2}{4} = 25\pi\times10^{-4} m^2$

Force of attraction $F = \frac{1}{2}\epsilon \frac{V^2}{d^2} A.$ Newton

$$5\times10^{-3} = \frac{1}{2}\times 8.84\times10^{-12}\times \frac{(10\times10^3)^2}{d^2}\times 25\pi\times10^{-4}$$



$d = 0.02635$ m.

$d = 26.35$ mm.

$$C = \frac{\epsilon A}{d} = \frac{8.84\times10^{-12}\times25\pi\times10^{-4}}{0.02635}$$

$= 2.63\,pF$ ✓

$\therefore$ Change in Capacitance

$$\underset{\uparrow m}{8.84\times10^{-12}}\times \underset{\uparrow m}{25\pi\times10^{-4}}\times 10^{3}\left(\frac{1}{\underset{\uparrow mm.}{26.35}}-\frac{1}{\underset{\uparrow mm}{27.35}}\right)$$

$= 0.0959\,pF.$

$C = 2.63\,pF$ for 26.35mm

$C' = 2.538\,pF$ for 27.35mm

Change in Capacitance $C - C' = 0.092\,pF$

C' for 2mm → 2.449 pF $\boxed{C - C' = 0.181\,pF}$

C' for 5mm → 2.214 pF

$\boxed{C - C' = 0.416\,pF}$

Ex: An absolute electrostatic voltmeter has a movable circular plate 8cms in diameter. If the distance b/w the plates during a measurement is 4mm. Determine the potential difference when the force of attraction is 0.2gm.wt

Soln Force of attraction $F = \frac{1}{2} \epsilon \frac{V^2}{d^2} A$ Newton.

Area of plates $A = \frac{\pi D^2}{4} = \frac{\pi 8^2}{4} = 16\pi\ cm^2$ or $16\pi \times 10^{-4}\ m^2$.

spacing b/w the plates $d = 4mm$ or 4×10^{-3} mt.

$$0.2 \times 10^{-3} \times 9.8 = \frac{1}{2} \times 8.854 \times 10^{-12} \times \frac{V^2}{16 \times 10^{-6}} \times 16\pi \times 10^{-4}$$

$$1.96 \times 10^{-3} = V^2$$

$$\boxed{\therefore V = 1188 \text{ volts.}}$$

Force
$1N = 9.8 kgf.$

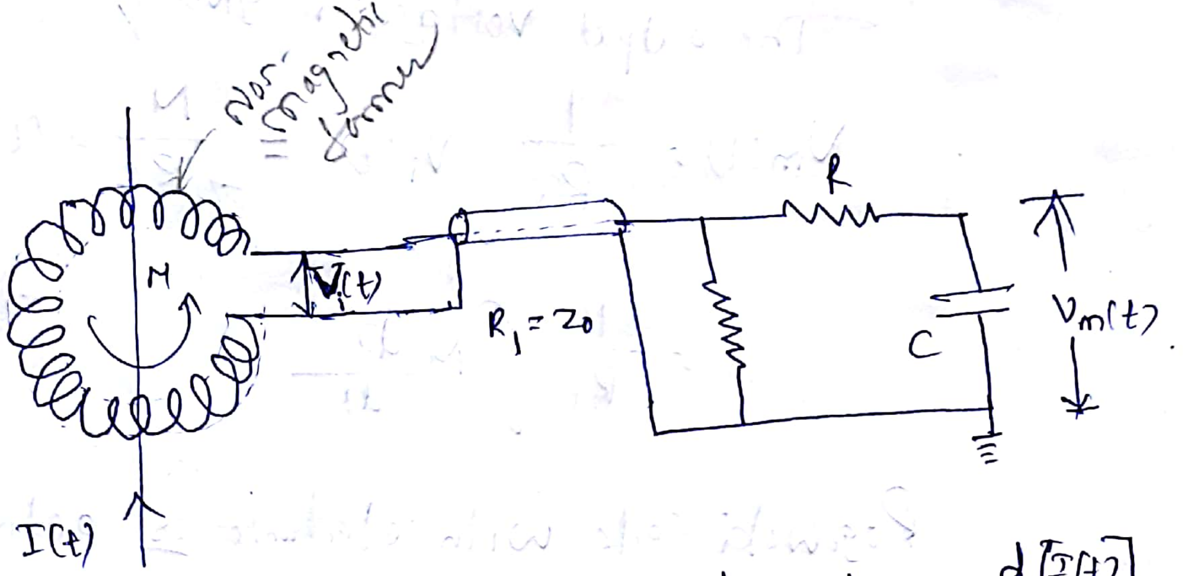
$\epsilon = \epsilon_0 \epsilon_r$
$\epsilon_0 = 8.854 \times 10^{-12}$ F/M

