CBCS SCHEME

USN 1CR16EE072

15EE73

Seventh Semester B.E. Degree Examination, Dec.2019/Jan.2020

High Voltage Engineering

Time: 3 hrs. Max. Marks: 80

Note: Answer any FIVE full questions, choosing ONE full question from each module.

Important Note : 1. On completing your answers, compulsorily draw diagonal cross lines on the remaining blank pages.
2. Any revealing of identification, appeal to evaluator and /or equations written eg, 42+8 = 50, will be treated as malpractice.

Module-1

1 a. Derive an expression for the current in the air gap that is $i = i_o e^{\alpha d}$ considering Townsend first ionization coefficient. **(07 Marks)**

b. What are the limitation of Townsend's theory? **(03 Marks)**

c. In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8}A at 8kV at a distance of 0.4cm between the plane electrodes. Keeping the field constant and reducing the distance to 0.1cm results in a current of 5.5×10^{-9}A. Calculate Townsend's primary ionization coefficient α. **(06 Marks)**

OR

2 a. Explain briefly suspended particle theory of breakdown in liquid dielectric. **(06 Marks)**

b. Explain the following breakdown mechanism in solids:
   i) Electro mechanical breakdown
   ii) Thermal breakdown. **(10 Marks)**

Module-2

3 a. With the help of a neat sketch, explain how cascade transformer generates High Voltage AC. **(06 Marks)**

b. What is Tesla coil? How are damped high frequency oscillation obtained from the Tesla coil? **(06 Marks)**

c. A Cockcroft-Walton type voltage multiplier has eight stages with capacitances, all equal to 0.05μF. The supply transformer secondary voltage is 125kV at a frequency of 150Hz. If the load current to be supplied is 5mA, find i) The percentage ripple ii) the regulation. **(04 Marks)**

OR

4 a. With neat sketch, explain the Mark's circuit arrangement for multistage impulse generator. **(07 Marks)**

b. With a neat diagram, explain the operation of trigatron gap. **(06 Marks)**

c. Define wave front and wave tail times of an impulse voltage wave. **(03 Marks)**

Module-3

5 a. With neat sketch, explain principle, working and construction of electrostatic voltmeter. **(06 Marks)**

b. Briefly explain the factors affecting measurement of voltage using sphere gap. **(05 Marks)**

c. Explain the working principle of generating voltmeter with a neat sketch. **(05 Marks)**

OR

6 a. Explain the Chubb-Fortscue method for measurement of peak value of an ac voltage waveform. **(06 Marks)**

b. With the help of a neat sketch, explain the working of Rogowski coil for high impulse current measurement. **(06 Marks)**

c. A generating voltmeter has to be designed so that it can have a range from 20 to 200kV dc. If the indicating meter reads a minimum current of 2μA and maximum current of 25μA, what should the capacitance of generating voltmeter be? **(04 Marks)**

Module-4

7 a. Explain the different theories of charge formation in clouds. **(08 Marks)**

b. Explain with suitable figures the principles and functioning of **(08 Marks)**

i) Expulsion gaps ii) Protector tubes.

OR

8 a. What is a surge arrester? Explain it function as a shunt protective device. **(08 Marks)**

b. Write short notes on: **(08 Marks)**

i) Rod gaps used as protective devices.

ii) Ground wires for protection of overhead lines.

Module-5

9 a. Discuss the method of discharge detection using straight detector. **(08 Marks)**

b. Explain the method of measuring dielectric loss at power frequency using high voltage Schering bridge. **(08 Marks)**

OR

10 a. Describe the various electrical tests done on transformers. **(08 Marks)**

b. Write a different methods of conducting a short circuit tests on circuit breakers. **(08 Marks)**

* * *

1a

Townsend's Theorem

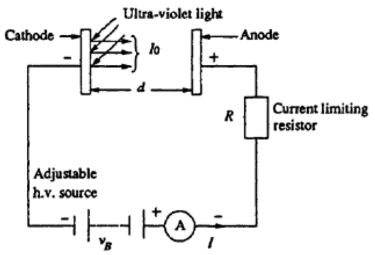
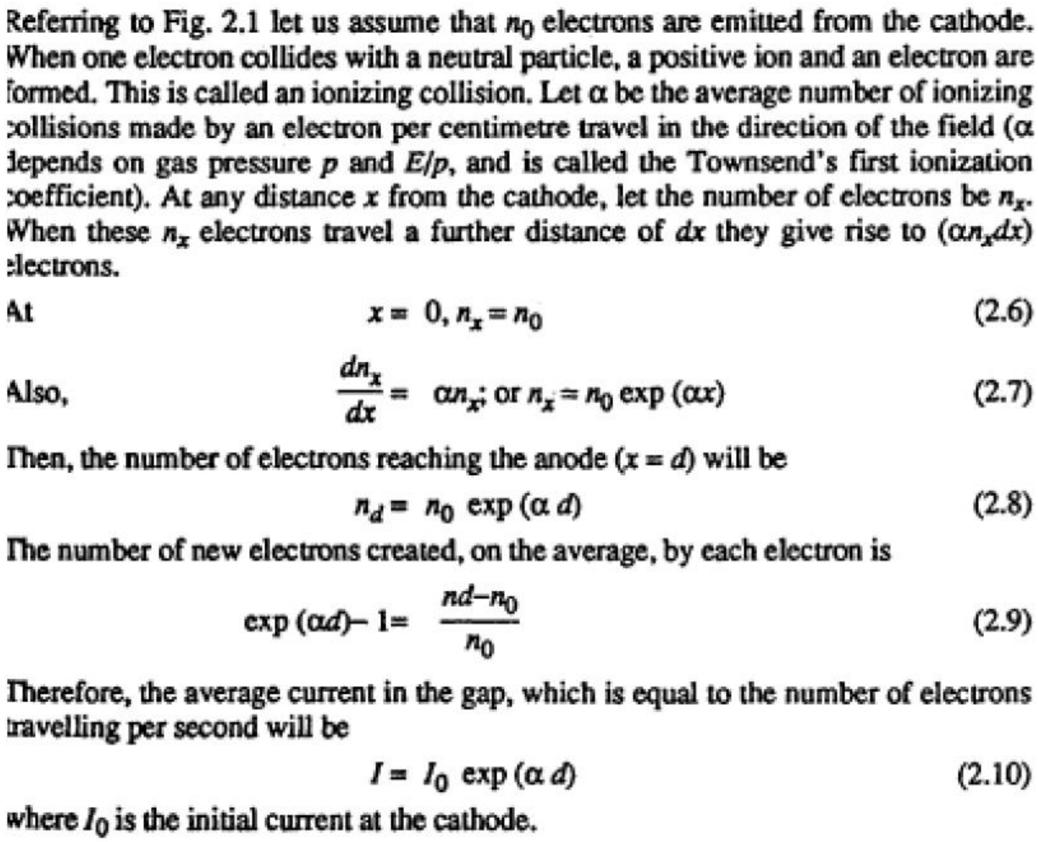


Fig. 2.1 Arrangement for study of a Townsend discharge

α, 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 EIp,)and is called the Townsend's first ionization coefficient).

The secondary ionization coefficient γ is defined in the same way as a, 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 coefficients due to the three different processes, i.e., $\gamma = \gamma1 + \gamma2 + \gamma3 = \gamma$ is called the Townsend's secondary ionization coefficient and is a function of the gas pressure p and E/p.



Referring to Fig. 2.1 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
$$x = 0, n_x = n_0 \tag{2.6}$$

Also,
$$\frac{dn_x}{dx} = \alpha n_x; \text{ or } n_x = n_0 \exp(\alpha x) \tag{2.7}$$

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

$$n_d = n_0 \exp(\alpha d) \tag{2.8}$$

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

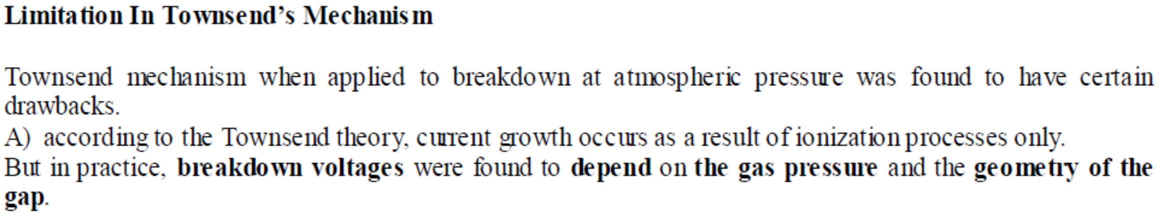
$$\exp(\alpha d) - 1 = \frac{nd - n_0}{n_0} \tag{2.9}$$

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

$$I = I_0 \exp(\alpha d) \tag{2.10}$$

where I_0 is the initial current at the cathode.

