GUDLAVALLERU ENGINEERING COLLEGE

(An Autonomous Institute with Permanent Affiliation to JNTUK, Kakinada)

Seshadri Rao Knowledge Village, Gudlavalleru – 521 356.

Department of Electrical and Electronics Engineering

Learning material

on

HIGH VOLTAGE ENGINEERING

UNIT – 1

BREAKDOWN IN GASEOUS AND LIQUID DIELECTRICS

Learning Objectives:

- To understand breakdown mechanisms occur in solids gases and liquid dielectrics.
- To impart the knowledge of Ionization and collision process.
- To familiarize the students with the various breakdown mechanism in pure and commercial liquids.
- To gain the knowledge on practical breakdown in solid, composite dielectrics

Syllabus:

Breakdown in Gaseous and Liquid Dielectrics

Gases as insulating media, collision process, Ionization process, Townsend's criteria of breakdown in gases, Paschen's law. Liquid as Insulator, pure and commercial liquids, breakdown in pure and commercial liquids. Intrinsic breakdown, electromechanical breakdown, thermal breakdown, breakdown of solid dielectrics in practice, Breakdown in composite dielectrics, solid dielectrics used in practice.

Learning outcomes:

Students will be able to

- Explain how electricity field intensity is controlled
- Explain the different numerical methods for solution of field problems
- Describe Ionization process.
- Discuss Townsends criteria of breakdown in gases
- Describe the different breakdown mechanism
- Discuss various Applications of insulating materials

UNIT-1

BREAK DOWN IN GASEOUS AND LIQUID DIELECTRICS

INTRODUCTION

In modern times, high voltages are used for a wide variety of applications covering the power systems, industry, and research laboratories. Such applications have become essential to sustain modern civilization. High voltages are applied in laboratories in nuclear research, in particle accelerators, and Van de Graaff generators. For transmission of large bulks of power over long distances, high voltages are indispensable. Also, voltages up to 100 kV are used in electrostatic precipitators, in automobile ignition coils, etc. X-ray equipment for medical and industrial applications also uses high voltages. Modern high voltage test laboratories employ voltages up to 6 MV or more. The diverse conditions under which a high voltage apparatus is used necessitate careful design of its insulation and the electrostatic field profiles.

1.1 GASES AS INSULATING MEDIA

The simplest and the most commonly found dielectrics are gases. Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as nitrogen (N_2), carbon dioxide (CO_2), freon (CC12F2) and sulphur hexa fluoride (SF_6) are also used. When the applied voltage is low, small currents flow between the electrode and the insulation retains its electrical properties. On the other hand, if the applied voltages are large, the current flowing through the insulation increases very sharply, and an electrical breakdown occurs. A strongly conducting spark formed during breakdown practically produces a short circuit between the electrodes. The electrical discharges in gases are of two types, i.e. (1) non-sustaining discharges, and *(2)* self-sustaining types. The breakdown in a gas, called spark breakdown is the transition of a non-sustaining discharge into a self-sustaining discharge. At present two types of theories, viz. (i) Townsend theory and *(ii)* Streamer theory are known which explain the mechanism for breakdown under different conditions. The various physical conditions of gases, namely, pressure, temperature, electrode field configuration, nature of electrode surfaces, and the availability of initial conducting particles are known to govern the ionization processes.

1.2 COLLISION PROCESS

An electric discharge is normally created from unionized gas by collision process. These processes are mainly gas processes which occur due to the collision between charged particles and gas atoms or molecules. These are of following two types

(i) Elastic collision

Elastic collisions are collisions which when occur, no charge takes place in the internal energy of the particles but only their kinetic energy gets redistributed. These collisions don't occur in practice. When electrons collide with gas molecules, a single electron traces a zig-zag path during its travel. But in between the collisions it is accelerated by the electric field. Since electrons are very light in weight, they transfer only a part of their kinetic energy to the much heavier ions or gas molecules with which they collide. This results in very little loss of energy by the electrons and therefore, electrons gain very high energies and travel at a much higher than the ions. Therefore in all electrical discharges electrons play a leading role.

(ii) Inelastic collision

Inelastic collisions, on the other hand, are those in which internal changes in energy takes place within an atom or a molecule at the expense of the total kinetic energy of the colliding particle. The collision often results in a change in the structure of the atom. Thus all collisions that occur in practice are inelastic collisions. For example ionization, attachment, excitation, recombination are inelastic collisions.

1.3 IONIZATION PROCESS

The process that is primarily responsible for the breakdown of a gas are ionization by collision, photo-ionization, and the secondary ionization processes. In insulating gases (also called electron-attaching gases) the process of attachment also plays an important role.

1.3.1 Ionization by Collision

The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionization. In the process of ionization by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion, if the energy (E) gained during this travel between collisions exceeds the ionization potential, V_i

Which is the energy required to dislodge an electron from its atomic shell, the ionization takes place. This process can be represented as

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

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

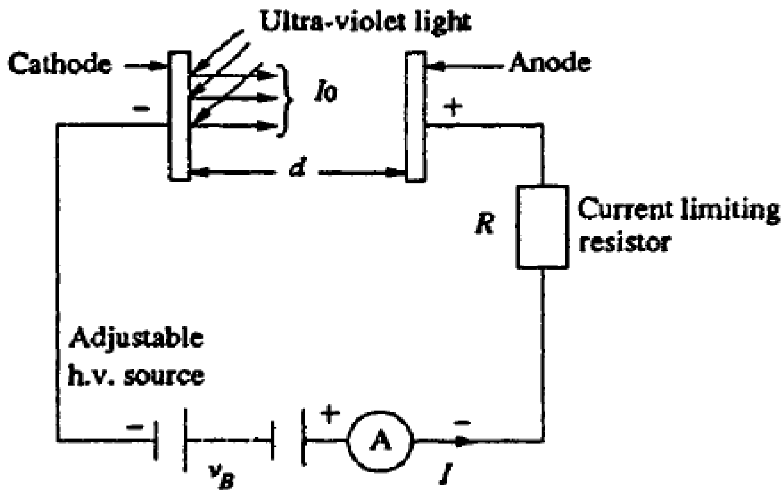

Fig: 1.1 Arrangement for study of a townsend discharge

1.3.2 Photo-ionization

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

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

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

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

Ionization occurs when

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

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

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

where V_i is in electron volts *(eV).* The higher the ionization energy, the shorter will be the wavelength of the radiation capable of causing ionization. It was observed experimentally that a radiation having a wavelength of 1250 *A*° is capable of causing photo-ionization of almost all gases.

1.3.3 Secondary Ionization Processes

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

They are briefly described below.

a)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

b)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.

$$h.\nu \geq \varphi$$

where φ is the work function of the metallic electrode. The frequency (v) is given by the relationship is known as the threshold frequency.

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

c) Electron Emission due to Metastable and Neutral Atoms

A metastable atom or molecule is an excited particle whose lifetime is very large (10^{-3}s) compared to the lifetime of an ordinary particle (10^{-8}s). Electrons can be ejected from the metal surface by the impact of excited (metastable) atoms, provided that their total energy is sufficient to overcome the work function.

1.4 TOWNSEND'S CRITERION OF BREAKDOWN IN GASES

The equation given below gives the total average current in a gap before the occurrence of breakdown. As the distance between the electrodes *d* is increased, the denominator of the equation tends to zero, and at some critical distance $d = d_s$

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

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

For values of $d < d_s$, I is approximately equal to I_O, and if the external source for the supply of I_O is removed, *I* becomes zero. If $d = d_s$, $I \to \infty$ 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

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

Normally, $\exp(\alpha d)$ is very large, and hence the above equation reduces to

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

For a given gap spacing and at a give pressure the value of the voltage *V* which gives the values of α and 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 pressures, corresponding *to p* x *d* (gas pressure x gap distance) values of 1000 torr-cm and below.

1.5 PASCHEN'S LAW

It has been shown earlier that the breakdown criterion in gases is given as

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

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

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

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

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

Substituting for *E* in the expressions for α and γ and rewriting Eq. we have

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

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

$$V = f(pd)$$

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

The sparking potentials for uniform field gaps in air, CO_2 and H_2 at 20^0c are shown in Fig. 1.2 It have been observed that the cathode materials also affect the breakdown values. This is shown in Fig. 2.8 for cathodes made of barium, magnesium and aluminum.

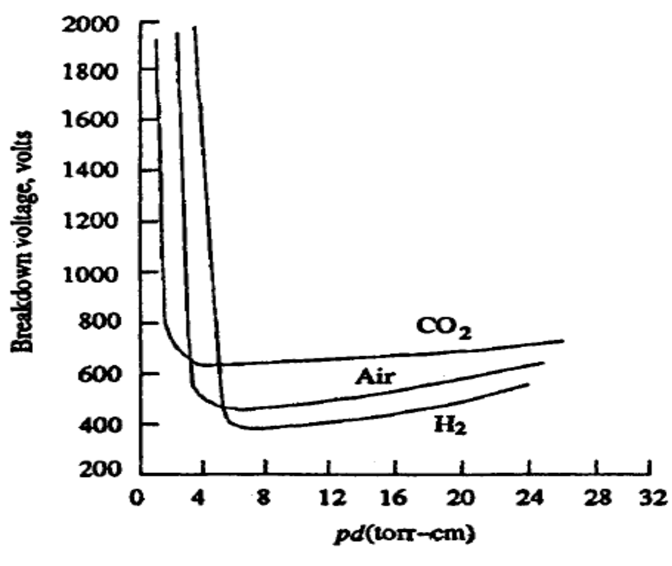

Fig: 1.2 Breakdown voltage-pd characteristics for air, CO_2 and Hydrogen

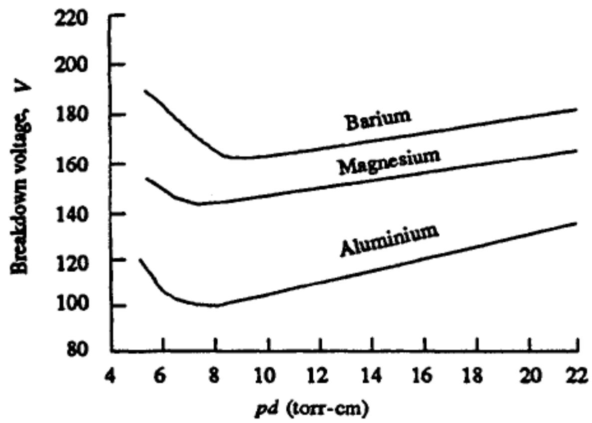

Fig: 1.3 Dependence of breakdown voltage on cathode materials

In order to account for the effect of temperature, the 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.

Based on the experimental results, the breakdown potential of air is expressed as a power function in *pd* as

$$V = 24.22\left[\frac{293\,pd}{760T}\right] + 6.08\left[\frac{293\,pd}{760T}\right]^{1/2}$$

It may be noted from the above formula that the breakdown voltage at constant pressure and temperature is not constant. At 760 ton and 2930AT

$$E = V/d = 24.22 + \left[\frac{6.08}{\sqrt{d}}\right] \text{kV/cm}$$

This equation yields a limiting value for *E* of 24 kV/cm for long gaps and a value of 30 kV/cm for *(293pd/760T)* = 1, which means a pressure of 760 torr at 20^0c with 1 cm gap. This is the usually quoted breakdown strength of air at room temperature and at atmospheric pressure.

1.6 LIQUID AS INSULATORS

Liquid dielectrics, because of their inherent properties, appear as though they would be more useful as insulating materials than either solids or gases. This is because both liquids and solids are usually 10^3 times denser than gases and hence, from Paschen's law it should follow that they possess much higher dielectric strength of the order of107 V/cm. Also, liquids, like gases, fill the complete volume to be insulated and simultaneously will dissipate heat by convection. Oil is about 10 times more efficient than air or nitrogen in its heat transfer capability when used in transformers. Although liquids are expected to give very high dielectric strength of the order of 10 MV/cm, in actual practice the strengths obtained are only of the order of 100 kV/cm. Liquid dielectrics are used mainly as impregnates in high voltage cables and capacitors, and for filling up of transformers, circuit breakers etc. Liquid dielectrics also act as heat transfer agents in transformers and as arc quenching media in circuit breakers

Electrical Properties

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

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

(b) its resistivity

(c) its loss tangent (tan Ƨ) or its power factor which is an indication of the power loss under AC voltage application

(d) its ability to withstand high electric stresses.

1.7 PURE LIQUIDS AND COMMERCIAL LIQUIDS

Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 109, and are structurally simple. Examples of such simple pure liquids are *n*-hexane (C_6H_{14}), *n*-heptane (C_7H_{16}) and other paraffin hydrocarbons. On the other hand, the commercial liquids which are insulating liquids like oils which are not chemically pure, normally consist of mixtures of complex organic molecules which cannot be easily specified or reproduced in a series of experiments.

1.8 BREAKDOWN IN PURE AND COMMERCIAL LIQUIDS

1.8.1 Breakdown in pure liquids

When low electric fields less than 1 kV/cm are applied, conductivities of 10^{-18} – 10^{-20} mho/cm are obtained. These are probably due to the impurities remaining after purification. However, when the fields are high (> 100 kV/cm) the currents not only increase rapidly, but also undergo violent fluctuations which will die down after sometime. A typical mean value of the conduction current in hexane is shown in Fig. 1.4. This is the condition nearer to breakdown. However, if this figure is redrawn starting from very small currents, a current-electric field characteristic as shown in Fig. 1.5, can be obtained. This curve will have three distinct regions as shown. At very tow fields the current is due to the dissociation of ions. With intermediate fields the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from the cathode gets multiplied in the liquid medium by a Townsend type of mechanism. The current multiplication also occurs from the Electrons generated at the interfaces of liquid and impurities. The increases in current by these processes continue still breakdown occurs.

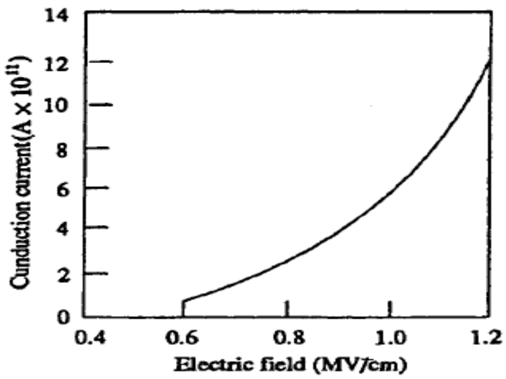

Fig: 1.4 Conduction current-electric field characteristic in hexane at high fields

The exact mechanism of current growth is not known; however, it appears that the electrons are generated from the cathode by field emission of electrons. The electrons o liberated get multiplied by a process similar to Townsend's primary and secondary ionization in gases the breakdown field Is approached, the current increases rapidly due to a process similar to the primary ionization process and also the positive ions reaching the cathode generate-secondary electrons, leading to breakdown. The breakdown voltage depends on the field, gap separation, cathode work-function, and the temperature of the cathode. In addition, the liquid viscosity, the liquid temperature, the density, and the molecular structure of the liquid also influence the breakdown strength of the liquid.

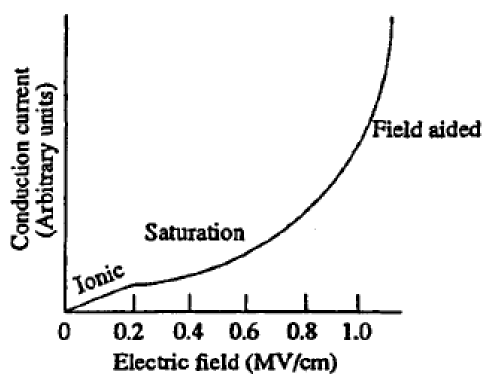

Fig: 1.5 Conduction current-electric field characteristic in a hydrocarbon liquid

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1.8.2 Breakdown in commercial liquids

The breakdown mechanisms are also considerably influenced by the presence of these impurities. In addition, when breakdown occurs in these liquids, additional gases and gas bubbles are evolved and solid decomposition products are formed. The electrode surfaces become rough, and at times explosive sounds are heard due to the generation of impulsive pressure through the liquid.

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

(a) Suspended Particle Mechanism

(b) Cavitation and Bubble Mechanism

(c) Stressed Oil Volume Mechanism

These are explained briefly below.

(a) Suspended Particle Theory

In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres or as dispersed solid particles. The permittivity of these particles *(e_2)* will be different from the permittivity of the liquid (e_1). If we consider these impunities to be spherical particles of radius r, and if the applied field is *E,* then the particles experience a force F, where

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

This force is directed towards areas of maximum stress, if $e_2 > e_1$ for example, in the case of the presence of solid particles like paper in the liquid. On the other hand, if only gas bubbles are present in the liquid, i.e. e2 < e1, the force will be in the direction of areas of lower stress. If the voltage is continuously applied (d.c.) or the duration of the voltage is long (a.c.), then this force drives the particles towards the areas of maximum stress. If the number of particles present is large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes. If there is only a single conducting particle between the electrodes, it will give rise to local field enhancement depending on its shape. If this field exceeds the breakdown 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.

(b) Cavitation and the Bubble Theory

It was experimentally observed that in many liquids, the breakdown strength depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of 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 between 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

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

where σ is the surface tension of the liquid, e_1 is the permittivity of the liquid, e_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).

(c) Stressed Oil Volume Theory

In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the "largest possible impurity" or “weak link”. On a statistical basis it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region. In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress (E_{max}) contour and 0.9 E_{max} contour. According to this theory the breakdown strength is inversely proportional to the stressed oil volume. The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage. The variation of the breakdown voltage stress with the stressed oil volume is shown in Fig. 1.6.

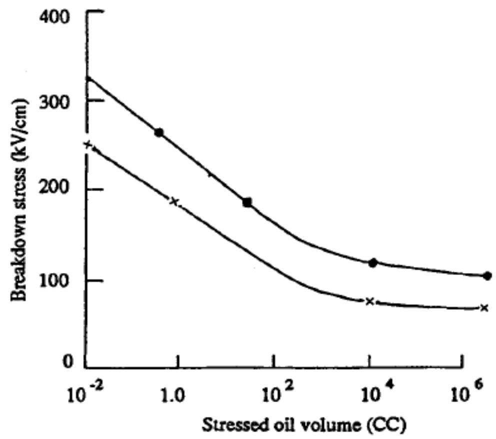


Fig: 1.6 Power frequency (50 Hz) a.c. breakdown stress as a function of the stressed oil volume

Breakdown in Solid Dielectrics

Introduction:

The various breakdown mechanisms can be classified as follows: (a) intrinsic or ionic breakdown, (b) electromechanical breakdown, (c) failure due to treeing and tracking, (d) thermal breakdown, (e) electrochemical breakdown, and (J) breakdown due to internal discharges.

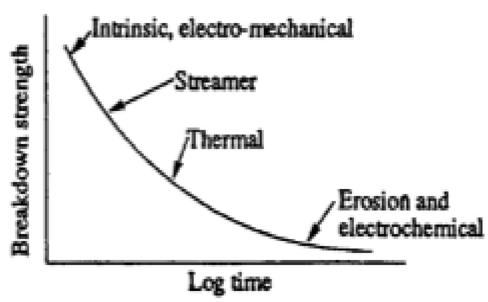


Fig: 1.7 Variation of breakdown strength with time after application of voltage

1.9 INTRINSIC BREAKDOWN

When voltages are applied only for short durations of the order of 10""8S the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength Usually, a small number of conduction elections are present in solid dielectrics, along with some structural imperfections and small amounts of impurities. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have been proposed.

1.9.1 Electronic Breakdown

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

1.9.2 Avalanche or Streamer Breakdown

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

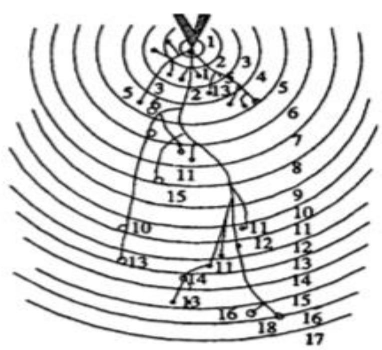


Fig 1.8 Breakdown channels in Perspex between point plane electrodes

1.10 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

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

Where Y is the Young's modulus,

From above equation

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

Usually, mechanical instability occurs when

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

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

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

1.11 THERMAL BREAKDOWN

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

When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material. The current heats up the specimen and the temperature 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

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

Where, σ is the D.C. conductivity of the specimen. Under a.c. fields, the heat generated

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

Where, f= frequency in Hz, δ= loss angle of the dielectric material, and E_{rms} value.