Scanned by CamScanner

1) Hall generator high for measuring high DC current
2) Resistive shunts for high freq & impulse currents
3) Rogowski coil CT
4) Magnetic links

Measurements of high impulse currents.

Rogowski coils Current Transformer



f > 100Hz response is affected by skin effect problem

Vi(t) → Induced Voltage in the coil = $M \frac{d[I(t)]}{dt}$

Z_0 → Coaxial cable of surge impedance Z_0

R.C → Integrating network

Vm(t) → output voltage   M → Mutual inductance

If a coil is placed surrounding a current carrying conductor, the voltage singal induced in the coil is $V_i(t) = M \frac{d[I(t)]}{dt}$ where 'M' is the mutual inductance b/w the conductor and the coil and I(t) is the current flowing in the conductor.

Usually, the coil is wound on a nonmagnetic former of toroidal shape and is coaxially placed surrounding the current carrying conductor. The number of turns on the coil is chosen to be large to get enough signal induced. The coil is wound cross-wise to reduce the leakage inductance.

Usually an integrating circuit is employed to get the out signal voltage proportional to the current to be measured.

The output voltage is given by

$$V_m(t) = \frac{1}{RC}\int_0^t V_i(t) = \frac{M}{RC} I(t)$$

$$= \frac{1}{RC}\int_0^t M\frac{dI(t)}{dt}$$

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

~~UNIT - IV~~ Module - 5

Non-Destructive Insulation Testing Techniques

Introduction :

Electrical insulating materials are used in various forms to provide insulation for the apparatus. The insulating materials may be solid, liquid, gas or even a combination of these, such as paper impregnated with oil. These materials should possess good insulating properties over a wide range of operating parameters, such as a wide temperature range (0°c to 110°c) and a wide frequency range (dc to several MHz in the radio and high frequency ranges). Since it is difficult to test the quality of an insulating material after it forms part of an equipment, suitable tests must be done to ensure their quality in the said ranges of operation. Also, these tests are devised to ensure that the material is not destroyed.