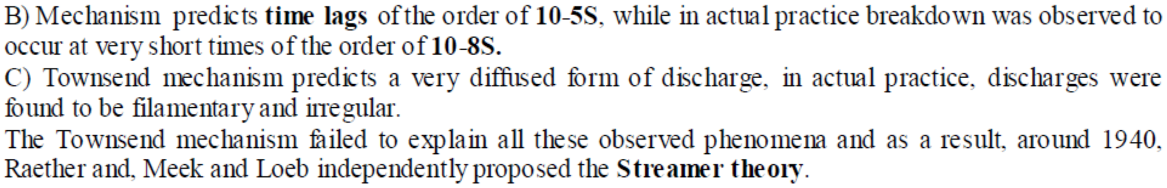
1b



Limitation In Townsend's Mechanism

Townsend mechanism when applied to breakdown at atmospheric pressure was found to have certain drawbacks.

A) according to the Townsend theory, current growth occurs as a result of ionization processes only. But in practice, **breakdown voltages** were found to **depend** on **the gas pressure** and the **geometry of the gap**.

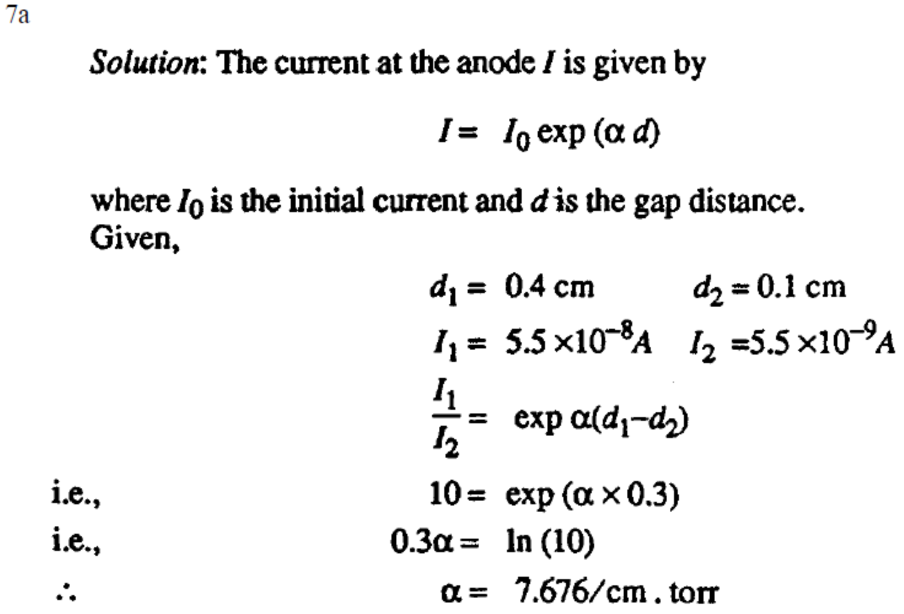


B) Mechanism predicts **time lags** of the order of **10-5S**, while in actual practice breakdown was observed to occur at very short times of the order of **10-8S.**

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

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

1c



7a

Solution: The current at the anode I is given by

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

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

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

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

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

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

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

∴ $$\alpha = 7.676/\text{cm . torr}$$

2a

i)Suspended Particle Theory

- In commercial liquids, the presence of solid impurities cannot be avoided.
- These impurities will be present as fibrous or as dispersed solid particles.
- The permittivity of these particles (**ε1**) will be different from the permittivity of the liquid **(ε2)**.
- If we consider these impurities to be spherical particles of radius r, and if the applied field is E, then the particles experience a force F, where

$$F = r^3 \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} E \cdot \frac{dE}{dx}$$

- this force is directed towards a place of higher stress if ε1 > ε2 and towards a place of lower stress if ε1 < ε2 when ε1 is the permittivity of gas bubbles.
- The force given above increases as the permittivity of the suspended particles (ε1) increases. If ε1 → ∞

$$F = r^3 \frac{1 - \varepsilon_2/\varepsilon_1}{1 + 2\varepsilon_2/\varepsilon_1} E \frac{dE}{dx}$$

Let $\varepsilon_1 \to \infty$

$$F = r^3 E \cdot \frac{dE}{dx}$$

- Force will tend the particle to move towards the strongest region of the field.
- In a uniform electric field which usually can be developed by a small sphere gap, the field is the strongest in the uniform field region. **Here *dE/dx → 0 so that the force on the particle is zero and the particle* remains in equilibrium**.
- Particles will be dragged into the uniform field region.
- Permittivity of the particles is higher than that of the liquid, the presence of particle in the uniform field region will cause flux concentration at its surface.
- Other particles if present will be attracted towards the higher flux concentration.
- The movement of the particle under the influence of electric field is opposed by the viscous force posed by the liquid and since the particles are moving into the region of high stress, diffusion must also be taken into account.
- We know that the viscous force is given by (Stoke's relation)
- **$Fv = 6\pi\eta r v$**
- where η is the viscosity of liquid, r the radius of the particle and v the velocity of the particle.
- Equating the electrical force with the viscous force we have

$$6\pi\eta r v = r^3 E \frac{dE}{dx} \quad \text{or} \quad v = \frac{r^2 E}{6\pi\eta}\frac{dE}{dx}$$

- However, if the diffusion process is included, the drift velocity due to diffusion will be given by

$$v_d = -\frac{D}{N}\frac{dN}{dx} = -\frac{KT}{6\pi\eta r}\frac{dN}{Ndx}$$

where D = KT/6πηr a relation known as Stokes-Einstein relation. Here K is Boltzmann's constant and T the absolute temperature.

At any instant of time, the particle should have one velocity and, therefore, equation

v = vd

We have

$$-\frac{KT}{6\pi\eta r}\cdot\frac{dN}{Ndx}=\frac{r^2E}{6\pi\eta}\cdot\frac{dE}{dx}$$

$$\frac{KT}{r}\frac{dN}{N}=-r^2E\,dE$$

$$\frac{KT}{r}\,\mathrm{1n}\,N=-\frac{r^2E^2}{2}$$

- It is clear that the breakdown strength *E depends upon the concentration of particles N, radius r* of particle, viscosity η of liquid and temperature *T of the liquid.*
- It has been found that liquid with solid impurities has lower dielectric strength as compared to its pure form.
- larger the size of the particles impurity the lower the overall dielectric strength of the liquid containing the impurity.
- If there is only a single conducting particle between the electrodes, it will give rise to local field enhancement depending on its shape.
- If this field exceeds the breakdown strength of the liquid, local breakdown will occur near the particle, and this will result in the formation of gas bubbles which may lead to the breakdown of the liquid.
- The values of the breakdown strength of liquids containing solid impurities was found to be much less than the values for pure liquids.
- The impurity particles reduce the breakdown strength, and it was also observed that the larger the size of the particles the lower were the breakdown strengths

2bi)

b) ELECTROMECHANICAL BREAKDOWN

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

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

where *Y is the Young's modulus.*
Usually, mechanical instability occurs when

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

Substituting this in above equation the highest apparent electric stress before breakdown,

$$d/d_0 = 0.6 \text{ or } d_0/d = 1.67$$

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

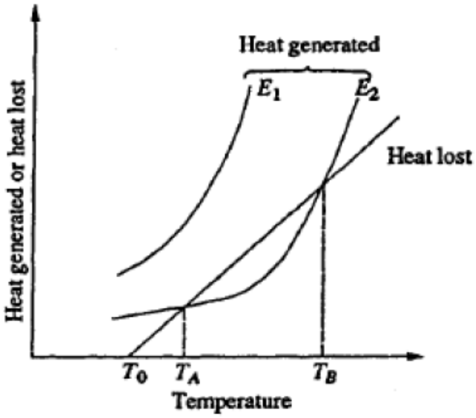
$$E_{\max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}}$$

2bii)

c) THERMAL BREAKDOWN

- The breakdown voltage of a solid dielectric should increase with its thickness.
- This is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction.
- When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material.
- The current heats up the specimen and the temperature 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 d.c. stress *E is given as*