The heat dissipated (W_T) is given by

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

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 (W_{dc} or W_{ac}.) becomes equal to the heat dissipated (W_T). In actual practice there is always some heat that is radiated out Breakdown occurs when W_{dc} or W_{ac} exceeds W_T. The thermal instability condition is shown in Fig. 1.9. Here, the heat lost is shown by a straight line, while the heat generated at fields E_1 and E_2 are shown by separate curves. At field E_2breakdown occurs both at temperatures T_A and T_B. In the temperature region of T_A and T_B heat generated is less than the heat lost for the field E_2 and hence the breakdown will not occur.

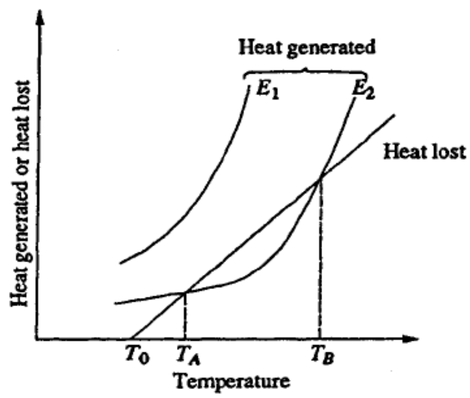


Fig. 1.9 Thermal instability in solid dielectrics

1.12 BREAKDOWN OF SOLID DIELECTRICS IN PRACTICE

There are certain types of breakdown which do not come under either intrinsic breakdown or thermal breakdown, but actually occur after prolonged operation.

Chemical and Electrochemical Deterioration and Breakdown

In the presence of air and other gases some dielectric materials undergo chemical changes when subjected to continuous electrical stresses. Some of the important chemical reactions that occur are: Oxidation: In the presence of air or oxygen, materials such as rubber and polyethylene undergo oxidation giving rise to surface cracks. Hydrolysis: When moisture or water vapour is present on the surface of a solid dielectric, hydrolysis occurs and the materials lose their electrical and mechanical properties. Electrical properties of materials such as paper, cotton tape, and other cellulose materials deteriorate very rapidly due to hydrolysis. Plastics like polyethylene undergo changes, and their service life considerably reduces.

Breakdown Due to Treeing and Tracking

When a solid dielectric subjected to electrical stresses for a long time fails, normally two kinds of visible markings are observed on the dielectric materials. They are: (a) the presence of a conducting path across the surface of the insulation; (b) a mechanism whereby leakage current passes through the conducting path finally leading to the formation of a spark. Insulation deterioration occurs as a result of these sparks. The spreading of spark channels during tracking, in the form of the branches of a tree is called treeing

Breakdown Due to Internal Discharges

Let us consider a dielectric between two conductors as shown. If we divide the insulation into three parts, an electrical network of $C_{1,}C_2\ and\ C_3$ can be formed as shown in Fig. 1.10. 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 the rest of the dielectric. When the applied voltage is V, the voltage across the void, V_1 is given by the same equation as

$$V_1 = \frac{Vd_1}{d_1 + (\frac{\varepsilon_1}{\varepsilon_2})d_2}$$

where d_1 and d_2 are the thickness of the void and the dielectric, respectively, having permittivities ε_0 and ε_1. Usually d_1 <<d_2, and if we assume that the cavity is filled with a gas, then

$$V_1 = V\varepsilon_{\mathrm{r}}\,(\frac{d_1}{d_2})$$

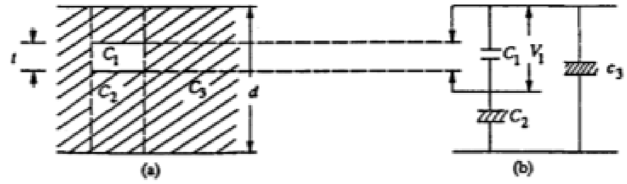


Fig: 1.10 Electrical discharge in a cavity and its equivalent circuit

Where ε_r is the relative permittivity of the dielectric When a voltage V is applied, V_1 reaches the breakdown strength of the medium in the cavity (V_i) and breakdown occurs. V_i is called the "discharge inception voltage". When the applied voltage is a.c., breakdown occurs on both the half cycles and the number of discharges will depend on the applied voltage. The voltage and the discharge current waveforms are shown in Fig. 1.11. When the first breakdown across the cavity occurs the breakdown voltage across 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 and again, and current pulses as shown, will be obtained both in the positive and negative half cycles.

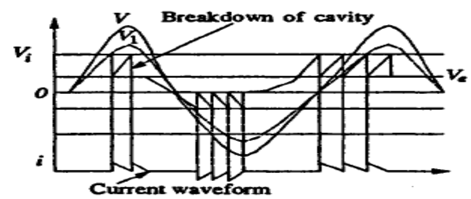


Fig: 1.11 Sequence of cavity breakdown under alternating voltages

These internal discharges (also called partial discharges) will have the same effect as "treeing" on the insulation. 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.

1.13 BREAKDOWN IN COMPOSITE DIELECTRICS

Introduction

It is difficult to imagine a complete insulation system in electrical equipment which does not consist of more than one type of insulation. If an insulation system as a whole is considered, it will be found that more than one insulating material is used. These different materials can be in parallel with each other, such as air or SF6 gas in parallel Current waveform Breakdown of cavity with solid insulation or in series with one another. Such insulation systems are called composite dielectrics.

Mechanisms of Breakdown in Composite Dielectrics

As mentioned in the earlier section, if dielectric losses are low the cumulative heat produced will be low and thermal breakdown will not occur. However, several other factors can cause short and long time breakdown.

(a) Short-Term Breakdown

If the electric field stresses are very high, failure may occur in seconds or even faster without any substantial damage to the insulating surface prior to breakdown. It has been observed that breakdown results from one or more discharges when the applied voltage is close to the observed breakdown value.

(b) Long-Term Breakdown

Long-term breakdown is also called the ageing of insulation. The principal effects responsible for the ageing of the insulation which eventually leads to breakdown arise from the thermal processes and partial discharges. In addition, the charge accumulation and conduction on the surface of the insulation also contributes significantly towards the ageing and failure of insulation.

(i) Ageing and breakdown due to partial discharges during the manufacture of composite insulation, gas filled cavities will be present within the dielectric or adjacent to the interface between the conductor and the dielectric. When a voltage is applied to such a system, discharges occur within the gas-filled cavities. These discharges are called the “partial discharges” and involve the transfer of electric charge between the two points in sufficient quantity to cause the discharge of the local capacitance

(ii) Ageing and breakdown due to accumulation of charges on insulator surfaces During discharges at the solid or liquid or solid-gas or solid-vacuum interfaces, certain quantity of charge (electrons or positive ions) gets deposited on the solid insulator surface. The charge thus deposited can stay there for very long durations, lasting for days or even weeks. The presence of this charge increases the surface conductivity thereby increasing the discharge magnitude in subsequent discharges. Increased discharge magnitude in subsequent discharges causes damage to the dielectric surface.

1.14 SOLID DIELECTRICS USED IN PRACTICE

The majority of the insulating systems used in practice are solids. They can be broadly classified into three groups: organic materials, inorganic materials and synthetic polymers. Organic materials are those which are produced from vegetable or animal matter and all of them have similar characteristics. They are good insulators and can be easily adopted for practical applications. However, their mechanical and electrical proper- ties always deteriorate rapidly when the temperature exceeds 100^0C. Therefore, they are generally used after treating with a varnish or impregnation with oil. Examples are paper and press board used in cables, capacitors and transformers.

Inorganic materials, unlike the organic materials, do not show any appreciable reduction (< 10%) in their electrical and mechanical properties almost up to 250^0C. Important inorganic materials used for electric applications are glasses and ceramics. They are widely used for the manufacture of insulators, bushings etc., because of their resistance to atmospheric pollutants and their excellent performance under varying conditions of temperature and pressure.

Synthetic polymers are the polymeric materials which possess excellent insulating properties and can be easily fabricated and applied to the apparatus. These are generally divided into two groups, the thermoplastic and the thermosetting plastic types. Although they have low melting temperatures in the range $100^0 - 120^0$C, they are very flexible and can be moulded and extruded at temperatures below their melting points. They are widely used in bushings, insulators etc. Their electrical use depends on their ability to prevent the absorption of moisture. Some of the important dielectric properties of the above materials are discussed below

(a) Paper

The kind of paper normally employed for insulation purposes is a special variety known as tissue paper or Kraft paper. The thickness and density of paper vary depending on the application. Low-density paper (0.8 gms/cm^3) is preferred in high frequency capacitors and cables, while medium density paper is used in power capacitors. High-density papers are preferable in d.c. and energy storage capacitors and for the insulation of d.c. machines. Paper is hygroscopic. Therefore, it has to be dried and impregnated with impregnants, such as mineral oil, chlorinated diphenyl and vegetable oils. The relative dielectric constant of impregnated paper depends upon the permittivity of cellulose of which the paper is made, and permittivity of the impregnant and the density of the paper.

(b) Fibers

Fibres when used for electrical purposes will have the ability to combine strength and durability with extreme fineness and flexibility. The fibres used are both natural and man-made. They include cotton, jute, flax, wool, silk (natural fibres), rayon, nylon, terylene, teflon and fibre glass. The properties of fibrous materials depend on the temperature and humidity. Figures 1.12 and 1.13 show the variation of ε_r and tanδ of various fibrous materials as a function of the frequency. It can be observed from these figures that ε_r decrease with frequency, while tanδ is higher at lower frequencies. Most of the perfectly-dried fibres have a dielectric constant between 3 and 8. The presence of ionic impurities (e.g., salt) considerably reduces the electrical resistance of the fibre. Artificial fibres, such as terylene and fibre glass absorb very little water and hence have very high resistance.

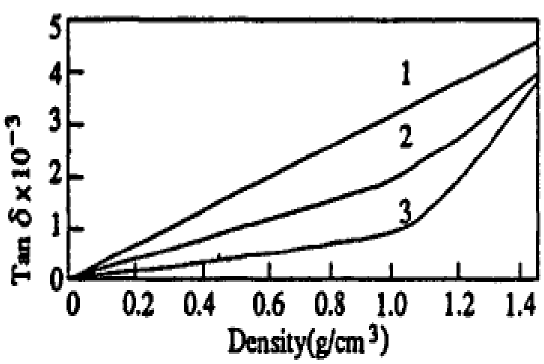


Fig: 1.12 variation of tanδ with density of paper

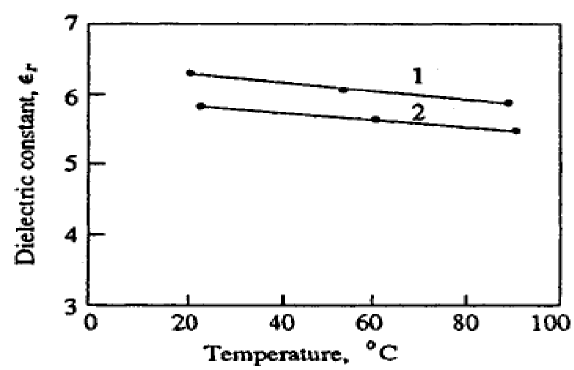


Fig: 1.13 variation of dielectric constant with temperature

(c) Mica and its products

Mica is the generic name of a class of crystalline mineral silicates of alumina and potash. It can be classified into four main groups: (i) muscovite, (ii) phlogopite, (iii) fibiolite, and (iv) lipidolite. The last two groups are hard and brittle and hence are unsuitable for electrical insulation purposes. Mica can be split into very thin flat laminae. It has got a unique combination of electrical properties, such as high dielectric strength, low dielectric losses, resistance to high temperatures and good mechanical strength. These have made it possible for it to be used in many electrical apparatus. Very pure mica is used for high frequency applications. Spotted mica is used for low voltage insulation, such as for commutator segment separators, armature windings, switchgear and in electrical heating and cooling equipments.

(d) Glass

Glass is a thermoplastic inorganic material comprising complex systems of oxides (SiO2). The dielectric constant of glass varies from 3.7 to 10 and the density varies from 2.2 to 6 g/cm. At room temperature, the volume resistivity of glass varies from 10^{10} to 10^{20} ohm-cm. The dielectric loss of glass varies from 0.004 to 0.020 depending on the frequency. The losses are highest at lowest frequencies. The dielectric strength of glass varies from 3000 to 5000 kV/cm and decreases with increase in temperature, reaching half the value at 100^0C. Glass is used as a cover and for internal supports in electric bulbs, electronic valves, mercury arc switches, x-ray equipment, and capacitors and as insulators in telephones.

(e) Ceramics

Ceramics are inorganic materials produced by consolidating minerals into monolithic bodies by high temperature heat treatment. Ceramics can be divided into two groups depending on the dielectric constant. Low permittivity ceramics (ε_r < 12) are used as insulators, while the high permittivity ceramics (ε_r > 12) are used in capacitors and transducers.

(f) Rubber

Rubber is a natural or synthetic vulcanizable high polymer having high elastic properties. Electrical properties of rubber depend on the degree of compounding and vulcanizing. General impurities, chemical changes due to ageing, moisture content and variations in temperature and frequency have substantial effects on the electrical properties of rubber.

UNIT – II

GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

Learning Objectives:

- To understand Different high voltage generation methods.
- To impart the knowledge High AC and DC currents.
- To familiarize the students with the various mechanism in Generation of Impulse voltage and current.
- To gain the knowledge on Tripping mechanism.

Syllabus:

Generation Of High Voltages And High Currents:

Generation of High Direct Current Voltages, Generation of High alternating voltages, Generation of Impulse Voltages, Generation of Impulse currents, Tripping and control of impulse generators.

Learning outcomes:

Students will be able to

- Explain the working Half and Full wave rectifier circuits
- Explain the operation of voltage doubler and multiplier circuit
- Describe the functions of van degraff generator
- Describe about cascade and resonant transformer
- Describe about standard impulse waveshape.
- Discuss about Tripping Mechanism

GENERATION OF HIGH VOLTAGES AND HIGH CURRENTS

In the fields of electrical engineering and applied physics, high voltages (DC, AC, and impulse) are required for several applications. For example, electron microscopes and x-ray units require high DC voltages of the order of 100 kV or more. Electrostatic precipitators, particle accelerators in nuclear physics, etc. require high voltages (DC) of several kilovolts and even megavolts.

Different forms of high voltages are classified as

(i) high DC voltages
(ii) high AC voltages of power frequency.
(iii) high AC voltages of high frequency.
(iv) high transient or impulse voltages of very short duration such as lightning over voltages, and
(v) transient voltages of longer duration such as switching surges.

2.1 GENERATION OF HIGH DC VOLTAGES

Generation of high DC voltages is mainly required in research work in the areas of pure and applied physics. Sometimes, high direct voltages are needed in insulation tests on cables and capacitors. Impulse generator charging units also require high DC voltages of about 100 to 200 kV. Normally, for the generation of DC voltages of up to 100 kV, electronic valve rectifiers are used and the output currents are about 100 mA.

Half and Full Wave Rectifier Circuits

Rectifier circuits for producing high DC voltages from AC sources may be (a) half wave, (b) full wave, or (c) voltage doubler type rectifiers. The rectifier may be an electron tube or a solid state device. Now-a-days single electron tubes are available for peak inverse voltages up to 250 kV, and semiconductor or solid state diodes up to 20 kV. For higher voltages, several units are to be used in series. When a number of units are used in series, transient voltage distribution along each unit becomes non-uniform and special care should be taken to make the distribution uniform.

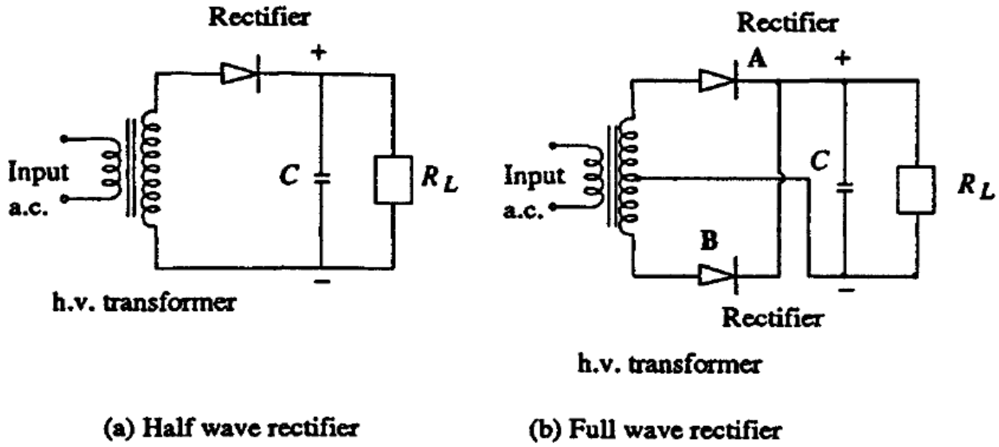


Fig: Full and half wave rectifiers

Commonly used half wave and full wave rectifiers are shown in Fig (a) and (b). In the half wave rectifier (Fig: a) the capacitor is charged to V_{max}, the maximum AC voltage of the secondary of the high voltage transformer in the conducting half cycle. In the other half cycle, the capacitor is discharged into the load. The value of the capacitor *C* is chosen such that the time constant CR_L is at least 10 times that of the period of the AC supply. The rectifier valve must have a peak inverse rating of at least $2V_{max.}$ To limit the charging current, an additional resistance R is provided in series with the secondary of the transformer (not shown in the figure). A full wave rectifier circuit is shown in (Fig: b). In the positive half cycle, the rectifier A conducts and charges the capacitor C, while in the negative half cycle the rectifier B conducts and charges the capacitor. The source transformer requires a centre tapped secondary with a rating of *2V.* Both full wave and half wave rectifiers produce DC voltages less than the AC maximum voltage. Also, ripple or the voltage fluctuation will be present, and this has to be kept within a reasonable limit by means of filters.

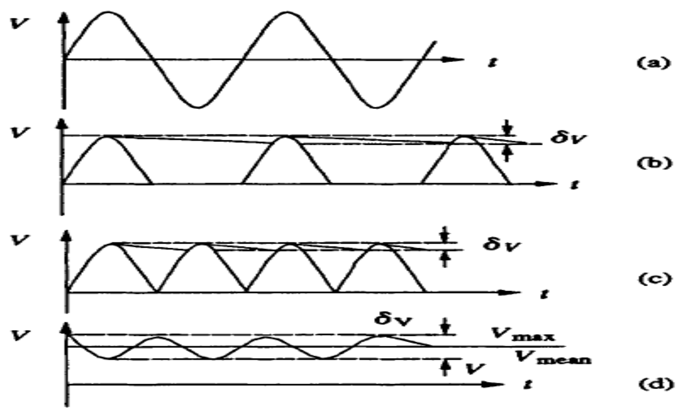


Fig 1: Input and output waveforms of half and full wave rectifiers

(a) Input sine wave
(b) Output with half wave rectifier and condenser filter
(c) Output with full wave rectifier and condenser filter
(d) V_{max}, V_{mean} and ripple voltage and δV with condenser filter of a full wave rectifier

Voltage Doubler Circuits

Both full wave and half wave rectifier circuits produce a DC voltage less than the AC maximum voltage. When higher DC voltages are needed, a voltage doubler or cascaded rectifier doubler circuits are used. The schematic diagram of voltage doublers are given in Fig (c). In voltage doubler circuit shown in Fig. c, the condenser C_1 is charged through rectifier R to a voltage of $+V_{max}$ with polarity as shown in the figure during the negative half cycle. As the voltage of the transformer rises to positive V_{max} during the next half cycle, the potential of the other terminal of C_1 rises to a voltage of $+2V_{max}$. Thus, the condenser C_2 in turn is charged through R_2 to $2V_{max}$. Normally the DC output voltage on load will be less than $2V_{max}$, depending on the time constant C_2 and the forward charging time constants. The ripple voltage of these circuits will be about 2% for $R_2/r \leq 10$ and $X/r \leq 0.25$, where X and r are the reactance and resistance of the input transformer. The rectifiers are rated to a peak inverse voltage of $2V_{max}$, and the condensers C_1 and C_2 must also have the same rating. If the load current is large, the ripple also is more.

Cascaded voltage doublers are used when larger output voltages are needed without changing the input transformer voltage level. A typical voltage doubler is shown in Fig (d) and its input and output waveforms are shown in Fig (e). The arrangement may be extended to give 6V, 8V, and so on by repeating further stages with suitable isolating transformers. In all the voltage doubler circuits, if valves are used, the filament transformers have to be suitably designed and insulated, as all the cathodes will not be at the same potential from ground. The arrangement becomes cumbersome if more than 4V is needed with cascaded steps.