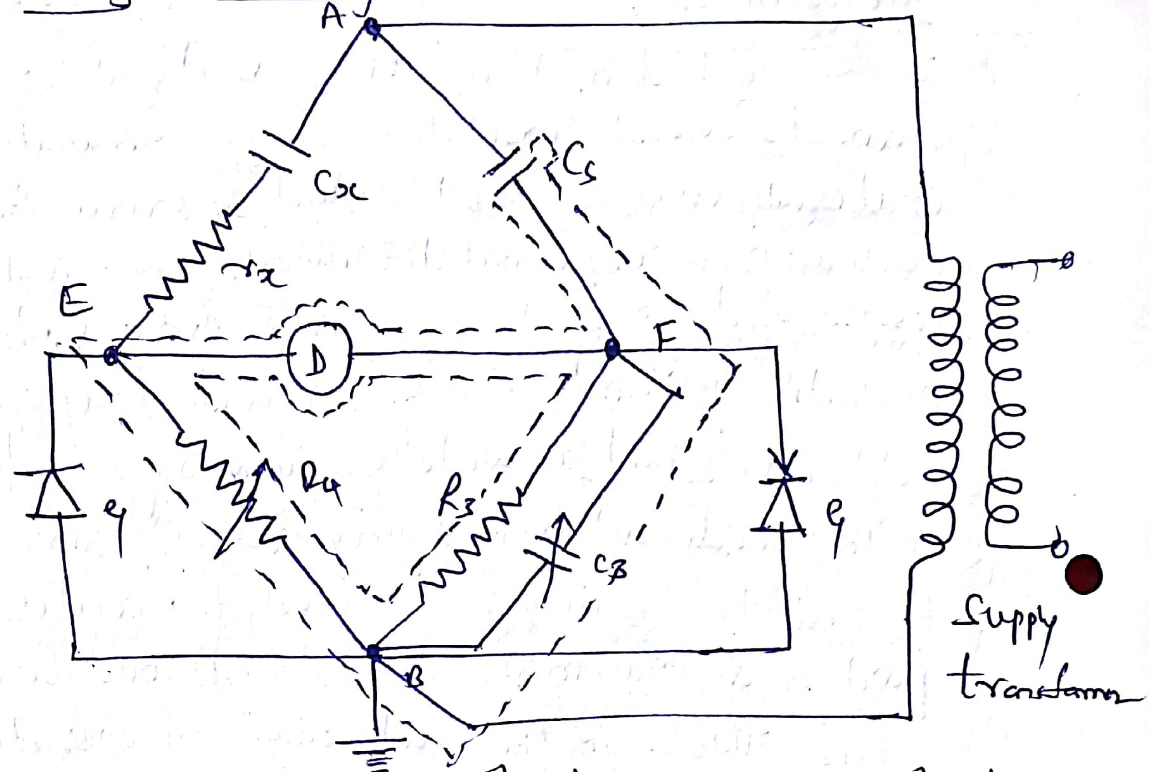
These tests are mainly done to assess the electrical properties, such as the resistivity (dc) the dielectric constant, and loss factor over a wide frequency range. In high-voltage apparatus, the quality of insulation is assessed by measuring the loss factor at high voltages and also by conducting partial discharge tests to detect any deterioration or faults in the internal insulation of the apparatus.

These tests may be conducted at a desired temperature or over a temperature range by keeping the test specimen in controlled temperature ovens. A knowledge of the variation of electrical properties over the operating range can be obtained from these tests and this will help the design engineer to take into account such variations in the design of electrical insulation for equipment.

Dielectric loss and loss angle Measurement

Power frequency measurement Methods -

High voltage Schering Bridge :



--- dotted line is the Shielding arrangement, Shield is Connected to B, the ground.

G: Protective device for Z_3, R_4 arms.

Fig ① Schematic diagram of a schering bridge

In the power frequency range (25 to 100 Hz) Schering-bridge is a very versatile and sensitive bridge and is readily suitable for high voltage measurements.

The Schematic diagram of the bridge is shown in fig ①

The lossy capacitor or capacitor with the dielectric between electrodes is represented as an imperfect capacitor of capacitance C_x together with a resistance r_x.

The standard capacitor is shown as C_s which will usually have a capacitance of 50 to 500pF. The variable arms are R_4 and $C_3 R_3$. Balanced is obtained when

$$\frac{Z_1}{Z_2} = \frac{Z_4}{Z_3}$$

Where $Z_1 = r_x + \frac{1}{j\omega C_x}$ $\quad Z_2 = \frac{1}{j\omega C_s}$

$$Z_3 = \frac{R_3}{1+j\omega C_3 R_3} \quad \text{and} \quad Z_4 = R_4$$

The balance equations are

$$C_x = \frac{R_3}{R_4} C_s \quad \text{and} \quad r_x = \frac{C_3}{C_s} R_4 \quad ①$$

The loss angle $\tan\delta_x = \omega C_x R_x$

$$= \omega C_3 R_3 \quad ②$$

Usually, δ_x will be small at power frequencies for the common dielectrics so that

$$\cos\theta_x = \sin\delta_x = \delta_x = \tan\delta_x = \omega C_3 R_3 \quad ③$$