- where, б is the d.c. conductivity of the specimen.
- $W_{d.c.} = E^2\sigma \quad W/cm^3$
- Under a.c. fields, the heat generated
- where, *f*= frequency in Hz,
- δ= loss angle of the dielectric material, and *E- rms value.*
- The heat dissipated *(W_T)is given by*
- $W_T = C_V \frac{dT}{dt} + \text{div}\,(K\ \text{grad}\ T)$
- where, C_V= *specific heat of the specimen,*
- T= temperature of the specimen,
- *K = thermal conductivity of the specimen, and*
- t = time over which the heat is dissipated.
- Equilibrium is reached when the heat generated (Wa.c.or Wd.c.) becomes equal to Equilibrium is reached when the heat generated Wa.c. or Wd.c becomes equal to the heat dissipated *(WT).*
- In actual practice there is always some heat that is radiated out
- Breakdown occurs when Wd.c. or Wa.c. exceeds WT.
- The thermal instability condition is shown in Fig.
- Here, the heat lost is shown by a straight line
- the heat generated at fields E1 and E2 are shown by separate curves.
- At field E1 breakdown occurs both at temperatures TA and TB.
- In the temperature region of TA and TB heat generated is less than the heat lost for the field E2 **the breakdown will not occur.**
- This is of great importance to practising engineers, as most of the insulation failures in high voltage power apparatus occur due to thermal breakdown.
- Thermal breakdown sets up an upper limit for increasing the breakdown voltage when the thickness of the insulation is increased.
- For a given loss angle and applied stress, the heat generated is proportional to the frequency and hence thermal breakdown is more serious at high frequencies.



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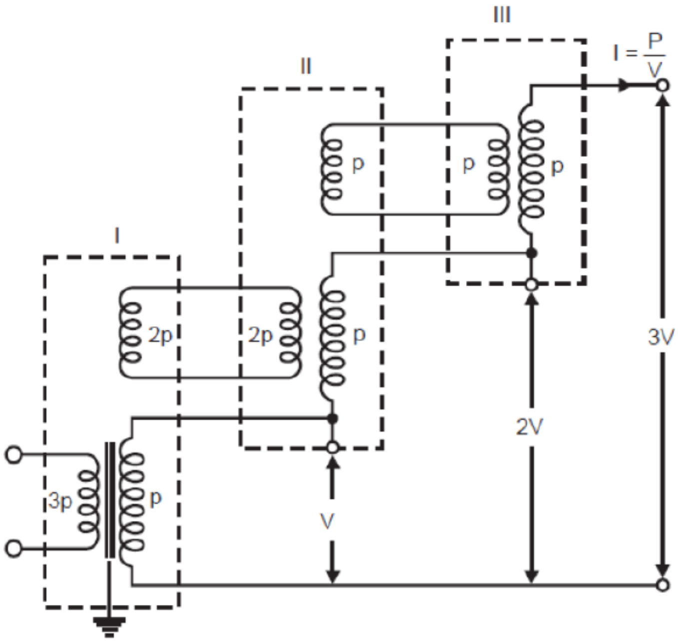
3a

Cascaded Transformer

Figure shows a basic scheme for cascading three transformers. The primary of the first stage transformer is connected to a low voltage supply. A voltage is available across the secondary of this transformer. The tertiary winding (excitation winding) of first stage has the same number of turns as the primary winding, and feeds the primary of the second stage transformer. The potential of the tertiary is fixed to the potential V of the secondary winding as shown in Fig. 2.9. The secondary winding of the second stage transformer is connected in series with the secondary winding of the first stage transformer, so that a voltage of $2V$ is available between the ground and the terminal of secondary of the second stage transformer. Similarly, the stage-III transformer is connected in series with the second stage transformer. With this the output voltage between ground and the third stage transformer, secondary is $3V$. it is to be noted that the individual stages except the upper most must have three-winding transformers. The upper most, however, will be a two winding transformer.

shows metal tank construction of transformers and the secondary winding is not divided. 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 and stage-III transformers have potentials of V and $2V$, respectively above 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 transformer.



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

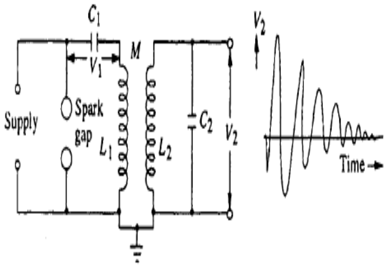
The loading of various windings is indicated by P in Fig. 2.9. For the three-stage transformer, the total output VA will be $3VI = 3P$ and, therefore, each of the secondary winding of the transformer would carry a current of $I = P/V$. The primary winding of stage-III transformer is loaded with P and 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 P. Therefore, while designing the primaries and tertiaries of these transformers, this factor must be taken into consideration.

3b Tesla Coil

- 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:

- the absence of iron core in transformers and hence saving in cost and size,
- pure sine wave output,
- slow build-up of voltage over a few cycles and hence no damage due to switching surges, and
- 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
- Doubly tuned resonant circuit
- The primary voltage rating is 10 kV
- The secondary may be rated to as high as 500 to 1000 kV.
- The primary is fed from a d.c. or a.c. supply through the condenser Ci.
- A spark gap G connected across the primary is triggered at the desired voltage V1 which induces a high self-excitation in the secondary.
- The primary and the secondary windings (L1)and (L2) are wound on an insulated former with no core (air-cored) and are immersed in oil.
- The windings are tuned to a frequency of 10 to 100 kHz by means of the condensers C1 and C2



(a) Equivalent circuit (b) Output waveform

- output voltage V2 is a function of L1, L2, C1, C2, M.
- winding resistances will be small , contribute only for damping of the oscillations.
- neglecting the winding resistances.

- Let the condenser C1 be charged to a voltage V1 when the spark gap is triggered.
- Let a current i1 flow through the primary winding L1 and produce a current i2 through L2 and C2

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

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

- Laplace Transform

$$\frac{V_1}{s} = \left[L_1 s + \frac{1}{C_1 s}\right] I_1 + MsI_2$$

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

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

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

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

where,

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

K = coefficient of coupling between the windings L_1 and L_2

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

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

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

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

•

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

$$a = \frac{L_2 C_2}{L_1 c_1} = \frac{W_1^2}{W_2^2}$$

Simplified analysis of Tesla coli from energy consideration

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

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

For high value of K and winding resistance the waveform may become unidirectional

3c

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

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

$I =$ 5 mA, $f =$ 150 Hz, $C = 0.05$ µF, and $n = 8$,

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

$$= 24\text{ kV}$$

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

$$= 1.2\%$$

(b) Calculation of Regulation

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

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

$$= 248\text{ kV}$$

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

$$= 12.4\%$$

4a

Multistage Impulse Generators—Marx Circuit

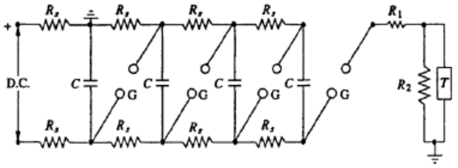


Fig. 6.17a Schematic diagram of Marx circuit arrangement for multistage impulse generator

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

- the generator capacitance **C1** is to be first charged and then discharged into the wave shaping circuits.
- A single capacitor **C1** may be used for voltages up to 200 kV.
- Beyond this voltage, a single capacitor and its charging unit may be too costly, 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**.
- Producing very **high voltages**, a bank of capacitors are **charged in parallel** and then **discharged in series**.
- The arrangement for charging the capacitors in parallel and then connecting them in series for discharging was originally proposed by **Marx**.

4b

- 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. 6.24b.
- Tripping of the impulse generator is affected 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

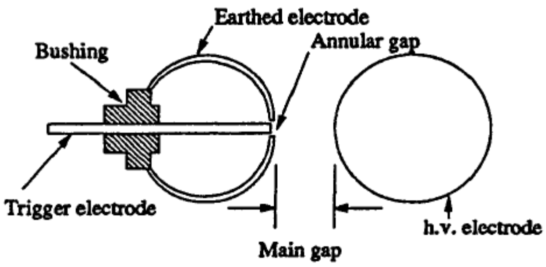


Fig. 6.24 (a) Trigatron gap

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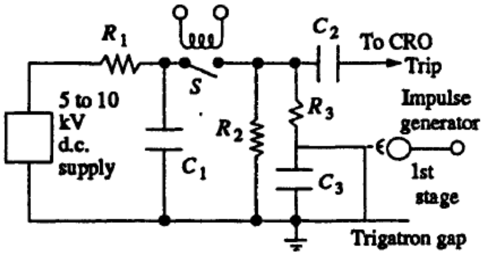

(b) Tripping circuit using a trigatron

Fig. 6.24 Trigatron gap and tripping circuit

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4c

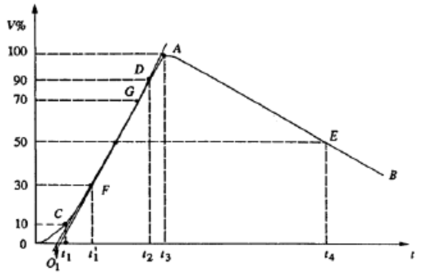

Fig. 6.14 Impulse waveform and its definitions

Referring to the waveshape in Fig. 6.14, the peak value A is fixed and referred to as 100% value. The points corresponding to 10% and 90% of the peak values are located in the front portion (points C and D).