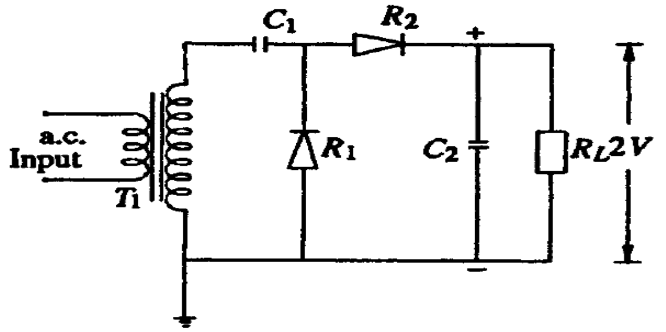


Fig (c): Simple voltage doubter

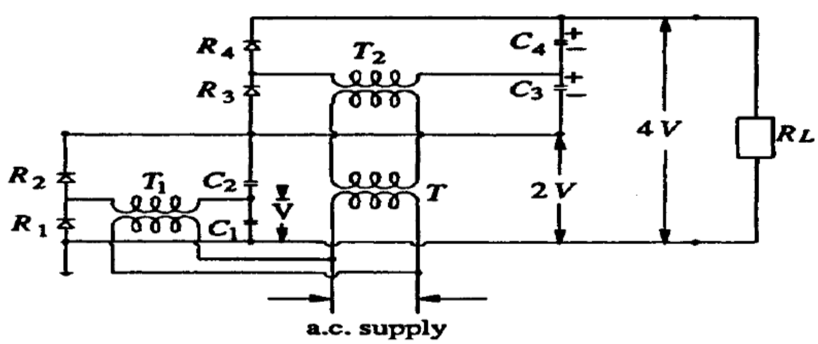


Fig (d): Cascaded voltage doubler

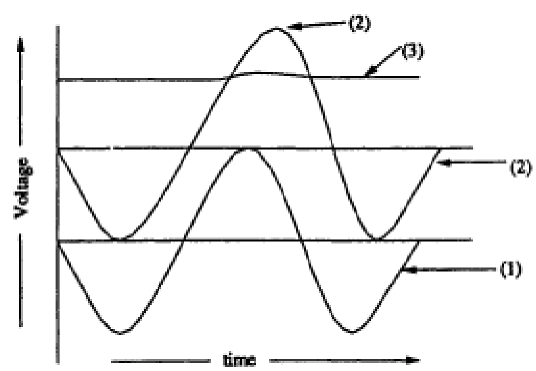


Fig (e): Waveforms of AC voltage and the DC output voltage on no-load of the voltage doublet shown in Fig(c). (1) AC input voltage waveform, (2) AC output voltage waveform without condenser filter, (3) AC output voltage waveform with condenser filter

Voltage Multiplier Circuits

Cascaded voltage multiplier circuits for higher voltages are cumbersome and require too many supply and isolating transformers. It is possible to generate very high DC voltages from single supply transformers by extending the simple voltage doubler circuits. A typical circuit of this form is shown in Fig: 2.

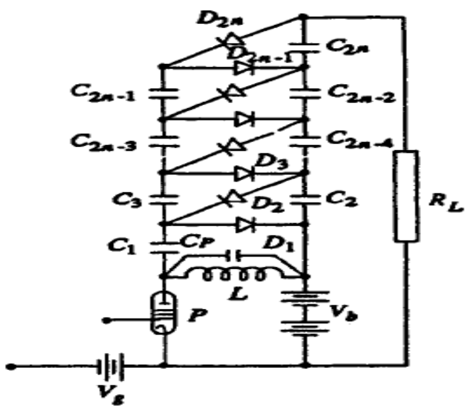


Fig: 2. Cascaded rectifier unit with pulse generator

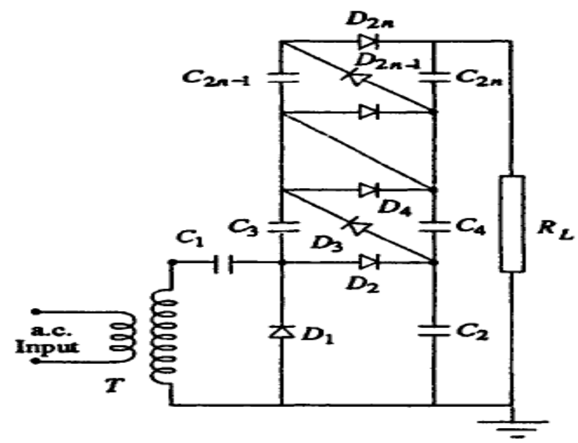


Fig: 3. Cock-craft Walton voltage multiplier circuit

The pulses generated in the anode circuit of the valve *P* are rectified and the voltage is cascaded to give an output of $2nV_{max}$ across the load R_L. A trigger voltage pulse of triangular waveform (ramp) is given to make the valve switched on and off. Thus, a voltage across the coil L is produced and is equal to $V_{max} = I\sqrt{L/C_p}$, where C_p is the stray capacitance across the coil of inductance L. A DC power supply of about 500V applied to the pulse generator, is sufficient to generate a high voltage DC of 50 to 100 kV with suitable number of stages. The pulse frequency is high (about 500 to 1000Hz) and the ripple is quite low (<1%). The voltage drop on load is about 5% for load currents of about 150µA. The voltage drops rapidly at high load currents.

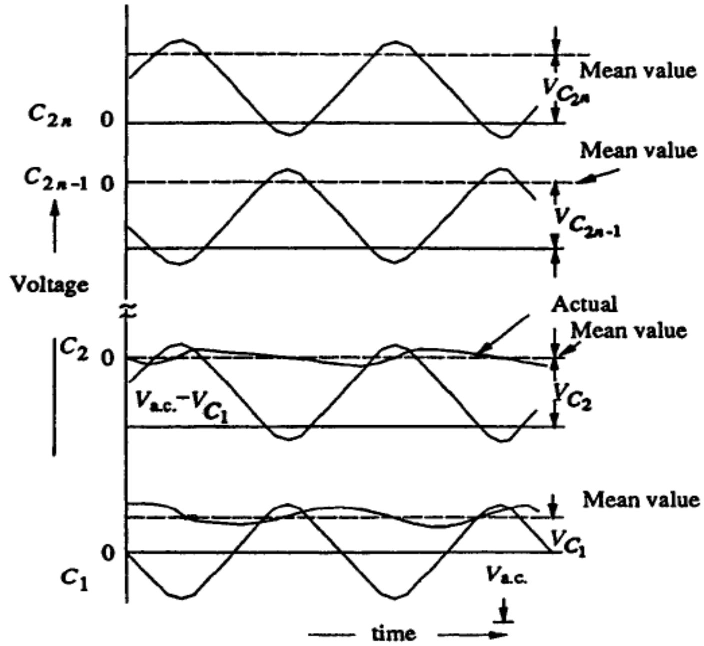


Fig 4: Voltage waveforms across the first and the last capacitors of the cascaded voltage multiplier circuit

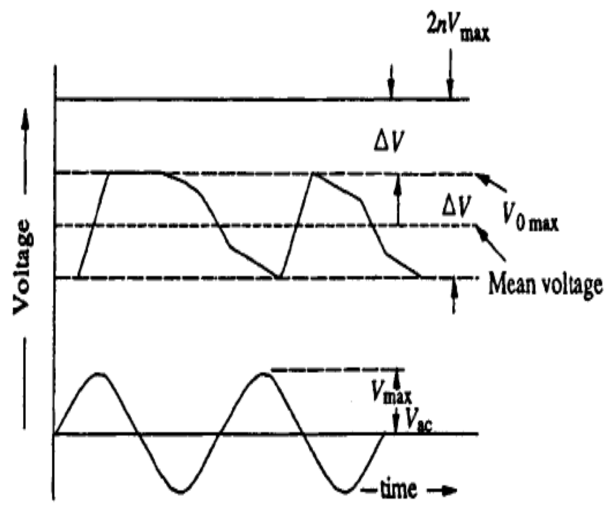


Fig 5: Ripple voltage and the voltage drop in a cascaded voltage multiplier circuit

Voltage multiplier circuit using the Cockcroft-Walton principle is shown in Fig: 3. The first stage, i.e. D_1, D_2, C_1, C_2, and the transformer *T* are identical as in the voltage doubler circuit. For higher output voltage of 4.6,... 2n of the input voltage *V,* the circuit is repeated with cascade or series connection. Thus, the condenser C_4 is charged to $4V_{max}$ and C_{2n} to $2nV_{max}$ above the earth potential. But the volt across any individual condenser or rectifier is only $2V_{max}$. The rectifiers D_1, D_3,...D_{2n-1} shown in Fig: 3 operate and conduct during the positive half cycles while the rectifiers D_2, D_4... D_{2n} conduct during the negative half cycles. Typical voltage waveforms of such a circuit are shown in Fig: 4. the mean voltage on C_2 is less than the positive peak charging voltage ($V_{ac} + V_{c1}$). The voltages across other condensers *C2* to C_{2n} can be derived in the same manner, (i.e.) from the difference between voltage across the previous condenser and the charging voltage. Finally the voltage after *2n* stages will be $V_{ac}(n_1 + n_2 + ...)$, where $n_1, n_2, ...$ are factors when ripple and regulation are considered in the next rectifier. The ripple voltage δV and the voltage drop ΔV in a cascaded voltage multiplier unit are shown in Fig. 5.

Ripple In Cascaded Voltage Multiplier Circuits

With load, the output voltage of the cascaded rectifiers is less than $2nV_{max}$, where n is the number of stages. The ripple and the voltage regulation of the rectifier circuit may be estimated as follows.

Let f is supply frequency,

q = charge transferred in each cycle, i_1 = load current from the rectifier,

t_1 = conduction period of the rectifiers, t_2 = non-conduction period of rectifiers, and

δV =ripple voltage.

Referring to Fig (c), when load current I_1 is 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 is related as follows.

$$I_1 = \frac{dq}{dt} \cong \frac{q}{t_2}$$

At the same time a charge q is transferred from C1to C2 during each cycle of

$$I_1 = \frac{dq}{dt} \cong \frac{q}{t_2}$$

Since $t_1 < t_2$ and $t_1 + t_2 = \frac{1}{f}$ (i.e. the period of these AC supply voltage),

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

Also, $q = C_2 \delta V$

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

At the same time a charge q is transferred from C_1 to C_2 during each cycle of $x = \frac{I_1}{fC_2}$

Hence, regulation = mean voltage drop from $2V_{max}$

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

Therefore, the mean output voltage

$$= 2V_{max} - \frac{I_1}{f}\left[\frac{1}{C_1} + \frac{1}{2C_2}\right]$$

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

Referring to above Fig: 3, to find an expression for the total ripple voltage, let it be assumed that all capacitances 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 condenser C2n will be $\frac{I_1}{fC}$

Simultaneously, C_{2n-2} transfers as charge q to the load and to C_{2n-1}.

Hence, the ripple at the condenser C_{2n-2} is $\frac{2I_1}{fC}$

Similarly, C_{2n-4} transfers a charge q to the load, to C_{2n-3} and to C_{2n-2}.

Therefore, the ripple at condenser 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 will be

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

2.1.1 Van de Graaff generator

The schematic diagram of a Van de Graaff generator is shown in Fig. 6. The generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure or in vacuum. Charge is sprayed on to an insulating moving belt from corona points at a potential of 10 to 100 kV above earth and is removed and collected from the belt connected to the inside of an insulated metal electrode through which the belt moves. The belt is driven by an electric motor at a speed of 1000 to 2000 meters per minute. The potential of the voltage electrode above the earth at any instant is $V = Q/C$ where Q is the charge stored and C is the capacitance of the high voltage electrode to the potential of the high volt age electrode rises at a rate

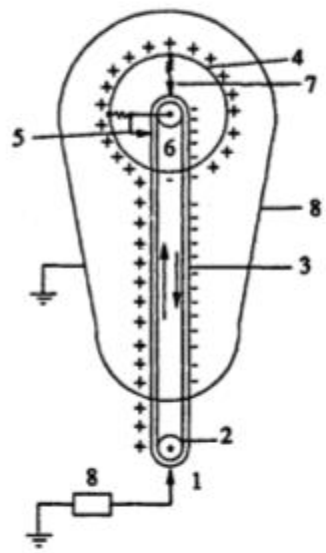


Fig: 6. Van de Graaff generator

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

$$\frac{dv}{dt} = \frac{I}{C}\frac{dQ}{dt} = \frac{I}{C}$$

Where *I* is the net charging current.

A steady potential will be attained by the high voltage electrode when the leakage currents and the load current are equal to the charging current. The shape of the high voltage electrode is so made with re-entrant edges as to avoid high surface field gradients, corona and other local discharges. The shape of the electrode is nearly spherical.

The charging of the belt is done by the lower spray points which are sharp needles and connected to a DC source of about 10 to 100 kV, so that the corona is maintained between the moving belt and the needles. The charge from the corona points is collected by the collecting needles from the belt and is transferred on to the high voltage electrode as the belt enters into the high voltage electrode. The belt returns with the charge dropped, and fresh charge is sprayed on to it as it passes through the lower corona point. Usually in order to make the charging more effective and to utilize the return path of the belt for charging purposes, a self-inducing arrangement or a second corona point system excited by a rectifier inside the high voltage terminal is employed. To obtain a self-charging system, the upper pulley is connected to the collector needle and is therefore maintained at a potential higher than that of the high voltage terminal. Thus a second row of corona points connected to the inside of the high voltage terminal and directed towards the pulley above its point of entry into the terminal gives a corona discharge to the belt. This neutralizes any charge on the belt and leaves an excess of opposite polarity to the terminal to travel down with the belt to the bottom charging point. Thus, for a given belt speed the rate of charging is doubled.

Van de Graaff generators are useful for very high voltage and low current applica- tions. The output voltage is easily controlled by controlling the corona source voltage and the rate of charging. The voltage can be stabilized to 0.01 %. These are extremely flexible and precise machines for voltage control.

2.2 GENERATION OF HIGH ALTERNATING VOLTAGES

2.2.1 Cascade Transformers

When test voltage requirements are less than about 300 kV, a single transformer can be used for test purposes. The impedance of the transformer should be generally less than 5% and must be capable of giving the short circuit current for one minute or more depending on the design. In addition to the normal windings, namely, the low and high voltage windings

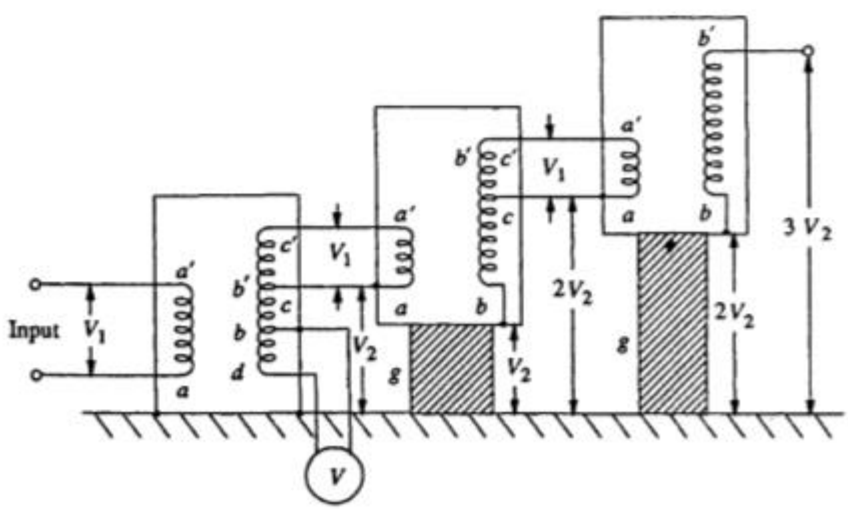


Fig: 7. Cascade transformer connection (schematic)

V_1 — Input voltage, V_2 — Output voltage, aa' — L.V. primary winding

bb' — H.V. secondary winding, cc' — Excitation winding

bd' — Meter winding (200 to 500 V)

a third winding known as meter winding is provided to measure the output voltage. For higher voltage requirements, a single unit construction becomes difficult and costly due to insulation problems. Moreover, transportation and erection of large transformers become difficult. These drawbacks are overcome by series connection or cascading of the several identical units of transformers, wherein the high voltage windings of all the units effectively come in series. Schematic diagrams of the cascade transformer units are shown in above and below

2.2.2 Cascade Transformers

Fig: 8. shows the cascade transformer units in which the first transformer is at the ground potential along with its tank. The second transformer is kept on insulators and maintained at a potential of V_2, the output voltage of the first unit above the ground. The high voltage winding of the first unit is connected to the tank of the second unit. The low voltage winding of this unit is supplied from the excitation winding of the first transformer, which is in series with the high voltage winding of the first transformer at its high voltage end. The rating of the excitation winding is almost identical to that of the primary or the low voltage winding. The high voltage connection from the first transformer winding and the excitation winding terminal are taken through a bushing to the second transformer.

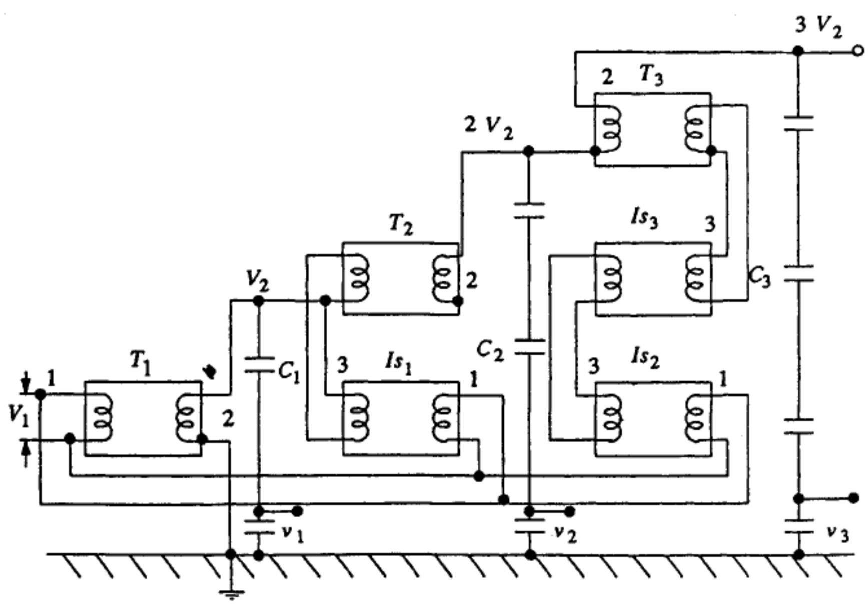


Fig: 8. Cascade transformer unit with isolating transformers for excitation

T_1, T_2, T_3 — Cascade transformer units

I_{s1}, I_{s2}, I_{s3} — Isolation transformer units

C_1, C_2, C_3 — Capacitance voltage dividers for h.v. measurement after 1st, 2nd and 3rd stages

V_1, V_2, V_3 — For metering after 1st, 2nd and 3rd stages

1. Primary (l.v. winding), 2.h.v. winding, 3. Excitation winding.

In a similar manner, the third transformer is kept on insulators above the ground at a potential of $2V_2$ and is supplied likewise from the second transformer. The number of stages in this type of arrangement are usually two to four, but very often, three stages are adopted to facilitate a three-phase operation so that $\sqrt{3V_2}$ can be obtained between the lines.

a second scheme for providing the excitation to the second and the third stages is shown in figure. Isolating transformers I_{s1}, I_{s2} and I_{s3} 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 transformers is also fed 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 transformers and the high voltage cascade units.

2.2.3 Resonant Transformers

The equivalent circuit of a high voltage testing transformer consists of the leakage reactances of the windings, the winding resistances, the magnetizing reactance, and the shunt capacitance across the output terminal due to the bushing of the high voltage terminal and also that of the test object. This is shown in Fig: 9(a) with its equivalent circuit in Fig: 9(b). It may be seen that it is possible to have series resonance at power frequency ω, if $(L_1 + L_2) = 1/\omega C$. With this condition, the current in the test object is very large and is limited only by the resistance of the circuit. The waveform of the voltage across the test object will be purely sinusoidal. The magnitude of the voltage across the capacitance C of the test object will be

$$V_c = \left|\frac{-jVX_c}{R + j(X_L - X_c)}\right| = \frac{V}{R}X_c = \frac{V}{\omega CR}$$

where R is the total series resistance of the circuit.