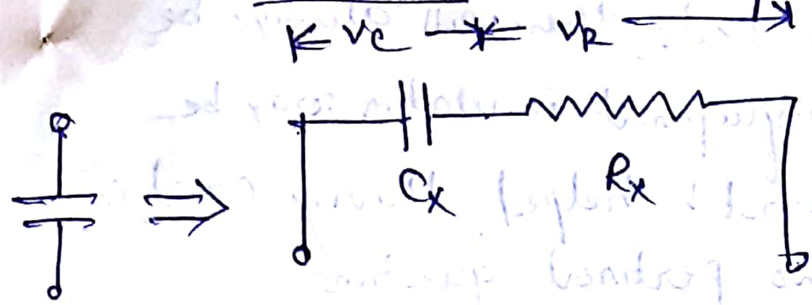
The lossy capacitor which is made as an equivalent C_x in series with r_x can be represented as a parallel combination of C_x and R_x where the parallel combination R_x is found to be

$$R_x = \frac{1}{\omega^2 C_x^2 r_x}$$ with C_x having the same value.

The arrangement shown in fig ① is suitable when the test specimen is not grounded. The standard capacitor C_s is usually a three terminal capacitor. The low voltage arms of the bridge (CR_4 and $R_3 C_3$) and the detector are enclosed in grounded shielded boxes to avoid stray capacitances during the measurements. The detector is either a vibration galvanometer or in modern bridges a tuned electronic null detector of high sensitivity. The protective gaps 'G' are so arranged that the low-voltage arms are protected from high voltages in case the test objects fail. The values of the impedances of the low-voltage arms are such that the voltage drop across EB or FB does not exceed 10 to 20V. The arms will be usually rated for a maximum instantaneous voltage of 100V.

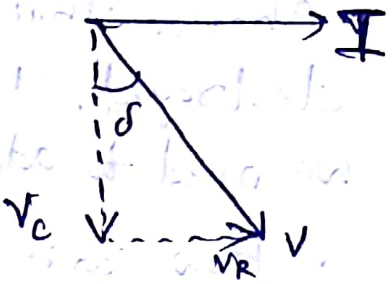
For a very accurate measurement of the dissipation factor at power frequency, the stray and grounded capacitances should be eliminated and the indirect capacitive and inductive coupling of the arms are to be minimized to a level lower than the accuracy of the bridge arms. In this bridge, the main source of error is the ground capacitance of the low-voltage terminals of high voltage arms i.e. the stray capacitances from E and F to ground. These are eliminated by shielding the low voltage arms using doubly shielded cables for connections and using the 'Waagner earthing device'. Sometimes, compensation for the stray capacitances is gi[illegible] by providing a parallel R-L circuit across R_4.

Measurement of Capacitance & Dissipation factor



Lossy Capacitor

① Circuit Model for a non-ideal Capacitor



② phasor diagram

On account of dielectric loss the current through a capacitor does not lead the voltage across it by 90° but by an angle (90° − δ) where δ is known as the loss angle as shown in the phase diagram of fig ②.

The dielectric loss is given by VI sinδ and assuming δ to be small by VI tanδ, where tanδ is known as the dissipation factor. A lossy capacitor may be modeled electrically by an ideal capacitor (having capacitance equal to that of the actual capacitor) connected in series with a hypothetical resistance or in parallel with a hypothetical resistance. The losses occur due to ionic and dipolar polarization and may be due to partial discharges. Considering the series model as shown in fig ①

$$\tan\delta = \frac{V_R}{V_C} = \frac{R_x}{1/\omega C_x} = \omega C_x R_x$$

The dissipation factor is an indication of the state of a dielectric. The more its value, the worse the condition of the insulation will be. Any variation and sudden change in the tanδ value with applied voltage is an indication of the onset of internal discharge.