The line joining these points is extended to cut the time axis at o1.

o1 is taken as the virtual origin. 1.25 times the interval between times t1 and t2 corresponding to points C and D (projections on the time axis) is defined as the **front time, i.e. 1.25 (o1t2 – o1t1).**

The point E is located on the wave tail corresponding to 50% of the peak value, and its projection on the time axis is t4. 0t4 is defined as the fall or tail time.

In case the point C is not clear or missing from the waveshape record, the point corresponding to 30% peak value F is taken and its projection t‘1 is located on time axis.

The wavefront time in that case will be defined as 1.67 (01t3 – o1t’1),

The tolerances that can be allowed in the front and tail times are respectively ± 30% and ± 20%.

Indian standard specifications define **1.2/50 µS** wave to be the standard impulse. The tolerance allowed in the peak value is **± 3%.**

5a

Electrostatic Voltmeter
D/E –Metal Dome
M/A-mounting Plate
G/C –guard plate
P/B –Fixed Plate

H- Guard loop or ring
B/D-Balance
C/G-Capacitance Divider
W Balancing Weight

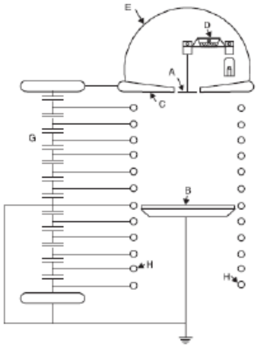

Fig. 4.7 Schematic diagram of electrostatic voltmeter

- Fig. shows a schematic diagram of an absolute electrostatic voltmeter.
- The hemispherical metal dome *D encloses a sensitive balance B which measures the force of attraction between the movable* disc which hangs from one of its arms and the lower plate *P.*
- *The movable electrode M hangs with a* clearance of above 0.01 cm, in a central opening in the upper plate which serves as a guard ring.
- The diameter of each of the plates is 1 metre.

- Fig. shows a schematic diagram of an absolute electrostatic voltmeter.
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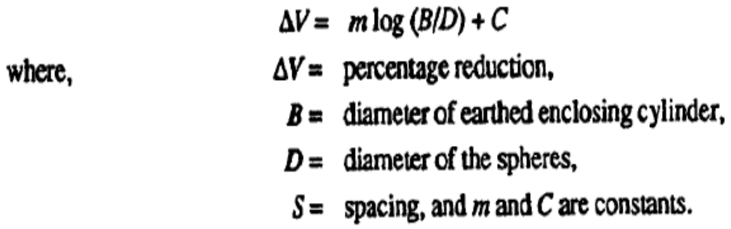
- **Principle:** The electric field according to Coulomb is the field of forces. The electric field is produced by voltage and, therefore, if the **field force** could be measured, the **voltage** can also be measured.
- The voltmeters are used for the measurement of high a.c. and d.c. voltages. The measurement of voltages lower than about 50 volt is, however, not possible, as the forces become too small.
- When a voltage is applied to a parallel plate electrode arrangement, an electric field is set up between the plates.
- It is possible to have uniform electric field between the plates with suitable arrangement of the plates.
- The field is uniform, normal to the two plates and directed towards the negative plate.
- If A is the area of the plate and E is the electric field intensity between the plates ε the permittivity of the medium between the plates, we know that the energy density of the electric field between the plates is given as,
- Consider a differential volume between the plates and parallel to the plates with area *A and* thickness *dx, the energy content in this differential volume Adx is*

5b

- **Effect of nearby earthed objects**
- The effect of nearby earthed objects was investigated by Kuffel by enclosing the earthed sphere inside an earthed cylinder.
- It was observed that the sparkover voltage is reduced.
- The reduction was observed to be



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

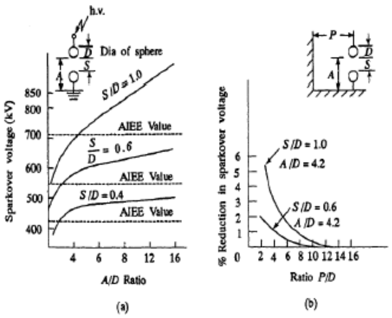
where,

ΔV = percentage reduction,

B = diameter of earthed enclosing cylinder,

D = diameter of the spheres,

S = spacing, and m and C are constants.



ii) Effect of atmospheric conditions

- The sparkover voltage of a spark gap depends on the air density which varies with the changes in both temperature and pressure.
- Let sparkover voltage = ***V*** *under test* conditions of temperature ***T*** *and pressure* ***p*** *torr*
- *sparkover voltage =V0* under standard conditions of temperature *T = 2O°C and pressure p = 760 torr, then V=kV0*
- where *k is a function of the air density factor d, given by*

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

- **Influence of Humidity**
- The a.c. breakdown voltage is slightly less than d.c. voltage.
- (ii) The breakdown voltage increases with the partial pressure of water vapour.
- It has also been observed that
- (i) The humidity effect increases with the size of spheres and is largest for uniform field electrodes.
- (ii) The voltage change for a given humidity change increase with gap length.

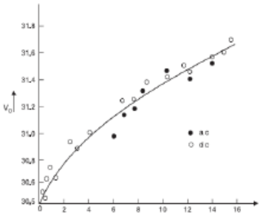
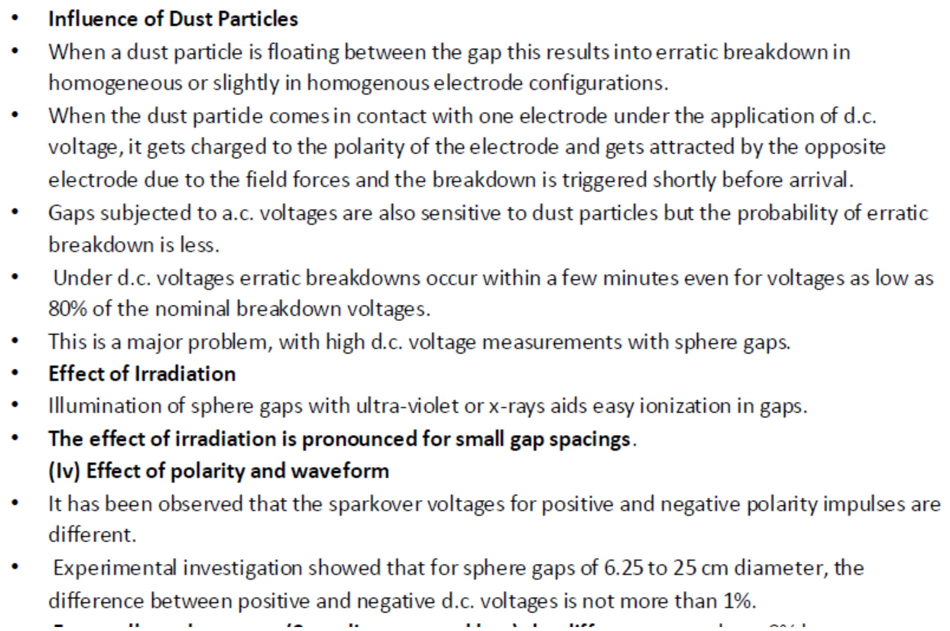


Fig. 4.4 Breakdown voltage humidity relation for a.c. and d.c. for 1.0 cm gap between 25 cms diameter spheres

- The increase in breakdown voltage with increase in partial pressure of water vapour and this increase in voltage with increase in gap length is due to the relative values of ionisation and attachment coefficients in air.
- The water partides readily attach free electrons, forming negative ions.
- Thmolecules under field conditions in which electrons will readily ionise.



- **Influence of Dust Particles**
- When a dust particle is floating between the gap this results into erratic breakdown in homogeneous or slightly in homogenous electrode configurations.
- When the dust particle comes in contact with one electrode under the application of d.c. voltage, it gets charged to the polarity of the electrode and gets attracted by the opposite electrode due to the field forces and the breakdown is triggered shortly before arrival.
- Gaps subjected to a.c. voltages are also sensitive to dust particles but the probability of erratic breakdown is less.
- Under d.c. voltages erratic breakdowns occur within a few minutes even for voltages as low as 80% of the nominal breakdown voltages.
- This is a major problem, with high d.c. voltage measurements with sphere gaps.
- **Effect of Irradiation**
- Illumination of sphere gaps with ultra-violet or x-rays aids easy ionization in gaps.
- **The effect of irradiation is pronounced for small gap spacings**.