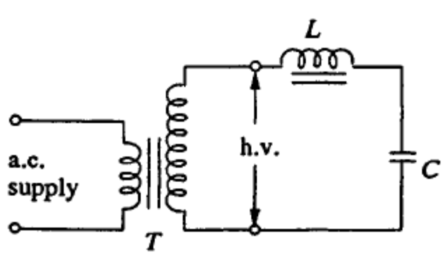


Fig: 9(a) Transformer

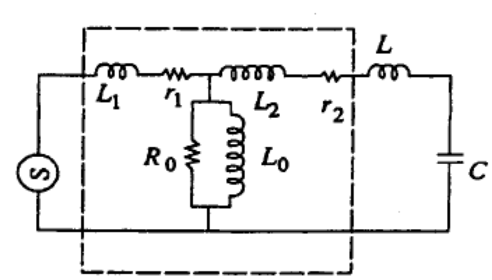


Fig: 9(b) Equivalent circuit

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

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

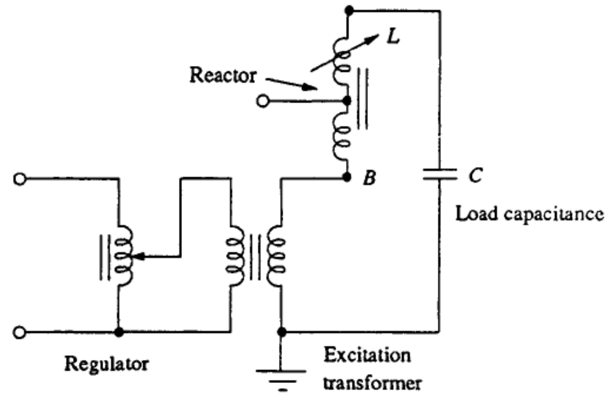


Fig: 10. Series resonant AC test system

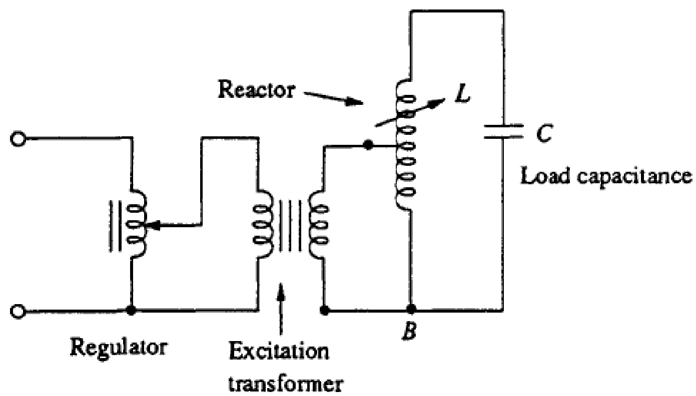


Fig: 11. Parallel resonant AC test system

Ratings: Regulator: 10 - 100 kVA Excitation transformer : 10 - 100 kVA

with an output voltage of about 10kV. Reactor voltage - each unit up to 300 kV.

The factor $X_c/R = 1/\omega CR$ is the Q factor of the circuit and gives the magnitude of the voltage multiplication across the test object under resonance conditions. Therefore, the input voltage required for excitation is reduced by a factor 1/Q, and the output kVA required is also reduced by a factor 1/Q. The secondary power factor of the circuit is unity. This principle is utilized in testing at very high voltages and on occasions requiring large current outputs such as cable testing, dielectric loss measurements, partial discharge measurements, etc. A transformer with 50 to 100 kV voltage rating and a relatively large current rating is connected together with an additional choke, if necessary.

The chief advantages of this principle are:

(a) it gives an output of pure sine wave,

(b) power requirements are less (5 to 10% of total kVA required),

(c) no high-power arcing and heavy current surges occur if the test object fails, as resonance ceases at the failure of the test object,

(d) cascading is also possible for very high voltages,

(e) simple and compact test arrangement, and

(f) no repeated flashovers occur in case of partial failures of the test object and insulation recovery. It can be shown that the supply source takes *Q* number of cycles at least to charge the test specimen to the full voltage.

The disadvantages are the requirements of additional variable chokes capable of withstanding the full test voltage and the full current rating.

A simplified diagram of the series resonance test system is given in Fig. 10. and that of the parallel resonant test system in Fig: 11. A voltage regulator of either the auto-transformer type or the induction regulator type is connected to the supply mains and the secondary winding of the exciter transformer is connected across the H.V. reactor, L, and the capacitive load C. The inductance of the reactor L is varied by varying its air gap and operating range is set in the ratio 10 : 1. Capacitance *C* comprises of the capacitance of the test object, capacitance of the measuring voltage divider, capacitance of the high voltage bushing etc. The Q-factor obtained in these circuits will be typically of the order of 50. In the parallel resonant mode the high voltage reactor is connected as an auto-transformer and the circuit is connected as a parallel resonant circuit. The advantage of the parallel resonant circuit is that more stable output voltage can be obtained along with a high rate of rise of test voltage, independent of the degree of tuning and the Q-factor. S ingle unit resonant test systems are built for output voltages up to 500 kV, while cascaded units for outputs up to 3000kV, 50/60 Hz are available.

2.3 GENERATION OF IMPULSE VOLTAGES

2.3.1 Standard Impulse Wave shapes

Transient over voltages due to lightning and switching surges cause steep build-up of voltage on transmission lines and other electrical apparatus. Experimental investigations showed that these waves have a rise time of 0.5 to 10 μs and decay time to 50% of the peak value of the order of 30 to 200 μs. The wave shapes are arbitrary, but mostly unidirectional. It is shown that lightning overvoltage wave can be represented as double exponential waves defined by the equation

$$V = V_0[exp(-\alpha t) - \exp(-\beta t)] \dots\dots\dots\dots\dots\dots\dots\dots\dots (2.1)$$

where α and β are constants of microsecond values.

The above equation represents a unidirectional wave which usually has a rapid rise to the peak value and slowly falls to zero value. The general wave shape is given in Fig: 12. Impulse waves are specified by defining their rise or front time, fall or tail time to 50% peak value, and the value of the peak voltage. Thus 1.2/50 μs, 1000 kV wave represents an impulse voltage wave with a front time of 1.2 μs, fall time to 50% peak value of 50 μs, and a

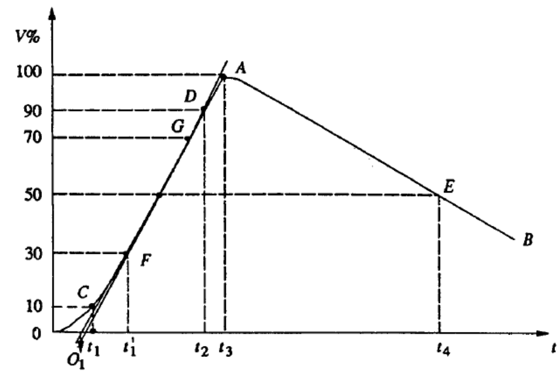


Fig: 12. Impulse waveform and its definitions

peak value of 1000 kV. When impulse wave shapes are recorded, the initial portion of the wave will not be clearly defined or sometimes will be missing. Moreover, due to disturbances it may contain superimposed oscillations in the rising portion. Hence, the front and tail times have to be defined.

Referring to the wave shape in Fig: 12, 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 O_1. O_1 is taken as the virtual origin. 1.25 times the interval between times t_1 and t_2 corresponding to points *C* and *D* (projections on the time axis) is defined as the front time, i.e. 1.25 $(O_1t_2 – O_1t_1)$. The point *E* is located on the wave tail corresponding to 50% of the peak value, and its projection on the time axis is t_4. Ot_4 is defined as the fall or tail time. In case the point *C* is not clear or missing from the wave shape record, the point corresponding to 30% peak value F is taken and its projection $t'\backslash$ is located on time axis. The wave front time in that case will be defined as 1.67 $(O_1t_3 – O_1t_1)$. 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%.

Theoretical Representation of impulse Waves

The impulse waves are generally represented by the Eq. (2.1) given earlier. V_0 in the equation represents a factor that depends on the peak value. For impulse wave of 1.2/50μs, α = - 0.0146, β= - 2.467, and V_o = 1.04 when time t is expressed in microseconds, α and β control the front and tail times of the wave respectively.

Circuits for Producing Impulse Waves

A double exponential waveform of the type mentioned in Eq. (A) 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 waves are given in Fig. (13): Below (a) to (d). Out of these circuits, the ones- shown in Figs. (a) to(d)are commonly used. Circuit shown in Fig. below (a) is limited to model generators only, and commercial generators employ circuits shown in Figs. below (b) to (d).

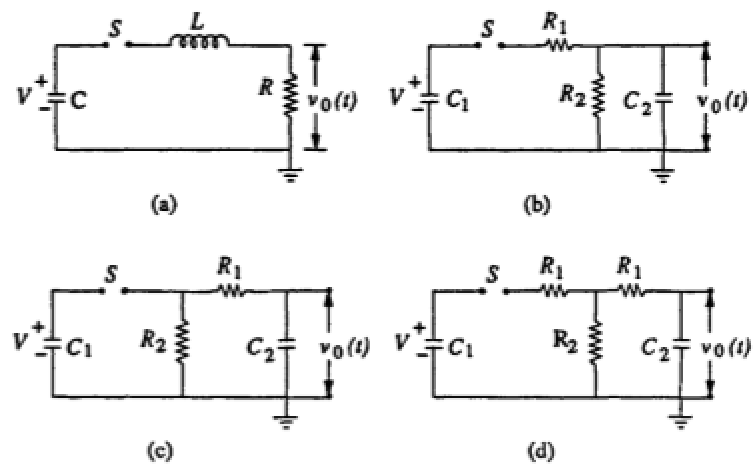


Fig. 13: Circuits for producing impulse waves

A capacitor (C_1 or C)previously charged to a particular DC voltage is suddenly discharged into the wave shaping network (LR, R1 R2C2 or other combination) by closing the switch S. The discharge voltage $V_o(t)$ shown in Fig. (13). Above gives rise to the desired double exponential wave shape.

Multistage Impulse Generators—Marx Circuit

In the above discussion, the generator capacitance C_1 is to be first charged and then discharged into the wave shaping circuits. A single capacitor C_1 may be used for voltages up to 200 kV. Beyond this voltage, a single capacitor and its charging unit may be too costly, and the size becomes very large. The cost and size of the impulse generator increases at a rate of square or cube of the voltage rating. Hence, for producing very high voltages, a bank of capacitors are charged in parallel and then discharged in series. The arrangement for charging the capacitors in parallel and then connecting them in series for discharging was originally proposed by Marx. Now-a- days modified Marx circuits are used for the multistage impulse generators.

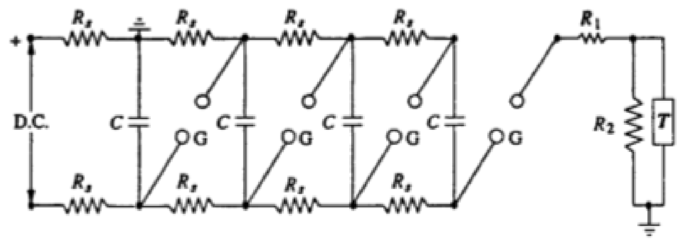


Fig. 14(a): Schematic diagram of Marx circuit arrangement for multistage impulse generator
C — Capacitance of the generator R_s — Charging resistors
G — Spark gap R_1, R_2 — Wave shaping resistors, T — Test object

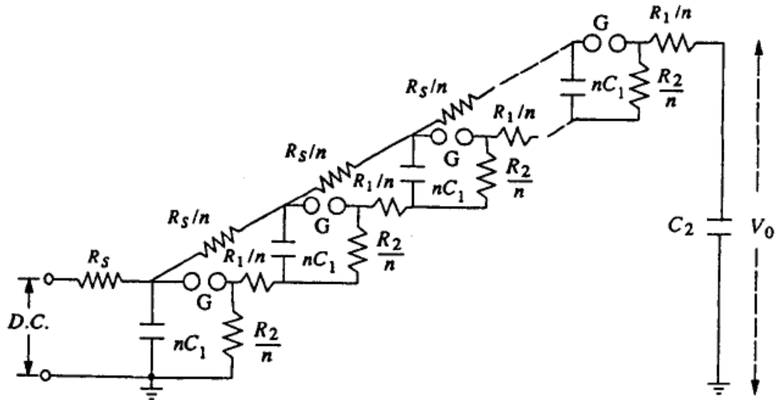


Fig. 14(b): Multistage impulse generator incorporating the series and wave tail resistances within the generator

The schematic diagram of Marx circuit and its modification are shown in above Figs. 14(a) and (b), respectively. 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 1min.

2.4 GENERATION OF IMPULSE CURRENTS

Lightening discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gear like surge diverters have to discharge the lightning currents without damage. Therefore, generation of impulse current waveforms of high magnitude (nearly=100 kA peak) find application in testing work as well as in basic research on non-linear resistors, electric arc studies, and studies relating to electric plasmas in high current discharges.

2.4.1 Definition of Impulse Current Waveforms

The waveshapes used in testing surge diverters are 4/10 and 8/20ns, the figures respectively representing the nominal wave front and wave tail times (see Fig.below). The tolerances allowed on these times are ± 10% only. Apart from the standard impulse current waves, rectangular waves of long duration are also used for testing. The wave shape should be nominally rectangular in shape. The rectangular waves generally have durations of the order of 0.5 to 5 ms, with rise and fall times of the waves being less than ±10% of their total duration. The tolerance allowed on the peak value is +20% and -0% (the peak value may be more than the specified value but not less). The duration of the wave is defined as the total time of the wave during which the current is at least 10% of its peak value.

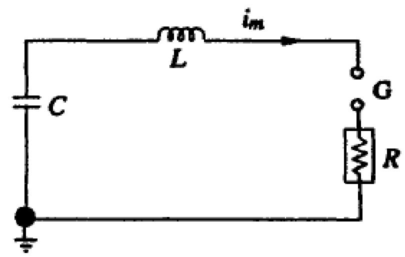
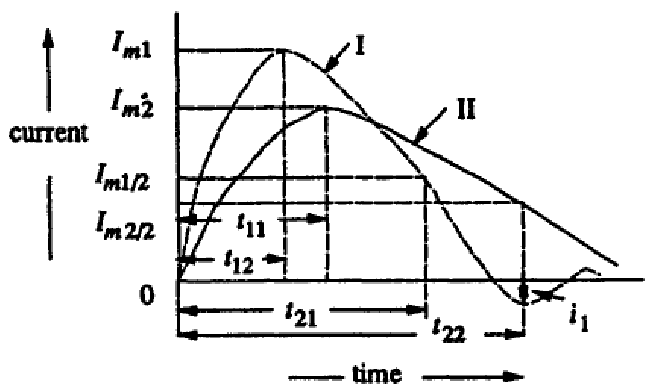


Fig 15(a): Basic circuit of an impulse current generator



t 1 and t_{12} - time-to-front of waves I and Il
t_{21} and t_{22} - time-to-tail of waves I and Il
I —damped oscillatory wave
II — overdamped wave
h —overshoot
Fig 15(b): Types of impulse current waveforms

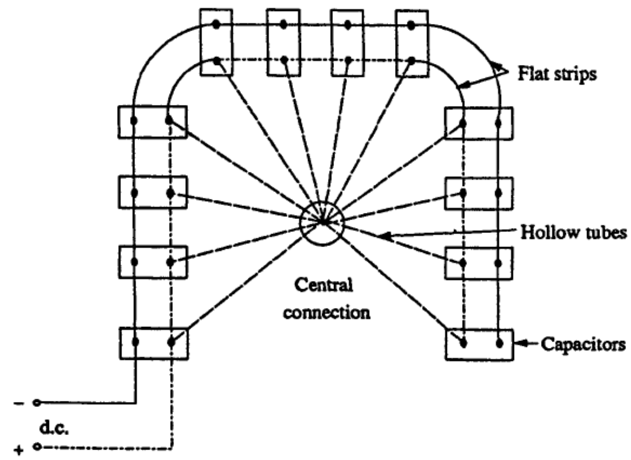


Fig 15(c): Arrangement of capacitors for high current generation

2.4.2 Circuit for producing impulse current waves

For producing impulse currents of large value, a bank of capacitors connected in parallel are charged to a specified value and are discharged through a series R-L circuit as shown in Fig. 15(a), Fig 15(c) represents a bank of capacitors connected in parallel which are charged from a DC source to a voltage up to 200 kV. R represents the dynamic resistance of the test object and the resistance of the circuit and the shunt L is an air cored high current inductor, usually a spiral tube of a few turns. If the capacitor is charged to a voltage V and discharged when the spark gap is triggered, the current i_m will be given by the equation

$$V = Ri_m + L\frac{di_m}{dt} + \frac{1}{C}\int_0^t i_m dt$$

The circuit is usually under damped, so that

$$\frac{R}{2} < \sqrt{L/C}$$

Hence, i_m is given by

$$i_m = \frac{V}{\omega L}[\exp(-\alpha t)]\sin(\omega t)$$

Where

$$\alpha = \frac{R}{2L} \ and \ \omega L = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

The time taken for the current i_m to rise from zero to the first peak value is

$$t_1 = t_f = \frac{1}{\omega} sin^{-1}\frac{\omega}{\sqrt{LC}} = \frac{1}{\omega} tan^{-1}\frac{\omega}{\alpha}$$

The duration for one half cycle of the damped oscillatory wave t_2 is,

$$t_2 = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}$$

It can be shown that the maximum value of im is normally independent of the value of V and C for a given energy W = $\frac{1}{2}CV^2$, and the effective inductance L. It is also clear from Eq. (i_m) that a low inductance is needed in order to get high current magnitudes for a given charging voltage V. The present practice as per IEC 60.2 is to express the characteristic time t_2 as the time for half value of the peak current, similar to the definition given for standard impulse voltage waves. With this definition, the values of α and ω for 8/20 µs impulse wave will be α = 0.0535 x 10^6 and ω = 0.113 x 10^6, when R, L, C are expressed in ohms, henries and farads respectively. The product LC will be equal to 65 and the peak value of i_m is given by (VC)/14. Here, the charging voltage is in kV and i_m is in kA.

2.4.3 Generation of high impulse currents

For producing large values of impulse currents, a number of capacitors are charged in parallel and discharged in parallel into the circuit. The arrangement of capacitors is shown in Fig 15(c). In order to minimize the effective inductance, the capacitors are subdivided into smaller units. If there are n_1 groups of capacitors, each consisting of n_2 units and if L_0 is the inductance of the common discharge path, L_1 is that of each group and $L_2$is that of each unit, then the effective inductance L is given by

$$L = L_o + \frac{L_1}{n} + \frac{L_2}{n_1 n_2}$$

Also, the arrangement of capacitors into a horse-shoe shaped layout minimizes the effective load inductance.

The essential parts of an impulse current generator are:

(i) a d.c. charging unit giving a variable voltage to the capacitor bank,

(ii) capacitors of high value (0.5 to 5 µF) each with very low self-inductance, capable of giving high short circuit currents,

(iii) an additional air cored inductor of high current value,

(iv) proper shunts and oscillograph for measurement purposes, and

(v) a triggering unit and spark gap for the initiation of the current generator.

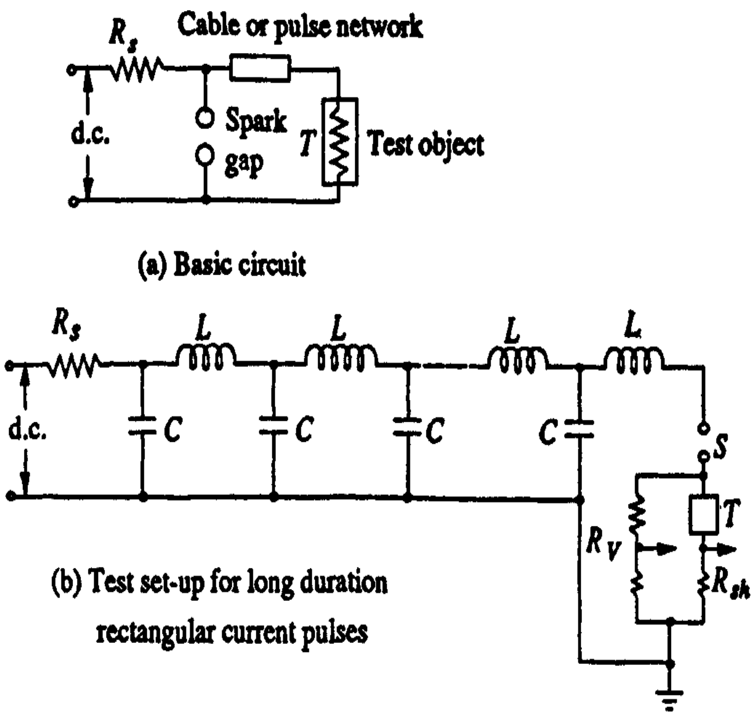


Fig 16: Basic circuit and schematic set-up for producing rectangular current pulses

R_s — Charging resistor
S — Trigger spark gap
T — Test object
L-C — Pulse forming network
Rv — Potential divider for voltage measurement
Rsh — Current shunt for current measurement

2.5 TRIPPING AND CONTROL OF IMPULSE GENERATORS

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

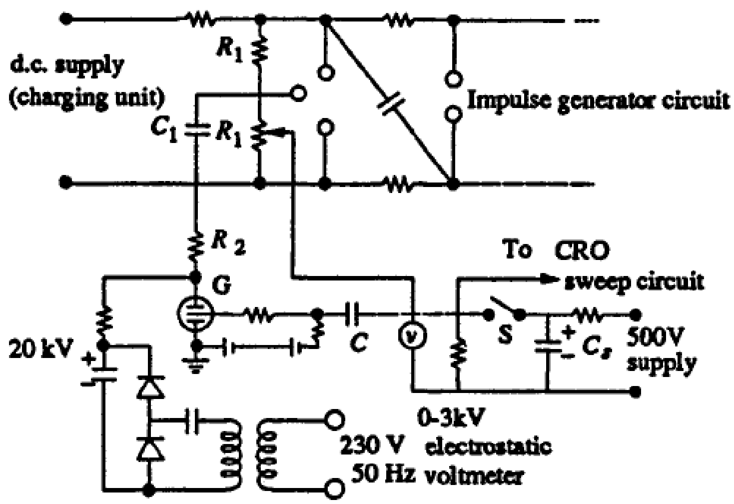


Fig 17: Tripping of an impulse generator with a three electrode gap

To trip the generator at a predetermined time, the spark gaps may be mounted on a movable frame, and the gap distance is reduced by moving the movable electrodes closer. This method is difficult and does not assure consistent and controlled tripping. A simple method of controlled tripping consists of making the first gap a three electrode gap and firing it from a controlled source. Figure above 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_L. The tripping is initiated by applying a pulse to the thyratron G by closing the switch S. The capacitor C produces an exponentially decaying pulse of positive polarity. The pulse goes and initiates the oscillograph time base. The thyratron conducts on receiving the pulse from the switch S and produces a negative pulse through the capacitance 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 oscillograph begins before the start of the impulse generator voltage.