Non-Destructive High voltage test

In high voltage tests, there will always be chances that the equipment insulation may be destroyed. This cannot be helped. Having said, so, we need to address two pertinent questions

1) How can it be ensured that the apparatus insulation has not deteriorated after a high voltage test even though it has withstood the test successfully?
2) How does one ensure the quality of insulation before it forms part of an equipment, within the working range of environment of the equipment?

The results of a couple of non-destructive high voltage tests may hold the answer to these questions. The first test determines the dissipation factor of a dielectric and the second one detects internal discharges taking place in the dielectric due to voids or other imperfections. Both the tests can be carried out on a sample of the insulation before it forms a part of an equipment or on an equipment itself after successful completion of a high voltage test. These non-destructive tests can be carried out over wide ranges of frequency and temperature

Transformer Ratio Arm Bridges

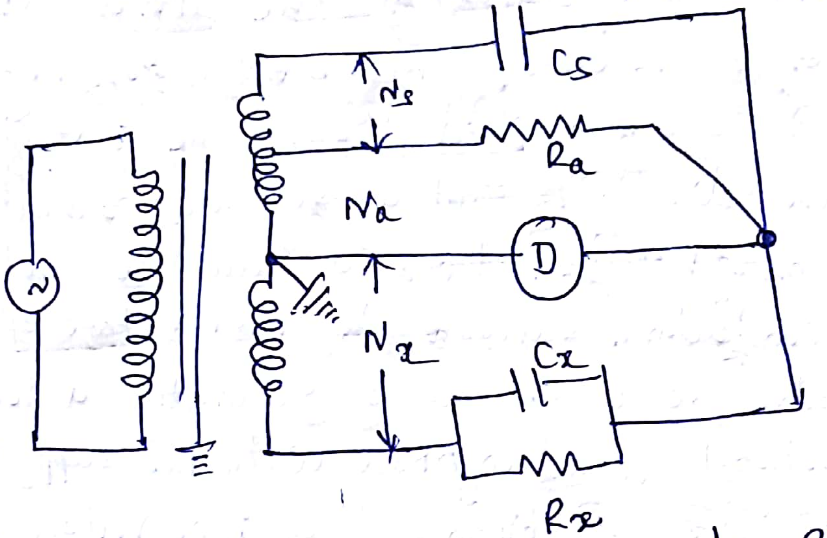


Fig ① Transformer voltage ratio arm bridge

It is a common practice to use the four-arm Wheatstone bridge network for AC measurements. In high frequency measurements, the arms with high values of resistances lead to difficulties due to their residual inductances, capacitances, and skin effect. Also, shielding and grounding becomes difficult in large arms, hence, at high frequencies the transformer ratio arm bridge which eliminate at least two arms are preferred. These bridges are also useful for the measurement of low value of capacitances accurately.

The ratio arm bridges can be either voltage-ratio type or current ratio type; the former being used for high frequency low voltage applications.

The schematic diagram of a ratio arm bridge (voltage ratio) is given in fig ①. Assuming ideal transformer conditions, for a null indication of the detector,

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

Where Cx & Cs are unknown and standard capacitances respectively, Rx & Ra are unknown and standard resistances and Nx, Na and Ns are the corresponding turns of the transformer ratio windings.

For high-voltage applications where sensitive measurements at fixed frequency (at 50 Hz) are required, the current comparator or the current ratio method (shown in fig ②) is used. This bridge has the advantage that full voltage is applied across the test capacitor but also has the drawback that a standard conductance has to be built for high voltages. It is difficult to construct a precision conductance suitable for high voltage operation.