(Iv) Effect of polarity and waveform

- It has been observed that the sparkover voltages for positive and negative polarity impulses are different.
- Experimental investigation showed that for sphere gaps of 6.25 to 25 cm diameter, the difference between positive and negative d.c. voltages is not more than 1%.

5c

2. **GENERATING VOLTMETER**

When the **source loading** is not permitted or when direct connection to the high voltage source is to be avoided, the generating principle is employed for the measurement of high voltages

Principle: A generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the voltage to be measured.

Similar to electrostatic voltmeter the generating voltmeter provides loss free measurement of d.c. and a.c. voltages.

The device is driven by an external constant speed motor and does not absorb power or energy from the voltage measuring source.

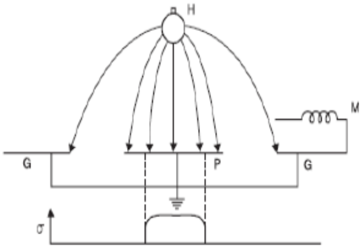


Fig. 4.8 Principle of generating voltmeter

$$i(t) = \frac{dq(t)}{dt} = \frac{d}{dt}\left[\int \sigma(a)da\right]$$

- The principle of operation explained with the help of Fig.
- **Construction:**
- H is a high voltage electrode
- the earthed electrode is subdivided into a sensing or pick up electrode P, a guard electrode G and a movable electrode M, all of which are at the same potential.
- The high voltage electrode H develops an electric field between itself and the electrodes P, G and M.
- The field lines are shown in Fig. 4.8.
- The **electric field density σ** is also shown.
- If electrode M is fixed and the voltage **V** is changed, the field density σ would change and thus a current **i (t)** would flow between P and the ground.
- If the voltage V to be measured is constant (d.c voltage), a current i(t) will flow only if it is moved i.e. now σ (a) will not be function of time but the charge q is changing because the area of the pick up electrode exposed to the electric field is changing.
  The current i(t) is given by

$$i(t) = \frac{d}{dt}\int_{A(t)} \sigma(a)da = \varepsilon\frac{d}{dt}\int_{A(t)} E(a)da$$

where **σ (a) = εE(a**) and ε is the permittivity of the medium between the high voltage electrode and the grounded electrode.

The integral boundary denotes the time varying exposed area.

The high voltage electrode and the grounded electrode in fact constitute a capacitance system. The capacitance is, however, a function of time as the area A varies with time and, therefore, the charge q(t) is given as

$$q(t) = C(t)V(t)$$

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

For d.c. voltages $\frac{dV(t)}{dt} = 0$

Hence $$i(t) = V\frac{dC(t)}{dt}$$

If the capacitance varies linearly with time and reaches its peak value C_m is time $T_c/2$ and again reduces to zero linearly in time $T_c/2$, the capacitance is given as

$$C(t) = 2\frac{C_m}{T_c}t$$

For a constant speed of n rpm of synchronous motor which is varying the capacitance, time T_c is given by $T_c = 60/n$.

Therefore $$I = 2C_m V\frac{n}{60} = \frac{n}{30}C_m V$$

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

$$C = C_0 + C_m \sin wt$$

and the current i is then given as

$$i(t) = i_m \cos wt \text{ where } i_m = VC_m\omega$$

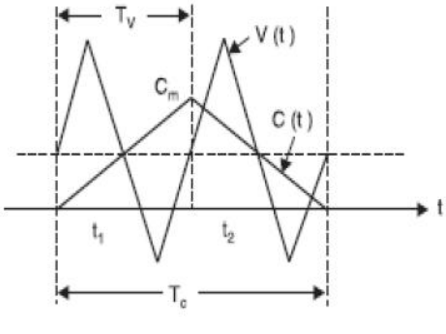


Fig. 4.9 Capacitance and voltage variation

- **ω** is the angular frequency of variation of the capacitance.
- If ω is constant the current measured is proportional to the voltage being measured.

- Generally the current is rectified and measured by a moving coil meter.

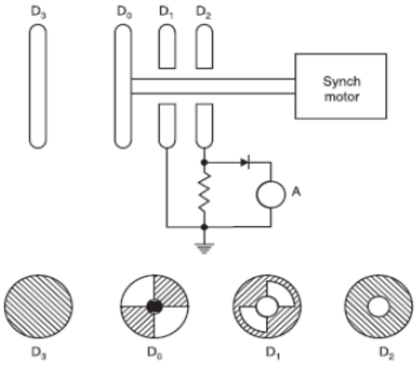


Fig. 4.10 Schematic diagram of generating voltmeter

- Fig. 4.10 shows a schematic diagram of a generating voltmeter which employs rotating vanes for variation of capacitance.
- The high voltage electrode is connected to a disc electrode *D3 which is* kept at a fixed distance on the axis of the other low voltage electrodes *D2, D1, and D0.*
- *The rotor D0 is* driven at a constant speed by a synchronous motor at a suitable speed.
- The rotor vanes of *D0 cause* periodic change in capacitance between the insulated disc *D2 and the high voltage electrode D3.*
- *The* number and shape of vanes are so designed that a suitable variation of capacitance (sinusoidal or linear) is achieved.
- The a.c. current is rectified and is measured using moving coil meters.
- If the current is small an amplifier may be used before the current is measured.

6a

4. **THE CHUBB-FORTESCUE METHOD**

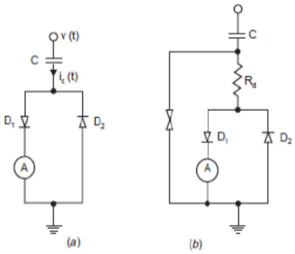
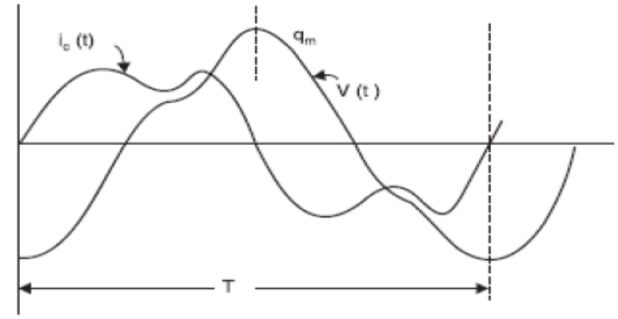


Fig. 4.11 (*a*) Basic circuit (*b*) Modified circuit

- **Chubb and Fortescue** suggested a simple and accurate method of measuring **peak value of a.c. voltages.**
- The basic circuit consists of a standard capacitor, two diodes and a current integrating ammeter (MC ammeter) as shown in Fig. 4.11 (a).
- The displacement current ic(t), Fig. 4.12 is given by the rate of change of the charge and hence the voltage V(t) to be measured flows through the high voltage capacitor C and is subdivided into positive and negative components by the back to back connected diodes.
- The voltage drop across these diodes can be neglected (1 V for Si Diodes) as compared with the voltage to be measured.
- The measuring instrument (M.C. ammeter) is included in one of the branches.
- The ammeter reads the mean value of the current.
- The relation is similar to the one obtained in case of generating voltmeters.
- An increased current would be obtained if the current reaches zero more than once during one half cycle.
- This means the wave shapes of the voltage would contain more than one maxima per half cycle.
- The standard a.c. voltages for testing should not contain any harmonics and, therefore, there could be very short and rapid voltages caused by the heavy predischarges, within the test circuit which could introduce errors in measurements.

To eliminate this problem filtering of a.c. voltage is carried out by introducing a damping resistor in between the capacitor and the diode circuit, Fig. 4.11 (



$$I = \frac{1}{T}\int_{t_1}^{t_2} C\frac{dv(t)}{dt}.dt = \frac{C}{T}.2V_m = 2V_m fC \text{ or } V_m = \frac{I}{2fC}$$

Also, if full wave rectifier is used instead of the half wave as shown in Fig. 4.11, the factor 2 in the denominator of the above equation should be replaced by 4.

Since the frequency f, the capacitance C and current I can be measured accurately, the measurement of symmetrical a.c. voltages using Chubb and Fortescue method is quite accurate and it can be used for calibration of other peak voltage measuring devices.