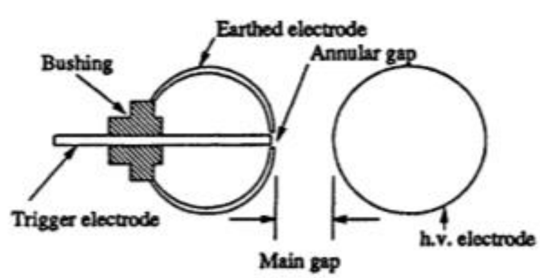


Fig (18): Trigatron gap

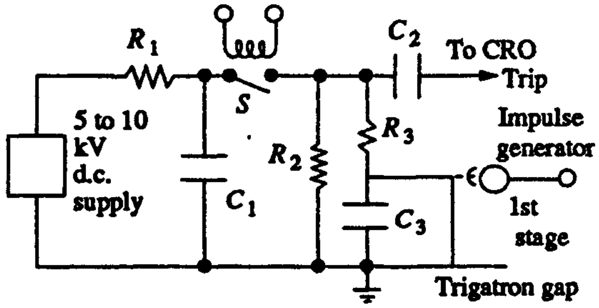


Fig (19): Tripping circuit using a trigatron

The resistance R^ ensures decoupling of voltage oscillations produced at the spark gap entering the oscilloscope through the common trip circuit. The three electrode gap requires larger space and an elaborate construction. Now-a-days a trigatron gap shown in Fig. 18 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. 19. 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, spark over of the main gap occurs. The trigatron gap is polarity sensitive and a proper polarity pulse should be applied for correct operation.

2.5.1 Three Electrode Gap for Impulse Current Generator

In the case of impulse current generators using three electrode gaps for tripping and control, a certain special design is needed. The electrodes have to carry high current from the capacitor bank. Secondly, the electrode has to switch large currents in a small duration of time (in about a microsecond). Therefore, the switch should have very low inductance. The erosion rate of the electrodes should be low.

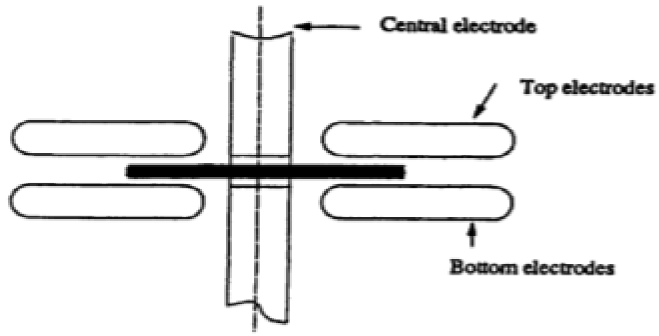


Fig 20: Three electrode gap for high current switching

For high current capacitor banks, a number of spark gap switches connected in parallel as shown in Fig. 20: are often used to meet the requirement. Recently, trigatron gaps are being replaced by triggered vacuum gaps, the advantage of the latter being fast switching at high currents (> 100 kA) in a few nanoseconds. Triggering of the spark gaps by focused laser beams is also adopted since the performance is better than the conventional triggering methods.

UNIT – 3

MEASUREMENT OF HIGH VOLTAGES AND CURRENTS

Syllabus:

Measurement of High Voltages And Currents

Measurement of High Direct Current voltages, Measurement of High Voltages alternating and impulse, Measurement of High Currents-direct, alternating and Impulse, Oscilloscope for impulse voltage and current measurements.

MEASUREMENT OF HIGH VOLTAGES AND CURRENTS

INTRODUCTION

3.1 Measurement of High Direct Current Voltages

Transient measurements have much in common with measurements of steady state quantities but the short-lived nature of the transients which we are trying to record introduces special problems. Frequently the transient quantity to be measured is not recorded directly because of its large magnitudes *e.g.* when a shunt is used to measure current, we really measure the voltage across the shunt and then we assume that the voltage is proportional to the current, a fact which should not be taken for granted with transient currents. Often the voltage appearing across the shunt may be insufficient to drive the measuring device; it requires amplification. On the other hand, if the voltage to be measured is too large to be measured with the usual meters, it must be attenuated. This suggests an idea of a measuring system rather than a measuring device.

Measurements of high voltages and currents involves much more complex problems which a specialist, in common electrical measurement, does not have to face. The high voltage equipments have large stray capacitances with respect to the grounded structures and hence large voltage gradients are set up. A person handling these equipments and the measuring devices must be protected against these over voltages. For this, large structures are required to control the electrical fields and to avoid flash over between the equipment and the grounded structures. Sometimes, these structures are required to control heat dissipation within the circuits. Therefore, the location and layout of the equipments is very important to avoid these problems. Electromagnetic fields create problems in the measurements of impulse voltages and currents and should be minimised. The chapter is devoted to describing various devices and circuits for measurement of high voltages and currents. The application of the device to the type of voltages and currents is also discussed.

3.1.1 SPHERE GAP

Sphere gap is by now considered as one of the standard methods for the measurement of peak value of d.c., a.c. and impulse voltages and is used for checking the voltmeters and other voltage measuring devices used in high voltage test circuits. Two identical metallic spheres separated by certain distance form a sphere gap. The sphere gap can be used for measurement of impulse voltage of either polarity provided that the impulse is of a standard wave form and has wave front time at least 1 micro sec. and wave tail time of 5 micro sec. Also, the gap length between the sphere should not exceed a sphere radius. If these conditions are satisfied and the specifications regarding the shape, mounting, clearances of the spheres are met, the results obtained by the use of sphere gaps are reliable to within ±3%. It has been suggested in standard specification that in places where the availability of ultraviolet radiation is low, irradiation of the gap by radioactive or other ionizing media should be used when voltages of magnitude less than 50 kV are being measured or where higher voltages with accurate results are to be obtained.

In order to understand the importance of irradiation of sphere gap for measurement of impulse voltages especially which are of short duration, it is necessary to understand the time-lag involved in the development of spark process. This time lag consists of two components—(*i*) The statistical time lag caused by the need of an electron to appear in the gap during the application of the voltage. (*ii*) The formative time lag which is the time required for the breakdown to develop once initiated.

The statistical time-lag depends on the irradiation level of the gap. If the gap is sufficiently irradiated so that an electron exists in the gap to initiate the spark process and if the gap is subjected to an impulse voltage, the breakdown will take place when the peak voltage exceeds the d.c. breakdown value. However, if the irradiation level is low, the voltage must be maintained above the d.c. breakdown value for a longer period before an electron appears. Various methods have been used for irradiation *e.g.* radioactive material, ultraviolet illumination as supplied by mercury arc lamp and corona discharges.

It has been observed that large variation can occur in the statistical time-lag characteristic of a gap when illuminated by a specified light source, unless the cathode conditions are also precisely specified. Irradiation by radioactive materials has the advantage in that they can form a stable source of irradiation and that they produce an amount of ionisation in the gap which is largely independent of the gap voltage and of the surface conditions of the electrode. The radioactive material may be placed inside high voltage electrode close behind the sparking surface or the radioactive material may form the sparking surface. The influence of the light from the impulse generator spark gap on the operation of the sphere gaps has been studied. Here the illumination is intense and occurs at the exact instant when it is required, namely, at the instant of application of the voltage wave to the sphere gap.

The formative time lag depends mainly upon the mechanism of spark growth. In case of secondary electron emission, it is the transit time taken by the positive ion to travel from anode to cathode that decides that formative time lag. The formative time-lag decreases with the applied over voltage and increase with gap length and field non-uniformity.

3.1.2 UNIFORM FIELD SPARK GAP

Bruce suggested the use of uniform field spark gaps for the measurements of a.c., d.c. and impulse voltages. These gaps provide accuracy to within 0.2% for a.c. voltage measurements an appreciable improvement as compared with the equivalent sphere gap arrangement. Fig.3.1.1 shows a half-contour of one electrode having plane sparking surfaces with edges of gradually increasing curvature.

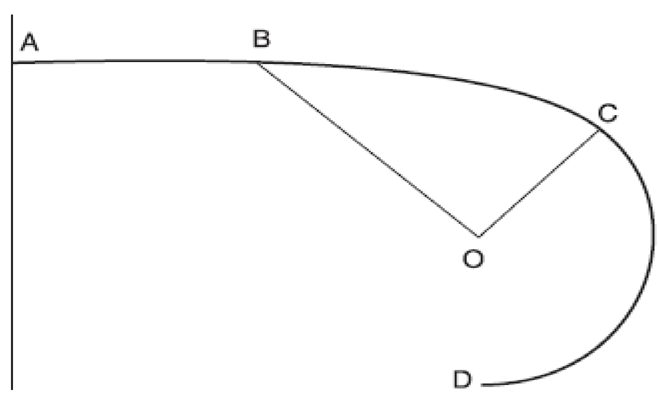


Fig : 3.1.1 Half contour of uniform spark gap

The portion *AB* is flat, the total diameter of the flat portion being greater than the maximum spacing between the electrodes. The portion *BC* consists of a sine curve based on the axes *OB* and *OC* and given by $XY = CO \sin (BX/BO \cdot \pi/2)$. *CD* is an arc of a circle with centre at *O*. Bruce showed that the breakdown voltage *V* of a gap of length *S* cms in air at 20°C and 760 mm Hg. pressure is within 0.2 per cent of the value given by the empirical relation.

$$V = 24.22S + 6.08 \sqrt{S}$$

This is a great advantage, that is, if the spacing between the spheres for breakdown is known the breakdown voltage can be calculated.

The other advantages of uniform field spark gaps are

(*i*) No influence of nearby earthed objects

(*ii*) No polarity effect.

However, the disadvantages are

(*i*) Very accurate mechanical finish of the electrode is required.

(*ii*) Careful parallel alignment of the two electrodes.

(*iii*) Influence of dust brings in erratic breakdown of the gap. This is much more serious in these gaps as compared with sphere gaps as the highly stressed electrode areas become much larger.

Therefore, a uniform field gap is normally not used for voltage measurements.

3.1.3 ROD GAP

A rod gap may be used to measure the peak value of power frequency and impulse voltages. The gap usually consists of two 1.27 cm square rod electrodes square in section at their end and are mounted on insulating stands so that a length of rod equal to or greater than one half of the gap spacing overhangs the inner edge of the support. The breakdown voltages as found in American standards for different gap lengths at 25° C, 760 mm Hg. pressure and with water vapour pressure of 15.5 mm Hg. are reproduced here.

Gap length in Cms.	*Breakdown Voltage KV peak*	*Gap Length in cms.*	*Breakdown Voltage KV peak*
2	26	80	435
4	47	90	488
6	62	100	537
8	72	120	642
10	81	140	744
15	102	160	847
20	124	180	950
25	147	200	1054
30	172	220	1160
35	198		
40	225		
50	278		
60	332		
70	382		

The breakdown voltage is a rod gap increases more or less linearly with increasing relative air density over the normal variations in atmospheric pressure. Also, the breakdown voltage increases with increasing relative humidity, the standard humidity being taken as 15.5 mm Hg. Because of the large variation in breakdown voltage for the same spacing and the uncertainties associated with the influence of humidity, rod gaps are no longer used for measurement of a.c. or impulse voltages. However, more recent investigations have shown that these rods can be used for d.c. measurement provided certain regulations regarding the electrode configurations are observed. The arrangement consists of two hemi spherically capped rods of about 20 mm diameter as shown in Fig.3.1.2

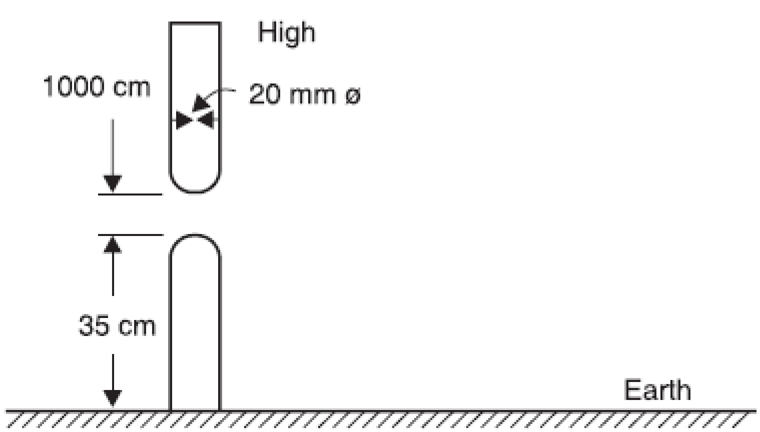


Fig : 3.1.2 Electrode Arrangement For a Rod gap to Measure HVDC

The earthed electrode must be long enough to initiate positive breakdown streamers if the high voltage rod is the cathode. With this arrangement, the breakdown voltage will always be initiated by positive streamers for both the polarities thus giving a very small variation and being humidity dependent. Except for low voltages (less than 120 kV), where the accuracy is low, the breakdown voltage can be given by the empirical relation.

$$V = \delta\,(A + BS)\,4\,\sqrt{5.1 \times 10^{-2}\,(h + 8.65)}\ \text{kV}$$

where *h* is the absolute humidity in gm/m3 and varies between 4 and 20 gm/m3 in the above relation. The breakdown voltage is linearly related with the gap spacing and the slope of the relation *B* = 5.1 kV/cm and is found to be independent of the polarity of voltage. However constant *A* is polarity dependent and has the values

A = 20 kV for positive polarity

= 15 kV for negative polarity of the high voltage electrode.

The accuracy of the above relation is better than ±20% and, therefore, provides better accuracy even as compared to a sphere gap.

3.1.4 ELECTROSTATIC VOLTMETER

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. Whenever 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,

$$W_d = \frac{1}{2}\,\varepsilon E^2$$

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

$$dW = W_d\, A dx = \frac{1}{2}\varepsilon E^2\; A dx$$

Now force *F* between the plates is defined as the derivative of stored electric energy along the field direction *i.e.*,

$$F = \frac{dW}{dx} = \frac{1}{2}\varepsilon\, E^2 A$$

Now $E = V/d$ where *V* is the voltage to be measured and *d* the distance of separation between the plates. Therefore, the expression for force

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

Since the two plates are oppositely charged, there is always force of attraction between the plates. If the voltage is time dependant, the force developed is also time dependant. In such a case the mean value of force is used to measure the voltage. Thus

$$F = \frac{1}{T}\int_0^T F(t)dt = \frac{1}{T}\int \frac{1}{2}\varepsilon \frac{V^2(t)}{d^2} A\; dt = \frac{1}{2}\frac{\varepsilon A}{d^2}\cdot\frac{1}{T}\int V^2(t)dt = \frac{1}{2}\varepsilon A\frac{V_{rms}^2}{d^2}$$

Electrostatic voltmeters measure the force based on the above equations and are arranged such that one of the plates is rigidly fixed whereas the other is allowed to move. With this the electric field gets disturbed. For this reason, the movable electrode is allowed to move by not more than a fraction of a millimetre to a few millimetres even for high voltages so that the change in electric field is negligibly small. As the force is proportional to square of *V*rms, the meter can be used both for a.c. and d.c. voltage measurement.

The force developed between the plates is sufficient to be used to measure the voltage. Various designs of the voltmeter have been developed which differ in the construction of electrode arrangement and in the use of different methods of restoring forces required to balance the electrostatic force of attraction.

Some of the methods are

(*i*) Suspension of moving electrode on one arm of a balance.

(*ii*) Suspension of the moving electrode on a spring.

(*iii*) Pendulous suspension of the moving electrode.

(*iv*) Torsional suspension of moving electrode.

The small movement is generally transmitted and amplified by electrical or optical methods. If the electrode movement is minimised and the field distribution can exactly be calculated, the meter can be used for absolute voltage measurement as the calibration can be made in terms of the fundamental quantities of length and force.

From the expression for the force, it is clear that for a given voltage to be measured, the higher the force, the greater is the precision that can be obtained with the meter. In order to achieve higher force for a given voltage, the area of the plates should be large, the spacing between the plates (*d*) should be small and some dielectric medium other than air should be used in between the plates. If uniformity of electric field is to be maintained an increase in area *A* must be accompanied by an increase in the area of the surrounding guard ring and of the opposing plate and the electrode may, therefore, become unduly large specially for higher voltages. Similarly the gap length cannot be made very small as this is limited by the breakdown strength of the dielectric medium between the plates. If air is used as the medium, gradients upto 5 kV/cm have been found satisfactory. For higher gradients vacuum or SF6 gas has been used.

The greatest advantage of the electrostatic voltmeter is its extremely low loading effect as only electric fields are required to be set up. Because of high resistance of the medium between the plates, the active power loss is negligibly small. The voltage source loading is, therefore, limited only to the reactive power required to charge the instrument capacitance which can be as low as a few picofarads for low voltage voltmeters.

The measuring system as such does not put any upper limit on the frequency of supply to be measured. However, as the load inductance and the measuring system capacitance form a series resonance circuit, a limit is imposed on the frequency range. For low range voltmeters, the upper frequency is generally limited to a few MHz.

Fig.3.1.3 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.

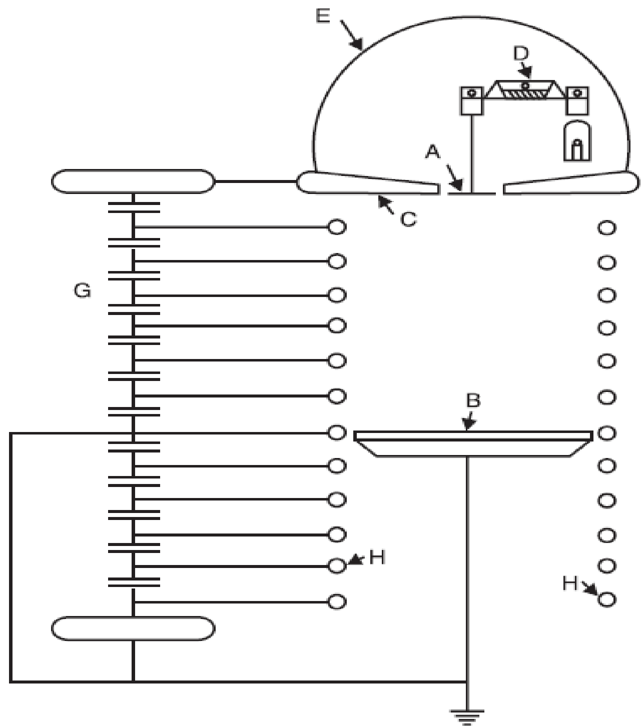


Fig : 3.1.3 Schematic Diagram of Electrostatic Voltmeter

The diameter of each of the plates is 1 metre. Light reflected from a mirror carried by the balance beam serves to magnify its motion and to indicate to the operator at a safe distance when a condition of equilibrium is reached. As the spacing between the two electrodes is large (about 100 cms for a voltage of about 300 kV), the uniformity of the electric field is maintained by the guard rings *G* which surround the space between the discs *M* and *P*. The guard rings *G* are maintained at a constant potential in space by a capacitance divider ensuring a uniform spatial potential distribution. When voltages in the range 10 to 100 kV are measured, the accuracy is of the order of 0.01 per cent.