This disadvantage is overcome by generating a low voltage signal E_f proportional to and in phase with the supply voltage E as shown in fig ③. At balance, there is no voltage across the current comparator winding. If the gain of the amplifier (A) is high, that is $E_f \approx \frac{C_s}{C_f} E$

The balance equations of the bridges are

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

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

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

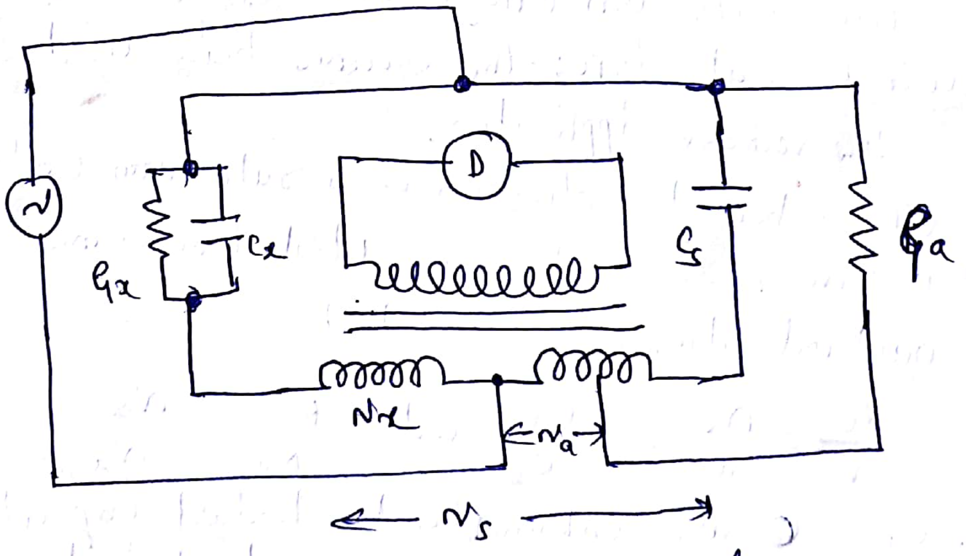


Fig ② Current Comparator Bridge

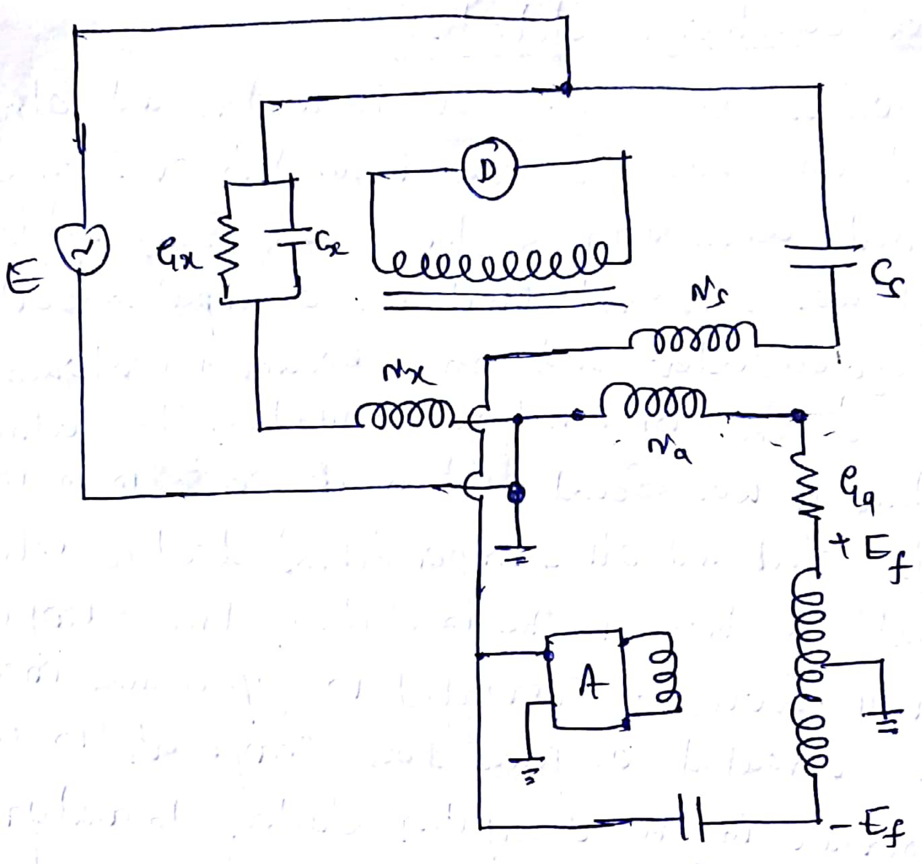


Fig ③ Current Comparator for high voltage application.