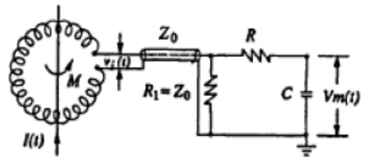
[illegible]

6b

Measurement of High Impulse Currents Using Magnetic Potentiometers

(Rogowski Coils)

- If a coil is placed surrounding a current carrying conductor, the voltage signal induced in the coil is $v_i(t) = M dI(t)/dt$
- *Where* **M** *is the mutual inductance between the conductor* and the coil, and **I** 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 conducto**r.
- The **number of turns** on the coil is chosen to be **large**, to get enough signal induced.
- The coil is wound cross-wise to reduce the leakage inductance.
- Usually an integrating circuit (see Fig. 7.52) is employed to get the output signal voltage proportional to the current to be measured.
- The output voltage is given by
-
$$V_m(t) = \frac{1}{CR}\int_0^t v_i(t) = \frac{M}{CR} I(t)$$



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

- **Fig. 7.52** Rogowski coil for high impulse current measurements

- Rogowski coils with electronic or active integrator circuits have large and widths (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.

6c

***Solution*: Assume that the driving motor has a synchronous speed of 1500 rpm.**

$$I_{\text{rms}} = \frac{VC_m}{\sqrt{2}}\,\omega$$

where, $V =$ applied voltage,
$C_m =$ capacitance of the meter, and
$\omega =$ angular speed of the drive

Substituting,

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

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

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

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

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

7a

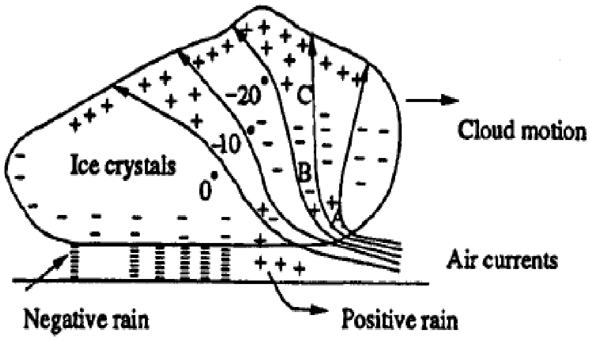


Fig. 8.2 Cloud model according to Simpson's theory

- According to **the Simpson's theory** (Fig. 8.2) there are **three essential regions** in the cloud to be considered for charge formation.
- Below region A, air currents travel above 800 cm/s, and no raindrops fall through.

In region A, air velocity is high enough to break the falling raindrops causing a positive charge spray in the cloud and negative charge in the air.

The spray is blown upwards, but as the velocity of air decreases, the positively charged water drops recombine with the larger drops and fall again.

Thus region A, eventually becomes **predominantly positively charged**, while **region B** above it, becomes **negatively charged** by air currents.

In the **upper regions in the cloud, the temperature is low (below freezing point) and only ice crystals exist**

The **impact of air** on these crystals makes them **negatively charged**, thus the distribution of the charge within the cloud becomes as shown in Fig. 8.2.

- **Reynolds and Mason** proposed modification, according to which the thunder clouds are developed at heights 1 to 2 km above the ground level and may extend up to 12 to 14 km above the ground.
- For thunder clouds and charge formation **air currents, moisture and specific temperature range** are required.
- The **air currents** controlled by the **temperature gradient** move upwards carrying

moisture and **water droplets**.

- The temperature is O^{0}C at about 4 km from the ground and may reach - 5O^{0}C at about 12 km height.
- But water droplets do not freeze as soon as the temperature is O^{0}C. They freeze below - 4O^{0}C only as solid particles on which crystalline ice patterns develop and grow.
- The larger the number of solid sites or nuclei present, the higher is the temperature (> -4O^{0}C) at which the ice crystals grow.
- Thus in clouds, the effective freezing temperature range is around - 33^{0}C to - 4O^{0}C.

The water droplets in the thunder cloud are blown up by air currents and get super

cooled over a range of heights and temperatures.

When such freezing occurs, the crystals grow into large masses and due to their weight and gravitational force start moving downwards.

Thus, a thunder cloud consists of supercooled water droplets moving upwards and large hail stones moving downwards.

When the upward moving super cooled water droplets act on cooler hail stone, it

freezes partially, i.e. the outer layer of the water droplets freezes forming a shell with

water inside.

When the process of cooling extends to inside warmer water in the core, it expands, thereby splintering and spraying the frozen ice shell. The splinters being fine in size are moved up by the air currents and carry a net positive charge to the upper region of the cloud.

The hail stones that travel downwards carry an equivalent negative charge to the lower regions of the cloud and thus negative charge builds up in the bottom side of the cloud

- According to Mason, the ice splinters should carry only positive charge upwards.
- Water being ionic in nature has concentration of H+ and OH- ions.
- The ion density depends on the temperature.
- Thus, in an ice slab with upper and lower surfaces at temperatures *T1and T2 (T1 < T2), there will be a higher concentration of ions in the* lower region.
- However, since H+ ions are much lighter, they diffuse much faster all over the volume.
- Therefore, the lower portion which is warmer will have a net negative charge density, and hence the upper portion, i.e. cooler region will have a net positive charge density.
- Hence, it must be appreciated, that the outer shells of the freezed water droplets coming into contact with hail stones will be relatively cooler (than their inner core—warmer water) and therefore acquire a net positive charge.
- When the shell splinters, the charge carried by them in the upward direction is positive.

7b

Expulsion gaps

Expulsion gap is a device which consists of a spark gap together with an arc quenching

device which extinguishes the current arc when the gaps breakover due to overvoltages.

A typical such arrangement is shown in Fig.

This essentially consists of a rod gap in air in series with a second gap enclosed within a fibre tube.

In the event of an overvoltage, both the spark gaps breakdown simultaneously.

The current due to the overvoltage is limited only by the tower footing resistance and the surge impedance of the ground wires.

The internal arc in the fibre tube due to lightning current vapourizes a small portion of the fibre material.

The gas thus produced, being a mixture of water vapour and the decomposed fibre product, drive away the arc products and ionized air.

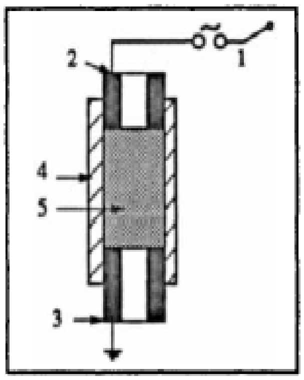
When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited.

Meanwhile the insulation recovers its dielectric strength, and the normal conditions are established.

The lightning and follow-up power frequency currents together can last for 2

to 3 half cycles only. Therefore, generally no disturbance in the network is produced.

For 132 or 220 kV lines, the maximum current rating may be about 7,500 A.



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

Fig. 8.20a Expulsion gap

) Protector tubes

A protector tube is similar to the expulsion gap in, construction and principle.

It also consists of a rod or spark gap in air formed by the line conductor and its high voltage terminal.

It is mounted underneath the line conductor on a tower.

The arrangement is shown in Fig. 8.2Ob.

The hollow gap in the expulsion tube is replaced by a nonlinear element which offers a very high impedance at low currents but has low impedance for high or lightning currents. When an overvoltage occurs and the spark gap breaksdown, the current is limited both by its own resistance and the tower footing resistance.

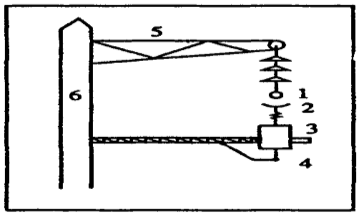
The overvoltage on the line is reduced to the voltage drop across the protector tube.

After the surge current is diverted and discharged to the ground, the follow-on normal power frequency current will be limited by its high resistance.

After the current zero of power frequency, the spark gap recovers the insulation strength quickly.

Usually, the flashover voltage of the protector tube is less than that of the line

insulation, and hence it can discharge the lightning overvoltage effectively.