Hueter has used a pair of sphares of 100 cms diameter for the measurement of high voltages utilising the electrostatic attractive force between them. The spheres are arranged with a vertical axis and at a spacing slightly greater than the sparking distance for the particular voltage to be measured. The upper high voltage sphere is supported on a spring and the extension of spring caused by the electrostatic force is magnified by a lamp-mirror scale arrangement. An accuracy of 0.5 per cent has been achieved by the arrangement.

Electrostatic voltmeters using compressed gas as the insulating medium have been developed. Here for a given voltage the shorter gap length enables the required uniformity of the field to be maintained with electrodes of smaller size and a more compact system can be evolved.

One such voltmeter using SF6 gas has been used which can measure voltages upto 1000 kV and accuracy is of the order of 0.1%. The high voltage electrode and earthed plane provide uniform electric field within the region of a 5 cm diameter disc set in a 65 cm diameter guard plane.

A weighing balance arrangement is used to allow a large damping mass. The gap length can be varied between 2.5, 5 and 10 cms and due to maximum working electric stress of 100 kV/cm, the voltage ranges can be selected to 250 kV, 500 kV and 100 kV. With 100 kV/cm as gradient, the average force on the disc is found to be 0.8681 N equivalent to 88.52 gm wt. The disc movements are kept as small as 1 μm by the weighing balance arrangement.

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.

3.1.5 GENERATING VOLTMETER

Whenever 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, 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. The principle of operation is explained with the help of Fig.3.1.4. *H* is a high voltage electrode and 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.3.1.4. 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.

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

Where σ (a) is the electric field density or charge density along some path and is assumed constant over the differential area da of the pick up electrode. In this case σ (a) is a function of time also and $\int da$ the area of the pick up electrode *P* exposed to the electric field. However, 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

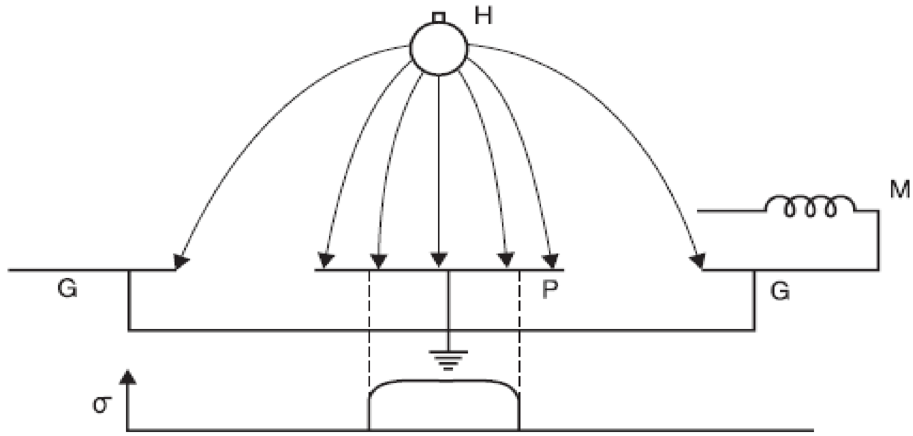


Fig : 3.1.4 Principle of generating voltmeter

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 $\sigma(a) = \varepsilon E(a)$ 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 Dc 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 *Cm* is time *Tc /2* and again reduces to zero linearly in time *Tc /*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 *Tc* is given by *Tc* = 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 + *Cm*) then

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

and the current *i* is then given as

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

Here 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. Generating voltmeters can be used for a.c. voltage measurement also provided the angular frequency ω is the same or equal to half that of the voltage being measured.

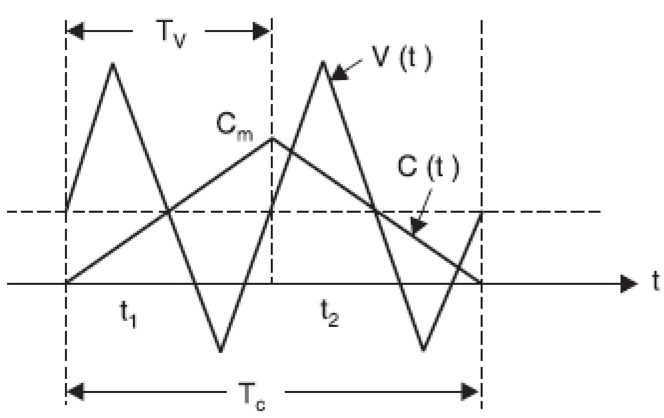


Fig: 3.1.5 capacitance and voltage variation

Fig 3.1.5 shows the variations of C as a function of time together with a.c. voltage, the frequency of which is twice the frequency of capacitance over the period Tv is equal to Cm/Tv. Therefore, the instantaneous value of current $i(t) = Cm\, fvV(t)$ where $fv = 1/Tv$ the frequency of voltage. Since $fv = 2fc$ and $fc = 60/n$ we obtain

$$I(t) = n/30\ C_m V(t)$$

Fig. 3.1.6 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 (sinusodial 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.

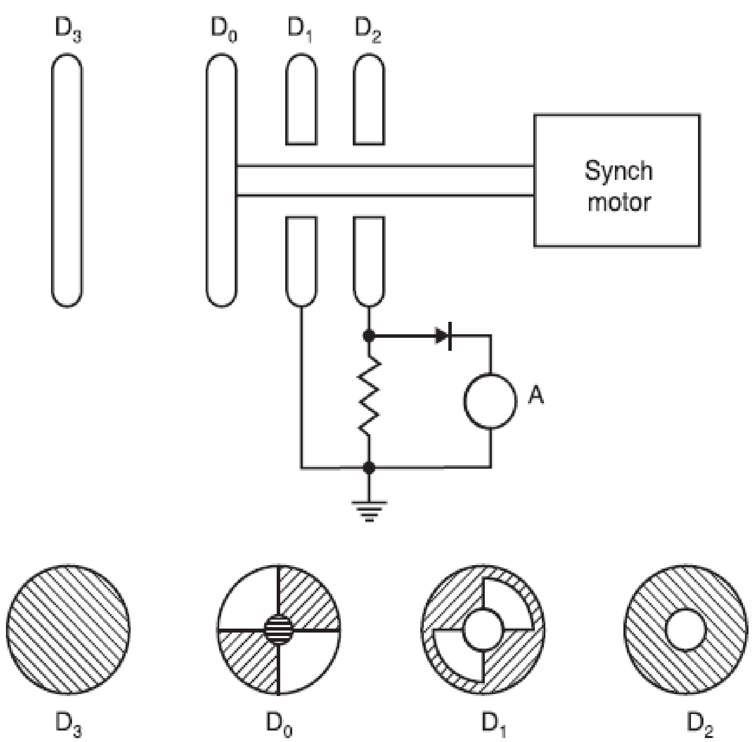


Fig : 3.1.6 schematic diagram of generating voltmeter

Generating voltmeters are linear scale instruments and applicable over a wide range of voltages. The sensitivity can be increased by increasing the area of the pick up electrode and by using amplifier circuits.

The main advantages of generating voltmeters are (*i*) scale is linear and can be extrapolated

(*ii*) source loading is practically zero (*iii*) no direct connection to the high voltage electrode.

However, they require calibration and construction is quite cumbersome. The breakdown of insulating materials depends upon the magnitude of voltage applied and the time of application of voltage. However, if the peak value of voltage is large as compared to breakdown strength of the insulating material, the disruptive discharge phenomenon is in general caused by the instantaneous maximum field gradient stressing the material. Various methods discussed so far can measure peak voltages but because of complex calibration procedures and limited accuracy call for more convenient and more accurate methods. A more convenient though less accurate method would be the use of a testing transformer wherein the output voltage is measured and recorded and the input voltage is obtained by multiplying the output voltage by the transformation ratio. However, here the output voltage depends upon the loading of the secondary winding and wave shape variation is caused by the transformer impedances and hence this method is unacceptable for peak voltage measurements.

3.2 MEASUREMENT OF HIGH VOLTAGES ALTERNATING AND IMPULSE

3.2.1 THE CHUBB-FORTESCUE METHOD

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.3.2.1.1 (*a*).

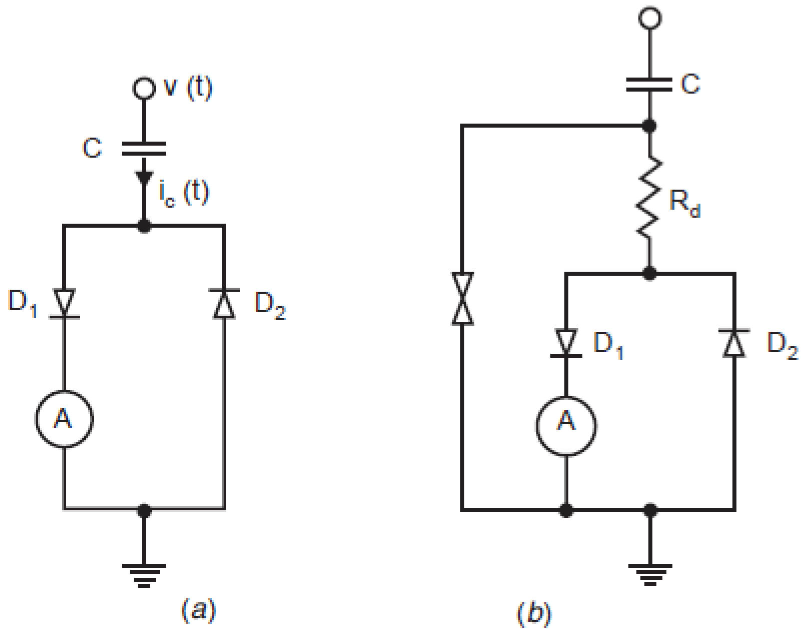


Fig : 3.2.1.1 (a) Basic circuit (b) Modified circuit

The displacement current *ic*(*t*), Fig. 3.2.1.3 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.

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

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. 3.2.1.1 (*b*).

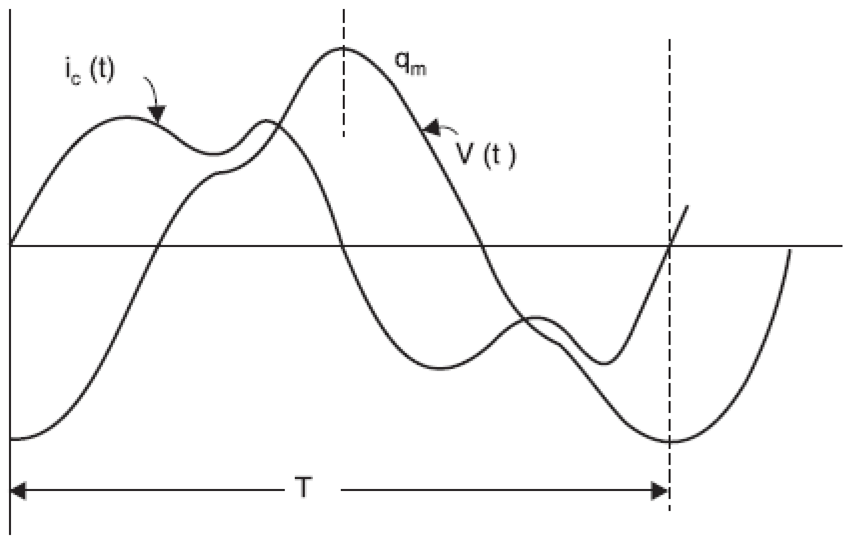


Fig : 3.2.1.3

Also, if full wave rectifier is used instead of the half wave as shown in Fig. 3.2.1.3, 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. Fig. 3.2.1.4 shows a digital peak voltage measuring circuit. In contrast to the method discussed just now, the rectified current is not measured directly, instead a proportional analog voltage signal is derived which is then converted into a proportional medium frequency for using a voltage to frequency convertor The frequency ratio *fm*/*f* is measured with a gate circuit controlled by the a.c. power frequency (supply frequency *f*) and a counter that opens for an adjustable number of period

$\Delta t = p/f$. The number of cycles *n* counted during this interval is

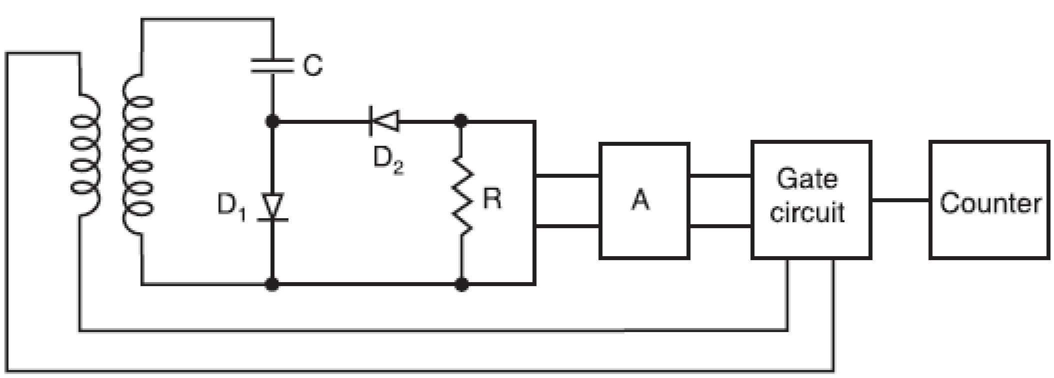


Fig : 3.2.1.4 digital peak voltmeter

$$n = \Delta t f_m = \frac{p}{f} fm$$

where p is a constant of the instrument.

Let $$A = \frac{f_m}{Ri_c} = \frac{f_m}{R 2 V_m f C} = \frac{f_m}{f} \cdot \frac{1}{2 R V_m C}$$

Therefore, $$n = p\, 2 A R V_m C$$

where A represents the voltage to frequency conversion factor. Thus the indicator can be calibrated to read Vm directly by selecting suitable values of A, p and R. The voltmeter is found to given an accuracy of 0.35%.

3.2.2 IMPULSE VOLTAGE MEASUREMENTS USING VOLTAGE DIVIDERS

If the amplitudes of the impulse voltage is not high and is in the range of a few kilovolts, it is possible to measure them even when these are of short duration by using CROS. However, if the voltages to be measured are of high magnitude of the order of magavolts which normally is the case for testing and research purposes, various problems arise. The voltage dividers required are of special design and need a thorough understanding of the interaction present in these voltage dividing systems. Fig. 3.2.2.1 shows a layout of a voltage testing circuit within a high voltage testing area. The voltage generator *G* is connected to a test object—*T* through a lead *L*.

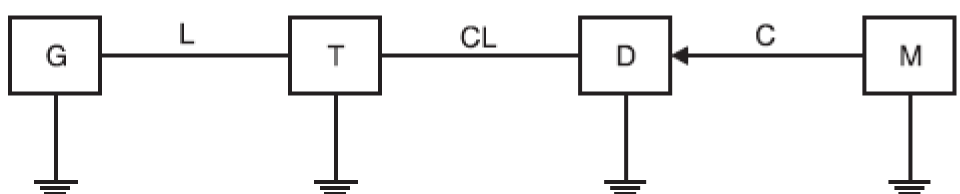


Fig : 3.2.2.1 Basic Voltage Testing Circuit

These three elements form a voltage generating system. The lead *L* consists of a lead wire and a resistance to damp oscillation or to limit short-circuit currents if of the test object fails. The measuring system starts at the terminals of the test object and consists of a connecting lead *CL* to the voltage divider *D*. The output of the divider is fed to the measuring instrument (CRO etc.) *M*.

The appropriate ground return should assure low voltage drops for even highly transient phenomena and keep the ground potential of zero as far as possible.

It is to be noted that the test object is a predominantly capacitive element and thus this forms an oscillatory circuit with the inductance of the load. These oscillations are likely to be excited by any steep voltage rise from the generator output, but will only partly be detected by the voltage divider. A resistor in series with the connecting leads damps out these oscillations. The voltage divider should always be connected outside the generator circuit towards the load circuit (Test object) for accurate measurement. In case it is connected within the generator circuit, and the test object discharges (chopped wave) the whole generator including voltage divider will be discharged by this short circuit at the test object and thus the voltage divider is loaded by the voltage drop across the lead *L*. As a result, the voltage measurement will be wrong.

Yet for another reason, the voltage divider should be located away from the generator circuit. The dividers cannot be shielded against external fields. All objects in the vicinity of the divider which may acquire transient potentials during a test will disturb the field distribution and thus the divider performance. Therefore, the connecting lead *CL* is an integral part of the potential divider circuit. In order to avoid electromagnetic interference between the measuring instrument *M* and *C* the high voltage test area, the length of the delay cable should be adequately chosen. Very short length of the cable can be used only if the measuring instrument has high level of electromagnetic compatibility (EMC). For any type of voltage to be measured, the cable should be co-axial type. The outer conductor provides a shield against the electrostatic field and thus prevents the penetration of this field to the inner conductor. Even though, the transient magnetic fields will penetrate into the cable, no appreciable voltage is induced due to the symmetrical arrangement. Ordinary coaxial cables with braided shields may well be used for d.c. and a.c. voltages. However, for impulse voltage measurement double shielded cables with predominently two insulated braided shields will be used for better accuracy. During disruption of test object, very heavy transient current flow and hence the potential of the ground may rise to dangerously high values if proper earthing is not provided. For this, large metal sheets of highly conducting material such as copper or aluminium are used. Most of the modern high voltage laboratories provide such ground return along with a Faraday Cage for a complete shielding of the laboratory. Expanded metal sheets give similar performance. At least metal tapes of large width should be used to reduce the impedance.

3.3 MEASUREMENT OF HIGH CURRENTS-DIRECT, ALTERNATING AND IMPULSE

High currents are used in power system for testing circuit breakers, cables lightning arresters etc. and high currents are encountered during lightning discharges, switching transients and shunt faults. These currents require special techniques for their measurements.

High Direct Currents

Low resistance shunts are used for measurement of these currents. The voltage drop across the shunt resistance is measured with the help of a milli-voltmeter. The value of the resistance varies usually between 10 micro-ohm and 13 milliohm. This depends upon the heating effect and the loading permitted in the circuit. The voltage drop is limited to a few milli-volts usually less than 1 V. These resistances are oil immersed and are made as three or four terminal resistances to provide separate terminals for voltage measurement for better accuracy.

3.3.1 Hall Generators

Hall effect (Fig.3.3.1) is used to measure very high direct current. Whenever electric current flows through a metal plate placed in a magnetic field perpendicular to it, Lorenz force will deflect the electrons in the metal structure in a direction perpendicular to the direction of both the magnetic field and the flow of current. The charge displacement results in an e.m.f. in the perpendicular direction called the Hall voltage. The Hall voltage is proportional to the current *I*, the magnetic flux density *B* and inversely proportional to the plate thickness *d i.e.,*

$$V_H = R\frac{BI}{d}$$

where *R* is the Hall coefficient which depends upon the material of the plate and temperature of the plate. For metals the Hall coefficient is very small and hence semiconductor materials are used for which the Hall coefficient is high.

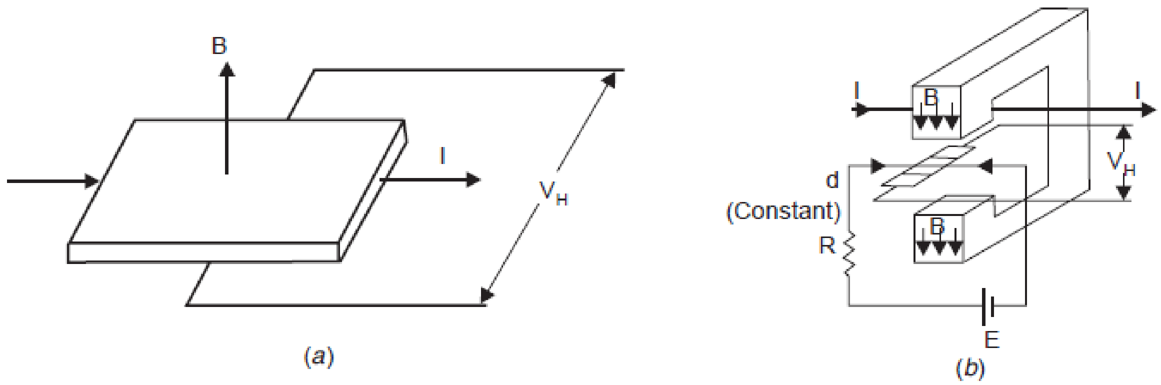


Fig : 3.3.1 Hall generator

When large d.c. currents are to be measured the current carrying conductor is passed through an iron cored magnetic circuit (Fig. 3.3.1 (*b*)). The magnetic field intensity produced by the conductor in the air gap at a depth *d* is given by

$$H = \frac{1}{2\,\pi\, d}$$

The Hall element is placed in the air gap and a small constant d.c. current is passed through the element. The voltage developed across the Hall element is measured and by using the expression for Hall voltage the flux density *B* is calculated and hence the value of current *I* is obtained.