Partial Discharges :

An electrical discharge that only partially bridges the dielectric or insulating medium between two conductors.
Examples are : internal discharges, surface discharges and corona discharges.

Internal discharges are discharges in cavities or voids which lie inside the volume of the dielectric or at the edges of conducting inclusions in a solid or liquid insulating medi

Surface discharges are discharges from the conductor into a gas or a liquid medium and form on the surface of the solid insulation not covered by the conductor.

Corona is a discharge in a gas or a liquid insulation around the conductors that are away or remote from the solid insulation.

Need for discharge detection :

Earlier the testing of insulators and other equipment was based on the insulation resistance measurements, dissipation factor measurements and breakdown tests. It was observed that the dissipation factor (tanδ) was voltage dependent and hence became a criterion for the monitoring of the high voltage insulation. In further investigations it was found that weak points in an insulation like voids, cracks and other imperfections lead to internal or intermittent discharges in the insulation. These imperfections being small were not revealed in Capacitance measurements but were revealed as power loss components in contributing for an increase in the dissipation factor. In modern terminology these are designated as 'partial discharges' which in course of time reduce the strength of insulation leading to a ~~total~~ or partial failure ~~or~~ breakdown of the insulation.

If the sites of partial discharges can be located inside an equipment like in a power cable or a transformer it gives valuable information to the insulation engineer about the regions of greater stress and imperfections in the fabrication. Based on this information, the design can be considerably improved. Partial discharge measurement have been used to access the life expectancy of insulating materials.

Partial Discharge Measurements

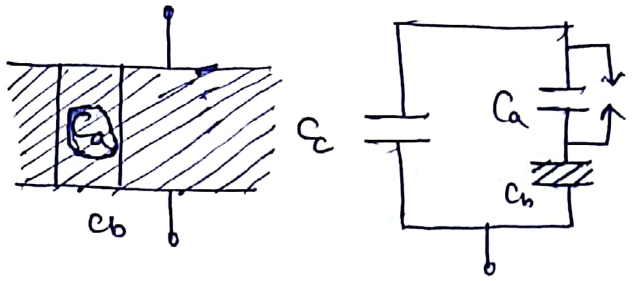
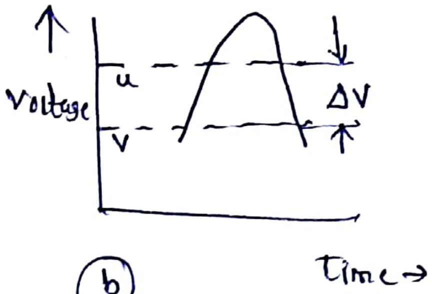


Fig 1 (a)



(b)

Ca → Capacitance of the void acting as a sparkgap

Cb → Capacitance of the remaining series insulation with the void

Cc → Remaining part of the discharge free insulation of the test object.

Fig 1 a) Insulating device with a void Ca and its simplified electrical equivalent circuit

b) Voltage across the void, Ca

Electrical insulation with imperfections or voids leading to partial discharges can be represented by an electrical equivalent circuit shown in fig ① Consider a capacitor with a void inside the insulation (Ca). The capacitance of the void is represented by a capacitor in series with the rest of the insulation capacitance (C_b). The remaining void-free material is represented by the capacitance C_c. When the voltage across the capacitor is raised, a critical value is reached across the capacitor Ca and a discharge occurs through the capacitor i.e. it becomes short circuited. This is represented by the closure of the switch.

Generally $C_a << C_b << C_c$. A charge Δq_a which was present in the capacitor Ca flows through C_b and C_c giving rise to a voltage pulse across the capacitor C_c. A measure of the voltage pulse across the capacitor gives the amount of <u>discharge quality</u>. But this measurement is difficult in practice and an apparent charge measurement across a detecting impedance is usually made.