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

Fig. 8.20b Protector tube mounting

8a

These are non-linear resistors in series with spark gaps which act as fast switches. A

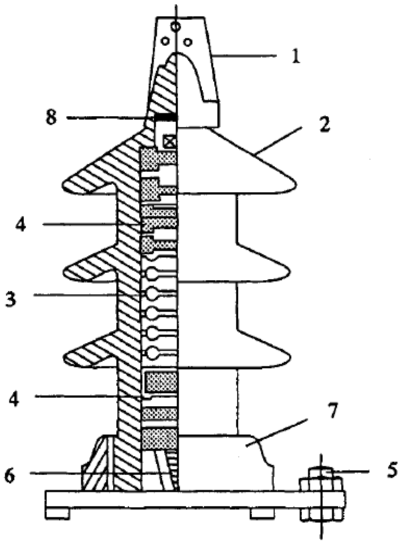
typical surge diverter or lightning arrester is shown in Fig. 8.23 and its characteristics are given in Fig. 8.24. A number of non-linear resistor elements made of silicon carbide are stacked one over the other into two or three sections. They are usually separated by spark gaps (see Fig. 8.23). the entire assembly is housed in a porcelain water-tight housing. The volt-ampere characteristic of a resistance element is of the form

$$I = kV^a$$

where, I= discharge current,

V = applied voltage across the element, and

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



1. Line end connector
2. Porcelain housing
3. Series gaps
4. Non-linear resistance element blocks
5. Ground connection
6. Spring
7. Base
8. Water tight sealing

Fig. 8.23 Non-linear element surge diverter

The lighter designs operate for smaller duration of currents, while the heavy *duty*

surge diverters with assisted or active gaps are designed for high currents and long

duration surges.

The lighter design arresters can interrupt 100 to 300 A of power frequency follow-on current and about 5000 A of surge currents.

If the current is to be more and has to be exceeded, the number of series elements has to be increased or some other method to limit the current has to be used. In heavy duty arresters, the gaps are so arranged that the arc burns in the magnetic field of the coils excited by power

frequency follow-on currents.

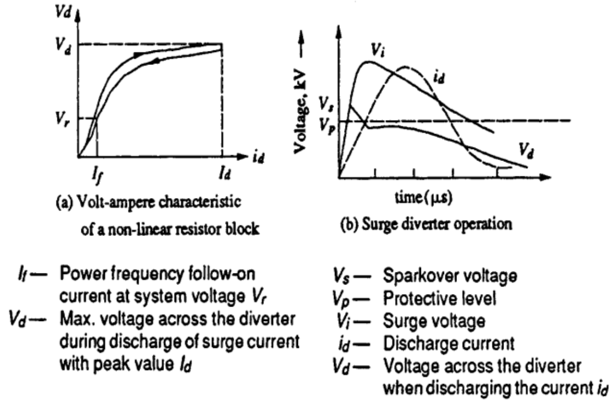
During lightning discharges, a high voltage is induced in the coil by the steep front of the surge, and sparking occurs in an auxiliary gap.

For power frequency follow-on currents, the auxiliary gap is extinguished, as sufficient

voltage will not be present across the auxiliary gap to maintain an arc.

The main gap arcs occur in the magnetic field of the coils.

The magnetic field, aided by the born shaped main gap electrodes, elongates the arc and quenches it rapidly.



(a) Volt-ampere characteristic of a non-linear resistor block

(b) Surge diverter operation

I_f — Power frequency follow-on current at system voltage V_r

V_d — Max. voltage across the diverter during discharge of surge current with peak value I_d

V_s — Sparkover voltage

V_p — Protective level

V_i — Surge voltage

i_d — Discharge current

V_d — Voltage across the diverter when discharging the current i_d

Fig. 8.24 Characteristics of a surge diverter

8bi)

Rod gaps

A much simpler and effective protective device is a rod-gap

However, it does not meet the complete requirement.

The sparkover voltage of a rod gap depends on the atmospheric conditions.

A typical volt-time characteristic of a 67 cm-rod gap is shown in Fig. with its protective margin.

There is no current limiting device provided so as to limit the current after sparkover, and hence a series resistance is often used.

Without a series resistance, the sparking current may be very high and the applied impulse voltage suddenly collapses to zero thus creating a steep step voltage, which sometimes proves to be very dangerous to the apparatus to be protected, such as transformer or the machine windings. Nevertheless, rod gaps do provide efficient protection where thunderstorm activity is less and the lines are protected by ground wires.

8bii)

Lightning Protection Using Shielded Wires or Ground Wires

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

discharge. The arrangements of ground wires over the line conductor is shown in Fig. 8.19.

The mechanism by which the line is protected may be explained as follows. If a positively charged cloud is assumed to be above the line, it induces a negative charge on the portion below it, of the transmission line. With the ground wire present, both the ground wire and the line conductor get the induced charge. But the ground wire is earthed at regular intervals, and as such the induced charge is drained to the earth potential only; the potential difference between the ground wire and the cloud and that between the ground wire and the transmission line wire will be in the inverse ratio of their respective capacitances [assuming the cloud to be a perfect conductor and the atmospheric medium (air) a dielectric]. As the ground wire is nearer to the line wire, the induced charge on it will be much less and hence the potential rise will be quite small. The effective protection or shielding given by the ground wire depends on the height of the ground wire above the ground *(H)* and the protection or shielding angle 85 (usually 30°) as shown in Fig. 8.19. The shielding angle 65 « 30° was considered adequate for tower heights of 30 m or less. The shielding wires may be one or more depending on the type of the towers used. But for EHV lines, the tower heights may be up to 50 m, and the lightning strokes sometimes occur directly to the line wires as shown in Fig. 8.19. The present trend in fixing the tower heights and shielding angles is by considering the "flashover rates" and failure probabilities.

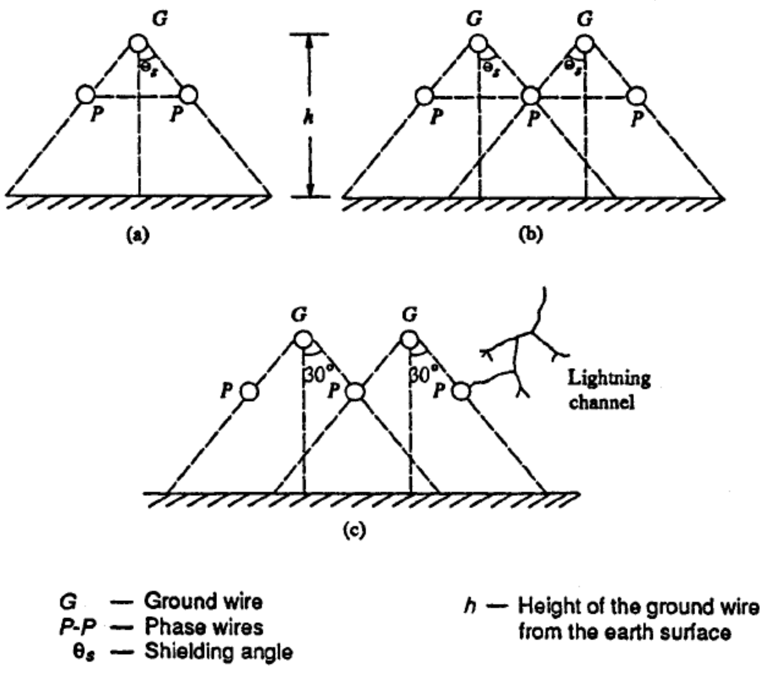
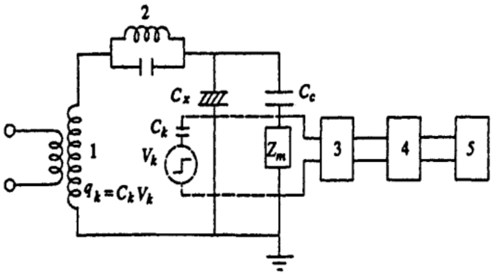


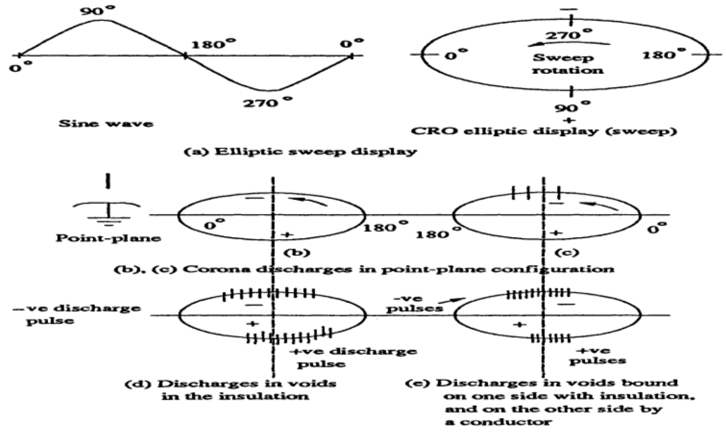
Fig. 8.19 Shielding arrangement of overhead lines by ground wires

- **Discharge Detection Using Straight Detectors**
- The circuit arrangement shown in Fig. 9.21 gives a simplified circuit for detecting "partial discharges".
- The high voltage transformer shown is free from internal discharges.
- A resonant filter is used to prevent any pulses starting from the capacitance of the windings and bushings of the transformer.
- Cx is the test object, Cc is the coupling capacitor, and Zm is a detection impedance.
- The signal developed across the impedance Zm is passed through a band pass filter and amplifier and displayed on a CRO or counted by a pulse counter multi-channel analyzer unit.