3.3.2 High Power Frequency Currents

High Power frequency currents are normally measured using current transformers as use of low resistance shunts involves unnecessary power loss. Besides, the current transformers provide isolation from high voltage circuits and thus it is safer to work on *HV* circuits Fig.3.3.2 shows a scheme for current measurements using current transformers and electro-optical technique.

A voltage signal proportional to the current to be measured is produced and is transmitted to the ground through the electro-optical device. Light pulses proportional to the voltage signal are transmitted by a glass optical fibre bundle to a photo-detector and converted back into an analog voltage signal. The required power for the signal convertor and optical device are obtained from suitable current and voltage transformers.

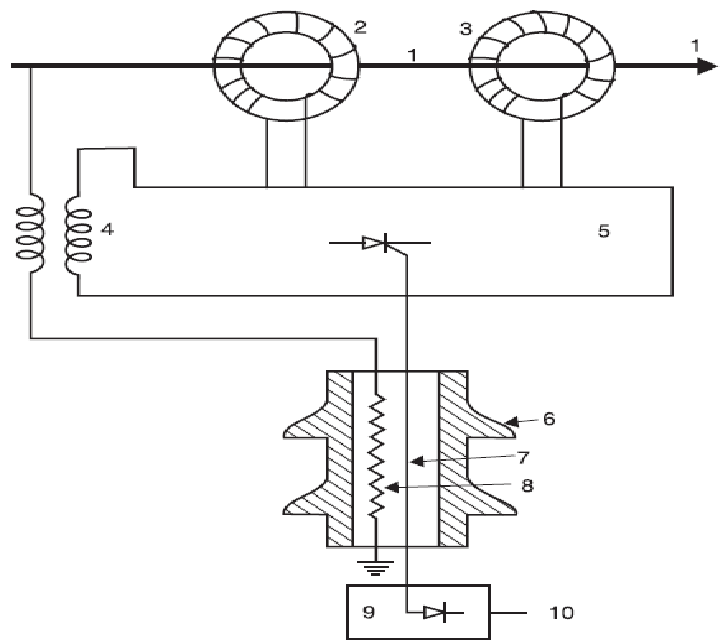


Fig 3.3.2 Current transformers and electro-optical system for high a.c. current measurements

3.3.3 High Frequency and Impulse Currents

In power system the amplitude of currents may vary between a few amperes to a few hundred kiloamperes and the rate of rise of currents can be as high as 1010*A*/sec and the rise time can vary between a few micro seconds to a few macro seconds. Therefore, the device to be used for measuring such currents should be capable of having a good frequency response over a very wide frequency band. The methods normally employed are—(*i*) resistive shunts; (*ii*) elements using induction effects; (*iii*) Faraday and Hall effect devices. With these methods the accuracy of measurement varies between 1 to 10%. Fig. 3.3.3.1 shows the circuit diagram of the most commonly used method for high impulse current measurement.

The voltage across the shunt resistance R due to impulse current $i(t)$ is fed to the oscilloscope through a delay cable D. The delay cable is terminated through an impedance Z equal to the surge impedance of the cable to avoid reflection of the voltage to be measured and thus true measurement of the voltage is obtained. Since the dimension of the resistive element is large, it will have residual inductance L and stray capacitance C.

The inductance could be neglected at low frequencies but at higher frequencies the inductive reactance would be comparable with the resistance of the shunt. The effect of inductance and capacitance above 1 MHz usually should be considered. The resistance values range between 10 micro ohm to a few milliohms and the voltage drop is of the order of few volts. The resistive shunts used for measurements of impulse currents of large duration is achieved only at considerable expense for thermal reasons. The resistive shunts for impulse current of short duration can be built with rise time of a few nano seconds of magnitude. The resistance element can be made of parallel carbon film resistors or low inductance wire resistors of parallel resistance wires or resistance foils. Assuming the stray capacitance to be negligibly small the voltage drop across the shunt in complex frequency domain may be written as

$$V(s) = I(s)[R + Ls]$$

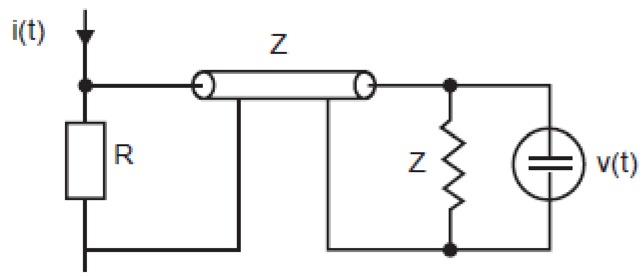


Fig 3.3.3.1 Circuit For High Impulse Current Measurement

It is to be noted that in order to have flat frequency response of the resistive element the stray inductance and capacitance associated with the element must be made as small as possible. In order to minimise the stray field effects following designs of the resistive elements have been suggested and used

1. Bifilar flat strip shunt.
2. Co-axial tube or Park's shunt
3. Co-axial squirrel cage shunt.

The bifilar flat strip shunts suffer from stray inductance associated with the resistance element and its potential leads are linked to a small part of the magnetic flux generated by the current that is being measured. In order to eliminate the problems associated with the bifilar shunts, coaxial shunts were developed (Fig. 3.3.3.2). Here the current enters the inner cylinder of the shunt element and returns through an outer cylinder.

The space between the two cylinders is occupied by air which acts like a perfacts insulator. The voltage drop across the element is measured between the potential pick up point and the outer case. The frequency response of this element is almost a flat characteristic upto about 1000 MHz and the response time is a few nanoseconds. The upper frequency limit is governed by the skin effect in the sensitive element.

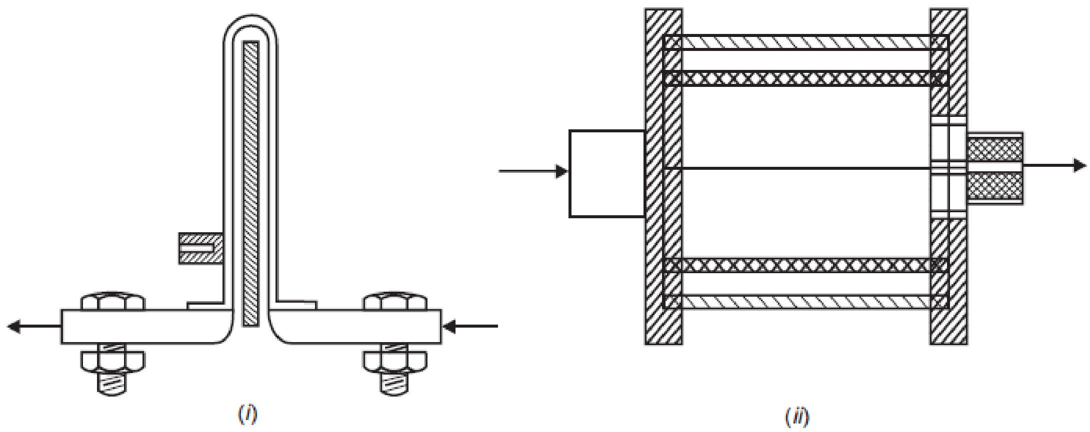


Fig 3.3.3.2 (i) Bifilar flat strip; (ii) Co-axial squirrel cage

Squirrel cage shunts are high ohmic shunts which can dissipate larger energies as compared to coaxial shunts which are unsuitable due to their limitation of heat dissipation, larger wall thickness and the skin effect. Squirrel cage shunt consists of thick metallic rods or strips placed around the periphery of a cylinder and the structure resembles the rotor construction of a double squirrel cage induction motor. The step response of the element is peaky and, therefore, a compensating network is used in conjunction with the element to improve its frequency response. Rise times less than 8 *n* sec and band width of 400 MHz have been obtained with these shunts.

3.3.4 Faraday Generator or Magneto Optic Method

These methods of current measurement use the rotation of the plane of polarisation in materials by the magnetic field which is proportional to the current (Faraday effect). When a linearly polarised light beam passes through a transparent crystal in the presence of a magnetic field, the plane of polarization of the light beam undergoes relation. The angle of rotation is given by

$$\theta = \alpha Bl$$

where 〈 = A constant of the cyrstal which is a function of the wave length of the light.

B = Magnetic flux density due to the current to be measured in this case.

l = Length of the crystal.

Fig : 3.3.4 shows a schematic diagram of Magneto-optic method. Crystal *C* is placed parallel to the magnetic field produced by the current to be measured. A beam of light from a stabilised light source is made incident on the crystal *C* after it is passed through the polariser *P*1. The light beam undergoes rotation of its plane of polarisation. After the beam passes through the analyser *P*2, the beam is focussed on a photomultiplier, the output of which is fed to a CRO. The filter *F* allows only the monochromatic light to pass through it. Photoluminescent diodes too, the momentary light emission of which is proportional to the current flowing through them, can be used for current measurement. The following are the advantages of the method (*i*) It provides isolation of the measuring set up from the main current circuit. (*ii*) It is insensitive to overloading. (*iii*) As the signal transmission is through an optical system no insulation problem is faced. However, this device does not operate for d.c. current.

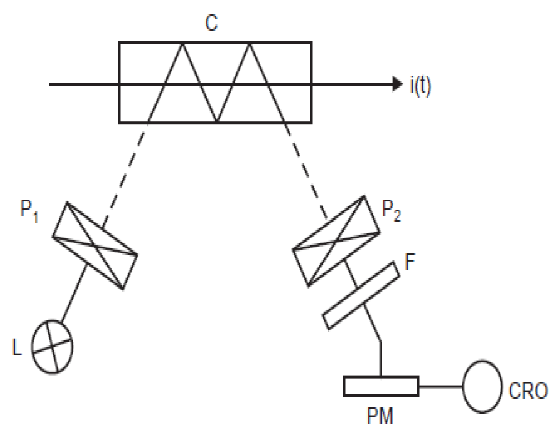


Fig : 3.3.4 Magneto-optical method

3.4 Oscilloscope for impulse voltage and current measurements

When waveforms of rapidly varying signals (voltages or currents) have to be measured or recorded, certain difficulties arise. The peak values of the signals in high voltage measurements are too large, may be several kilovolts or kiloamperes. Therefore, direct measurement is not possible. The magnitudes of these signals are scaled down by voltage dividers or shunts to smaller voltage signals. The reduced signal *Vm(f)* is normally proportional to the measured quantity. The procedure of transmitting the signal and displaying or recording it is very important The associated electromagnetic fields with rapidly changing signals induce disturbing voltages, which have to be avoided.

3.4.1 Cathode Ray Oscillographs for Impulse Measurements

Modern oscillographs are sealed tube hot cathode oscilloscopes with photographic arrangement for recording the waveforms. The cathode ray oscilloscope for impulse work normally has input voltage range from 5 m V/cm to about 20 V/cm. In addition, there are probes and attenuators to handle signals up to 600 V (peak to peak). The bandwidth and rise time of the oscilloscope should be adequate. Rise times of 5 n s and bandwidth as high as 500 MHz may be necessary. Sometimes high voltage surge test oscilloscopes do not have vertical amplifier and directly require an input voltage of 10 V. They can take a maximum signal of about 100 V (peak to peak) but require suitable attenuators for large signals. Oscilloscopes are fitted with good cameras for recording purposes. Tektronix model 7094 is fitted with a lens of 1: 1.2 polaroid camera which uses 10,000 ASA film which possesses a writing speed of 9 cm/n s. With rapidly changing signals, it is necessary to initiate or start the oscilloscope
time base before the signal reaches the oscilloscope deflecting plates, otherwise a portion of the signal may be missed. Such measurements require an accurate initiation of the horizontal time base and is known as triggering. Oscilloscopes are normally provided with both internal and external triggering facility.

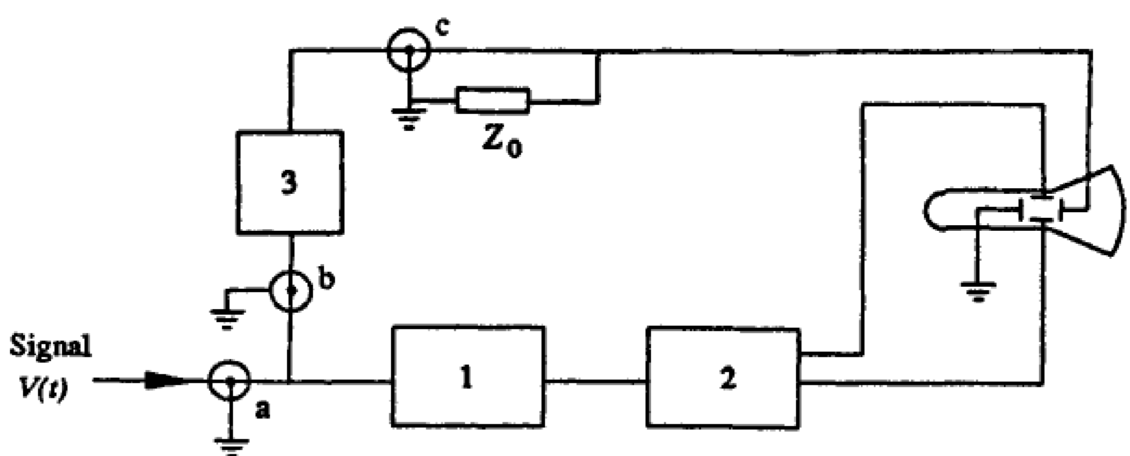


Fig : 3.4.1 a Block diagram of a surge test oscilloscope (older arrangement)

1. Trigger amplifier
2. Sweep generator
3. External delay line

(a) Vertical amplifier input
(b) Input to delay line
(c) Output of delay line to CRO Y plates

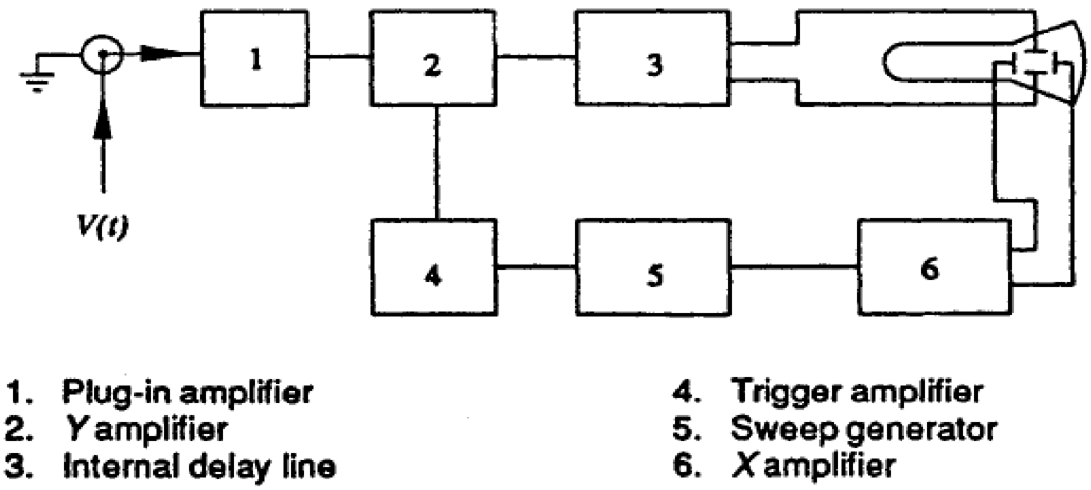


Fig : 3.4.2 b Simplified block diagram of surge test oscilloscopes (recent schemes)

When external triggering is used, as with recording of impulses, the signal is directly fed to actuate the time base and then applied to the vertical or *Y* deflecting plates through a delay line. The delay is usually 0.1 to *0.5* |i s. The delay is obtained by:

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

(2) The measuring signal is transmitted to the CRO by a normal coaxial cable. The delay is obtained by an externally connected coaxial long cable to give the necessary delay. This arrangement is shown in Fig. 3.4.2.

(3) The impulse generator and the time base of the CRO are triggered from an electronic tripping device. A first pulse from the device starts the CRO time base and after a predetermined time a second pulse triggers the impulse generator.

Instrument Leads and Arrangement of Test Circuits

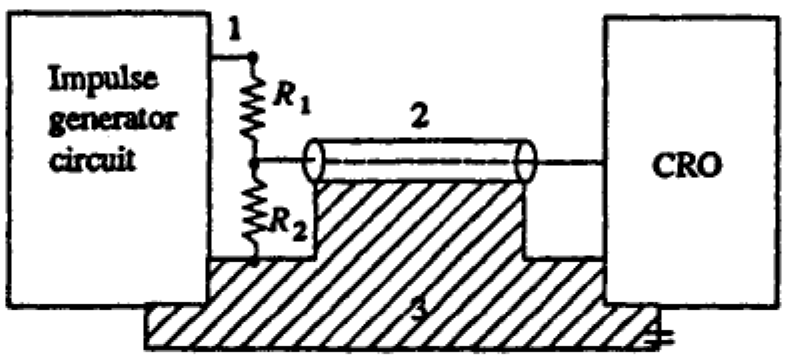
It is essential that leads, layout, and connections from the signal sources to the CRO are to be arranged such that the induced voltages and stray pick-ups due to electromagnetic interference are avoided. For slowly varying signals, the connecting cables behave as either capacitive or inductive depending on the load at the end of the cable. For fast rising signals, however, the cables have to be accounted as transmission lines with distributed parameters. A travelling wave or signal entering such a cable encounters the surge impedance of the cable. To avoid unnecessary reflections at the cable ends, it has to be terminated properly by connecting a resistance equal to the surge impedance of the cable. In cables, the signal travels with a velocity less than that of light which is given by:

$$v = \frac{C}{\sqrt{\varepsilon_r \mu_r}}$$

where *C* = 3 x 108 m/s and er and *\ir* are the relative permittivity and relative permeability respectively of the cable materials. Therefore the cable introduces a finite propagation time

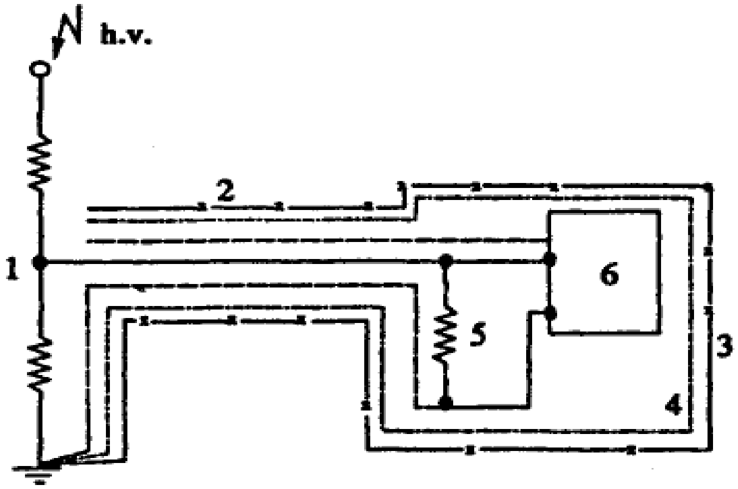
$$t = \frac{1}{v} \text{ length of the cable}$$

Measuring devices such as oscilloscopes have finite input impedance, usually about 1 to 10 MQ resistance in parallel with a 10 to 50 pF capacitance. This impedance at high frequencies (f * 100 MHz) is about 8OQ and thus acts as a load at the end of a surge cable. This load attenuates the signal at the CRO end. Cables at high frequencies are not lossless transmission lines. Because of the ohmic resistance loss in the conductor and the dielectric loss in the cable material, they introduce attenuation and distortion to the signal. Cable distortion has to, be eliminated as far as possible. Cable shields also generate noise, voltages due to ground loop currents and due to the electromagnetic coupling from other conductors. In Fig.3.4.3, the ground loop currents and their path are indicated. To eliminate these noise
voltages multiple shielding arrangement as shown in Fig3.4.4 may have to be used.