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

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



(a) Elliptic sweep display

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

(d) Discharges in voids in the insulation

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

- the discharge pattern displayed on the CRO screen of a partial discharge detector with an elliptical display is shown.
- The sinusoidal voltage and the corresponding ellipse pattern of the discharge are shown in Fig. 9.22a and a single corona pulse in a point-plane spark gap geometry is shown in Figs. 9.22b and c.
- When the voltage applied is greater than that of **the critical inception voltage,** multiple pulses appear (see Fig. 9.22c), and all the pulses are of equal magnitude.
- A typical discharge pattern in cavities inside the insulation is shown in Fig. 9.22d.

- This pattern of discharge appears on the quadrants of the ellipse which correspond to the test voltage rising from zero to the maximum, either positively or negatively.

9b

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 stress dependence of K' or εr and tanδ can be readily obtained with this bridge.
- The schematic diagram of the bridge is shown in Fig.
- The lossy capacitor or capacitor with the dielectric between electrodes is represented as an imperfect capacitor of capacitance Cx together with a resistance rx.

The standard capacitor is shown as Cs which will usually have a capacitance of 50 to 500 μF.

The variable arms are R4 and C3 /R3.

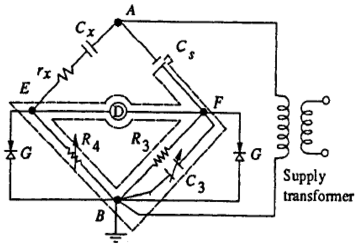
Balance is obtained when

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

where,

$$Z_1 = r_x + \frac{1}{j\omega C_x}, \qquad Z_2 = \frac{1}{j\omega C_s}$$

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



- - - dotted line is the shielding arrangement. Shield is connected to B, the ground

Fig. 9.11 Schematic diagram of a Schering bridge

$$C_x = \frac{R_3}{R_4} C_s; \text{ and } r_x \;===\; \frac{C_3}{C_2} R_1$$

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

$$= \omega C_3 R_3$$

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

$$\cos\theta_x = \sin\delta_x = \delta_x = \tan\theta_x = \omega C_2 R_3 \qquad (9.17)$$

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

$$R_x = \frac{1}{\omega^2 C_x^2 r_x} \qquad (9.18)$$

with C_x having the same value.

- The normal method of balancing is **by fixing** the value of **R3** and **adjusting C3 and** ***R4.***
- C3 giving a direct reading of tan δ.
- R4 will be a decade box with 5 to 6 decade dials.
- The maximum value of R4 is limited *to* 10^4'Ω *and the* lowest value will not be less than 0.01'Ω

This range adequately takes care of the errors due to contact resistances as well as the stray capacitance effects across *R4* which are usually very small.

It is important to see that **the resistances are pure** and not **reactive and the standard capacitor has negligible tan δ** (air or gas Filled capacitor is used).

- The arrangement shown in Fig. is suitable when the test specimen is not grounded.
- The standard condenser Cs is usually a three terminal condenser.
- The **low voltage arms** of the bridge (R4 and R3 C3) 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 impedances of the low voltage arms are such that the voltage drop across EB or FB does not exceed 10 to 20 V.

The arms will be usually rated for a maximum instantaneous voltage of 100 V.

- **SOURCES OF ERROR:**
- 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 "**Wagner earthing device**".

Compensation for the stray capacitances is given by providing a parallel *R-L circuit* across *R4.*

10a

TESTING OF TRANSFORMERS

Transformers are very important and costly apparatus in power systems. Great care has to be exercised to see that the transformers are not damaged due to transient overvoltages of either lightning or power frequency. Hence, overvoltage tests become very important in the testing of transformers. Here, only the overvoltage tests are discussed, and other routine tests like the temperature rise tests, short circuit tests, etc. 3re not included and can be found in the relevent specifications.

(a) Induced Overvoltage Test

Transformers are tested for overvoltages by exciting the secondary of the transformer from a high frequency a.c. source (100 to 400 Hz) to about twice the rated voltage. This reduces the core saturation and also limits the charging current necessary in large power transformers. The insulation withstand strength can also be checked.

(b) Partial Discharge Tests

Partial discharge tests on the windings are done to assess the discharge magnitudes and the radio interference levels (see also Sec. 10.6). The transformer is connected in a manner similar to any other equipment (see Sec. 9.4) and the discharge measurements are made. The location of the fault or void is sometimes done by using the travelling wave technique similar to that for cables. So far, no method has been standardized as to where the discharge is to be measured. Multi-terminal partial discharge measurements are recommended. Under the application of power frequency voltage, the discharge magnitudes greater than 104 pico coulomb are considered to be severe, and the transformer insulation should be such that the discharge magnitude will be far below this value.

Impulse Testing of Transformers

The purpose of the impulse tests is to determine the ability of the insulation of the transformers to withstand the transient voltages due to lightning, etc. Since the transients are impulses of short rise time, the voltage distribution along the transformer winding will not be uniform. The equivalent circuit of a transfomer winding for impulses is shown in Fig. 10.11. If an impulse wave is applied to such a network (shown in Fig. 10.11) the voltage distribution along the element will be uneven, and oscillations will be set in producing voltages much higher than the applied voltage. Impulse testing of transformers is done using both the full wave and the chopped wave of the standard impulse, produced by a rod gap with a chopping time of 3 to 6 μs. To prevent large overvoltages being induced in the windings not under test, they are short circuited and connected to ground. But the short circuiting reduces the impedance of the transformer and hence poses problems in adjusting the standard waveshape of the impulse generators. It also reduces the sensitivity of detection.

10b

Short Circuit Tests

The most important tests carried out on circuit breakers arc short circuit tests, since these tests assess the primary performance of these devices, i.e. their ability to safely interrupt the fault currents. These tests consists of determining the making and breaking capacities at various load currents and rated voltages. In the case of isolators, the short circuit tests are conducted only with the limited purpose to determine their capacity to carry the rated short circuit current for a given duration; and no breaking or making current test is done. The different methods of conducting short circuit tests are

(I) Direct Tests

(a) using a short circuit generator as the source (b) using the power utility system or network as the source.

(II) Synthetic Tests

(a) Direct Testing in the Networks or in the Fields Circuit breakers are sometimes tested for their ability to make or break the circuit under normal load conditions or under short circuit conditions in the network itself. This is done during period of limited energy consumption or when the electrical energy is diverted to other sections of the network which are not connected to the circuit under test. The advantages of field tests are:

The circuit breaker is tested under actual conditions like those that occur in a given network.

Special occasions like breaking of charging currents of long lines, very short line faults, interruption of small inductive currents, etc. can be tested by direct testing only.

to assess the thermal and dynamics effects of short circuit currents, to study applications of safety devices, and to revise the performance test procedures, etc.

The disadvantages are:

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

The necessity to interrupt the normal services and to test only at light load conditions.

Extra inconvenience and expenses in installation of controlling and measuring equipment in the Held.

Direct Testing in Short Circuit Test Laboratories In order to test the circuit breakers at different voltages and at different short circuit currents, short circuit laboratories are provided. The schematic layout of a short circuit testing laboratory is given in Fig. 10.3. It consists of a short circuit generator in association with a master circuit breaker, resistors, reactors and measuring devices. A make switch initiates the short circuit and the master circuit breaker isolates the test device from the source at the end of a predetermined time set on a test sequence controller. Also, the master circuit breaker can be tripped if the test device fails to operate properly. Short circuit generators with induction motors as prime movers are also available.

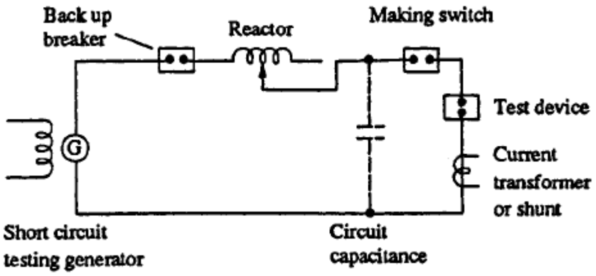


Fig. 10.3 Schematic diagram showing basic elements of a short circuit testing laboratory