1. Potential divider
2. Coaxial signal cable
3. Ground loop

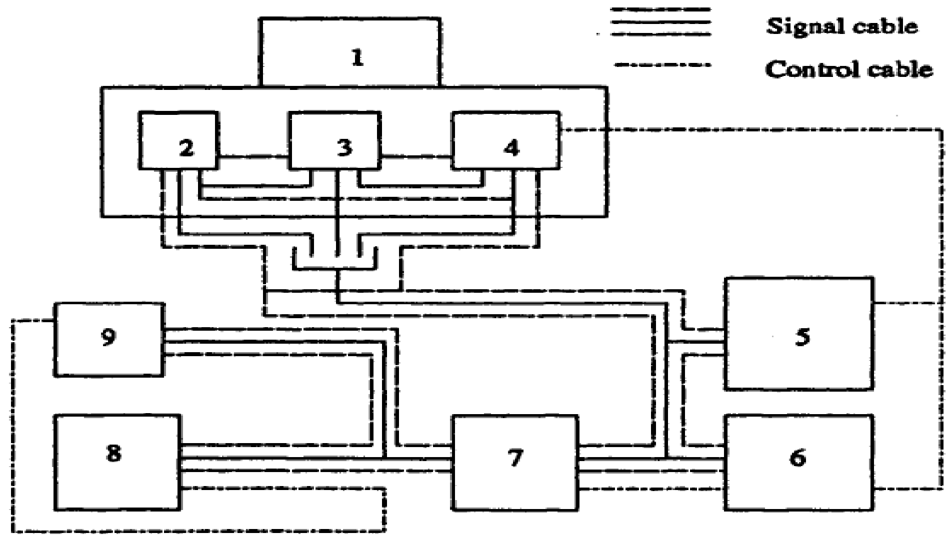
Fig : 3.4.3 Ground Loops in Impulse measuring systems



1. Potential divider
2. Triple shielded cable
3. Outer shield enclosure
4. Inner shielded enclosure
5. Terminating impedance
6. CRO

Fig : 3.4.4 Impulse measurements using multiple shield enclosures and signal cable

Another important factor is the layout of power and signal cables in the impulse testing laboratories. Power and interconnecting cables should not be laid in a zig-zag manner and should not be cross connected. All power cables and control cables have to be arranged through earthed and shielded conduits. A typical schematic layout is shown in Fig.3.4.5. The arrangement should provide for branched wiring from the cable tree and should not form loops. Where environmental conditions are so severe that true signal cannot be obtained with all countermeasures, electro-optical techniques for transmitting signal pulses may have to be used.



1. Control room
2. Peak reading meter
3. Oscillograph
4. Control centre
5. Rectifier for impulse generator
6. Impulse generator
7. Voltage divider
8. Test object
9. Sphere gap

Fig : 3.4.5 Layout of an impulse testing laboratory with control and signal cables

UNIT – 4

NON-DISTRUCTIVE TESTING OF MATERIAL AND ELECTRICAL APPARATUS

Syllabus:

Non-destructive testing of material and electrical apparatus:

Measurement of D.C Resistivity, Measurement of Dielectric Constant and loss factor**:** The Schering bridge, Schering bridge method for grounded test specimen, Schering bridge for measurement of high loss factor, Transformer ratio arm bridge, Loss measurement on complete equipment. Null detectors, Partial discharge measurements: The basic PD test circuit, PD currents, PD measuring systems within the PD test circuit, Measuring systems for apparent charge, Sources and reduction of disturbances, Other PD quantities, Calibration of PD detectors in a complete test circuit, Digital PD instruments and measurements.

NON-DISTRUCTIVE TESTING OF MATERIAL AND ELECTRICAL APPARATUS

Nondestructive Insulation Test Techniques:

All electrical appliances are insulated with gaseous or liquid or solid or a suitable combination of these materials. The insulation is provided between live parts or between live part and grounded part of the appliance. The materials may be subjected to varying degrees of voltages, temperatures and frequencies and it is expected of these materials to work satisfactorily over these ranges which may occur occasionally in the system. The dielectric losses must be low and the insulation resistance high in order to prevent thermal breakdown of these materials. The void formation within the insulating materials must be avoided as these deteriorate the dielectric materials.

When an insulating material is subjected to a voltage for investigation, it is usually not possible to draw conclusion regarding the cause of breakdown from the knowledge of the breakdown voltage particularly in solid materials. Earlier, the quality of insulation was judged, mainly by the insulation resistance and its dielectric strength. However, these days high voltage equipments and installations are subjected to various tests. These tests should also yield information regarding the life expectancy and the long term stability of the insulating materials.

One of the possible testing procedures is to over-stress insulation with high a.c. and/ or d.c. or surge voltages. However, the disadvantage of the technique is that during the process of testing the equipment may be damaged if the insulation is faulty. For this reason, following non-destructive testing methods that permit early detection for insulation faults are used:

(i) Measurement of the insulation resistance under d.c. voltages.
(ii) Determination of loss factor tan δ and the capacitance *C*.
(iii) Measurement of partial discharges.

LOSS IN A DIELECTRIC:

A real dielectric is always associated with loss. The following are the mechanisms which lead to the loss:

(i) Conduction loss P_c by ionic or electronic conduction. The dielectric has σ as conductivity.
(ii) Polarization loss P_p by orientation boundary layer or deformation polarization.
(iii) Ionization loss P_i by partial discharges Internal or external zones.

Fig. 4.1 shows an equivalent circuit of a dielectric with loss due to conduction, polarization and partial discharges. An ideal dielectric can be represented by a pure capacitor C_1, conduction losses can be taken into account by a resistor R_0 (σ) in parallel. Polarization losses produce a real component of the displacement current which is simulated by resistor R_1. Pulse partial discharges are simulated by right hand branch. C_3 is the capacitance of the void and *S* is the spark gap which fires during *PD* discharge and the repeated recharging of C_3 is effected either by a resistor R_2 or a capacitor C_2.

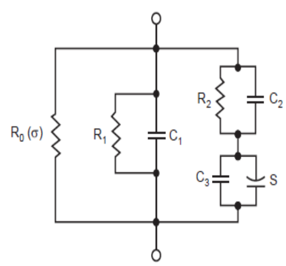


Fig. 4.1 Equivalent circuit of a dielectric

4.1 MEASUREMENT OF RESISTIVITY

When a dielectric is subjected to a steady state static electric field *E* the current density J_c is given by

$$J_c = \sigma E$$

Assuming a cuboid of the insulating material with thickness *d* and area *A*, then

Current $I = J_c A$ and power loss = VI

$$= VJ_c A = V\sigma EA = V\sigma \frac{V}{d} A.\frac{d}{d} = \frac{V}{d}\sigma\frac{V}{d} A.d = \sigma E^2.\text{ Volume}.$$

Therefore, specific dielectric loss = σ□E^2 Watts/m^3.

The conductivity of the insulating materials viz liquid and solid depends upon the temperature and the moisture contents. The leakage resistance *R*0 (σ) of an insulating material is determined by measuring the current when a constant d.c. voltage is applied. Since the current is a function of time as different mechanisms are operating simultaneously. So to measure only the conduction current it is better to measure the current about 1 min after the voltage is switched on. For simple geometries of the specimen (cuboid or cube) specific resistivity (p = 1/σ) can be calculated from the leakage resistance measured. If I is the conduction current measure and V the voltage applied, the leakage resistance is given by

$$R = \frac{V}{I} = \rho\frac{d}{A}$$

where d is the thickness of the specimen and A is the area of section.

Fig. 4.2. shows a simple arrangement for measurement of resistivity of the insulating material. The d.c. voltage of 100 volt or 1000 volt is applied between electrode 1 and the earth. The measuring electrode 2 is earthed through a sensitive ammeter. The third electrode known as guard ring electrode surrounds the measuring electrode and is directly connected to ground so as to eliminate boundary field effects and surface currents. The width of the guard electrode should be at least twice the thickness of the specimen and the unguarded electrode (1) must extend to the outer edge of the guard electrode. The gap between electrode 2 and 3 should be as small as possible. A thin metallic foil usually of aluminum or lead of about 20 □m thickness is placed between the electrodes and specimen for better contact. The specific conductivity for most of the insulating material lies in the range of 10^{-16} to 10^{-10} S/cm, which gives currents to be measured of these specimen to be of the order of pico amperes or nano amperes.

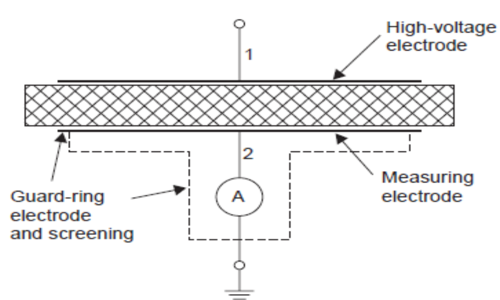


Fig. 4.2 Electrode arrangement to measure the specific

Resistivity of an insulation specimen

The measuring leads should be appropriately and carefully screened. The measurement of conduction current using d.c. voltage not only provides information regarding specific resistivity of the material but it gives an idea of health of the insulating material. If conduction currents are large, the insulating properties of the material are lost. This method, therefore, has proved very good in the insulation control of large electrical machines during their period of operation.

4.2 MEASUREMENT OF DIELECTRIC CONSTANT AND LOSS FACTOR:

Dielectric loss and equivalent circuit

In case of time varying electric fields, the current density *Jc* using Amperes law is given by

$$J_c = \sigma E + \frac{\partial D}{\partial t} = \sigma E + \varepsilon \frac{\partial E}{\partial t}$$

For harmonically varying fields

$$E = E_m e^{j\omega t}$$

$$\frac{\partial E}{\partial t} = jE_m \omega e^{j\omega t} = j\,\omega E$$

Therefore,

$$J_c = \sigma E + j\,\omega\,\varepsilon E$$
$$= (\sigma + j\,\omega\,\varepsilon)E$$

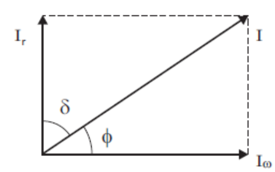


Fig. 4.3 Phasor diagram for a real dielectric material

In general, in addition to conduction losses, ionization and polarization losses also occur and, therefore, the dielectric constant **ε**□= **ε**$_0$ **ε**$_r$ is no longer a real quantity rather it is a complex quantity. By definition, the dissipation factor tanδ□is the ratio of real component of current *I*ω

to the reactive component *Ir* (Fig. 4.3).

$$\tan\delta = \frac{I_\omega}{I_r} = \frac{p_{\text{did}}}{P_r}$$

Here δ is the angle between the reactive component of current and the total current flowing through the dielectric at fundamental frequency. When δ is very small tan δ = δ when δ is expressed in radians and

tan δ = sin δ = sin (90 – φ) = cos φ *i.e.*, tan δ then equals the power factor of the dielectric material.

As mentioned earlier, the dielectric loss consists of three components corresponding to the three loss mechanism.

$$P_{diel} = P_c + P_p + P_i$$

and for each of these an individual dissipation factor can be given such that

$$\tan\delta = \tan\delta_c + \tan\delta_p + \tan\delta_I$$

If only conduction losses occur then

$$P_{diel} = P_c = \sigma E^2 Ad = V^2\omega C \tan\delta = \frac{V^2\omega\,\varepsilon_0\,\varepsilon_r A}{d}\tan\delta$$

$$\sigma E^2 = \frac{V^2}{d^2}\omega\varepsilon_0\varepsilon_r \tan\delta = E^2\omega\varepsilon_0\varepsilon_r \tan\delta$$

$$\tan\delta = \frac{\sigma}{\omega\varepsilon_0\,\varepsilon_r}$$

This shows that the dissipation factor due to conduction loss alone is inversely proportional to the frequency and can, therefore, be neglected at higher frequencies. However, for supply frequency each loss component will have considerable magnitude.

In order to include all losses, it is customary to refer the existence of a loss current in addition to the charging current by introducing complex permittivity.

$$\varepsilon^* = \varepsilon' - j\,\varepsilon''$$

and the total current I is expressed as

$$I = (j\,\omega\varepsilon' + \omega\varepsilon'')\frac{C_0}{\varepsilon_0}V$$

where C_0 is the capacitance without dielectric material.

$$\text{or} \qquad I = j\,\omega\,C_0\,\varepsilon_r^*\,.\,V$$

$$\text{where} \qquad \varepsilon_r^* = \frac{(\varepsilon' - j\,\varepsilon'')}{\varepsilon_0} = \varepsilon'_r - j\,\varepsilon''_r$$

ε_r* is called the complex relative permittivity or complex dielectric constant, **ε′**□and **ε**r ′ called the permittivity and relative permittivity and □″□and □r″□are called the loss factor and relative loss factor respectively.

The loss tangent

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon_r''}{\varepsilon_r'}$$

The product of the angular frequency and **ε″**□is equivalent to the dielectric conductivity σ″□*i.e.*, σ″□□□ωε.

The dielectric conductivity takes into account all the three power dissipative processes including the one which is frequency dependent. Fig. 4.4 shows two equivalent circuits representing the electrical behavior of insulating materials under a.c. voltages, losses have been simulated by resistances.

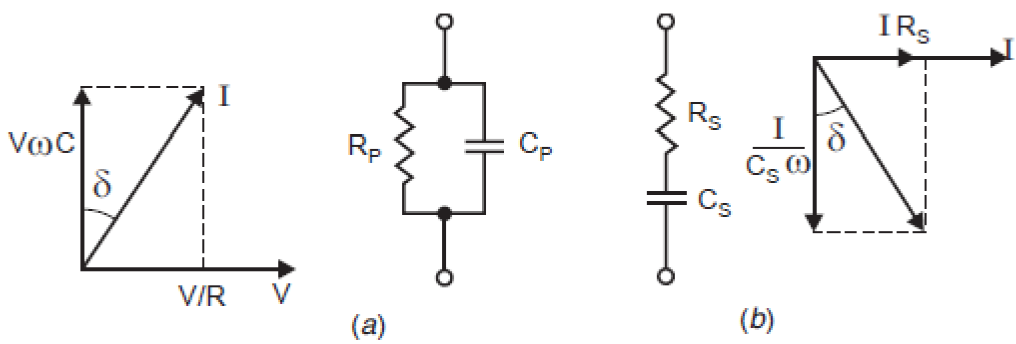


Fig. 4.4 Equivalent circuits for an insulating material

Normally the angle between *V* and the total current in a pure capacitor is 90°. Due to losses, this angle is less than 90°. Therefore, δ□is the angle by which the voltage and charging current fall short of the 90°displacement.

For the parallel circuit the dissipation factor is given by

$$\tan \delta = \frac{1}{\omega C_p R_p}$$

and for the series circuit

$$\tan \delta = \omega\, C_s R_s$$

For a fixed frequency, both the equivalents hold good and one can be obtained from the other. However, the frequency dependence is just the opposite in the two cases and this shows the limited validity of these equivalent circuits.

The information obtained from the measurement of tan δ and complex permittivity is an indication of the quality of the insulating material.

(i) If tan δ varies and changes abruptly with the application of high voltage, it shows inception of internal partial discharge.

(ii) The effect to frequency on the dielectric properties can be studied and the band of frequencies where dispersion occurs *i.e.*, where that permittivity reduces with rise in frequency can be obtained.

4.2.1 HIGH VOLTAGE SCHERING BRIDGE:

The bridge is widely used for capacity and dielectric loss measurement of all kinds of capacitances, for instance cables, insulators and liquid insulating materials. We know that most of the high voltage equipments have low capacitance and low loss factor. This bridge is then more suitable for measurement of such small capacitance equipments as bridge uses either high voltage or high frequency supply. If measurements for such low capacity equipments is carried out at low voltage, the results so obtained are not accurate.

Fig. 4.5 shows a high voltage schering bridge where the specimen has been represented by a parallel combination of *Rp* and *Cp*.

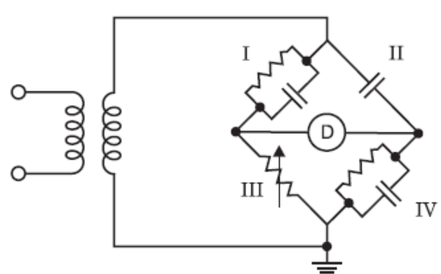


Fig. 4.5 basic high voltage Schering Bridge

The special features of the bridge are:

1. High voltage supply, consists of a high voltage transformer with regulation, protective circuitry and special screening. The input voltage is 220 volt and output continuously variable between 0 and 10kV. The maximum current is 100 mA and it is of 1 kVA capacity.

2. Screened standard capacitor *Cs* of 100 *pF* ±□5%, 10 kV max and dissipation factor tan $\delta = 10^{-5}$. It is a gas-filled capacitor having negligible loss factor over a wide range of frequency.
3. The impedances of arms I and II are very large and, therefore, current drawn by these arms is small from the source and a sensitive detector is required for obtaining balance. Also, since the impedance of arm I and II are very large as compared to III and IV, the detector and the impedances in arm III and IV are at a potential of only a few volts (10 to 20 volts) above earth even when the supply voltage is 10 kV, except of course, in case of breakdown of one of the capacitors of arm I or II in which case the potential will be that of supply voltage. Spark gaps are, therefore, provided to spark over whenever the voltage across arm III or IV exceeds 100 volt so as to provide personnel safety and safety for the null detector.
4. *Null Detector:* An oscilloscope is used as a null detector. The γ–plates are supplied with the bridge voltage V_{ab} and the *x*-plates with the supply voltage *V*. If *Vab* has phase difference with respect to *V*, an ellipse will appear on the screen (Fig. 4.6). However, if magnitude balance is not reached, an inclined straight line will be observed on the screen. The information about the phase is obtained from the area of the eclipse and the one about the magnitude from the inclination angle. Fig. 4.6*a* shows that both magnitude and phase are balanced and this represents the null point condition. Fig. (4.6*c*) and (*d*) shows that only phase and amplitude respectively are balanced.

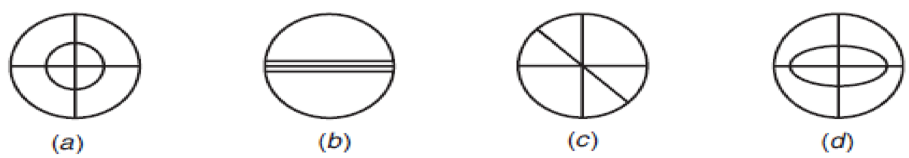


Fig. 4.6 Indications on null detector

The handling of bridge keys allows to meet directly both the phase and the magnitude conditions in a single attempt. A time consuming iterative procedure being used earlier is thus avoided and also with this a very high order of accuracy in the measurement is achieved.

The high accuracy is obtained as these null oscilloscopes are equipped with a γ□–amplifier of automatically controlled gain. If the impedances are far away from the balance point, the whole screen is used. For nearly obtained balance, it is still almost fully used. As *Vab* becomes smaller, by approaching the balance point, the gain increases automatically only for deviations very close to balance, the ellipse area shrinks to a horizontal line.

5. *Automatic Guard Potential Regulator:* While measuring capacitance and loss factors using a.c. bridges, the detrimental stray capacitances between bridge junctions and the ground adversely affect the measurements and are the source of error. Therefore, arrangements should be made to shield the measuring system so that these stray capacitances are either neutralised, balanced or eliminated by precise and rigorous

calculations. Fig. 6.7 shows various stray capacitance associated with High Voltage Schering Bridge.

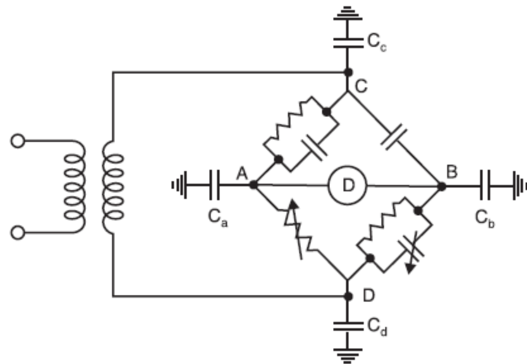


Fig. 4.7 Schering bridge with stray capacitances

Ca, *Cb*, *Cc* and *Cd* are the stray capacitances at the junctions *A*, *B*, *C* and *D* of the bridge. If point *D* is earthed during measurement capacitance *Cd* is thus eliminated. Since *Cc* comes across the power supply for earthed bridge, has no influence on the measurement. The effect of other stray capacitances *Ca* and *Cb* can be eliminated by use of auxiliary arms, either guard potential regulator or auxiliary branch as suggested by Wagner.

Fig. 4.8 shows the basic principle of Wagner earth to eliminate the effect of stray capacitances *Ca* and *Cb*. In this arrangement an additional arm *Z* is connected between the low voltage terminal of the four arm bridge and earth. The stray capacitance *C* between the high voltage terminal of the bridge and the grounded shield and the impedance *Z* together constitute a six arm bridge and a double balancing procedure is required.

Switch *S* is first connected to the bridge point *b* and balance is obtained. At this point *a* and *b* are at the same potential but not necessarily at the ground potential. Switch *S* is now connected to point *C* and by adjusting impedance *Z* balance is again obtained. Under this condition point '*a*' must be at the same potential as earth although it is not permanently at earth potential. Switch *S* is again connected to point *b* and balance is obtained by adjusting bridge parameters. The procedure is repeated till all the three points *a*, *b* and *c* are at the earth potential and thus *Ca* and *Cb* are eliminated.

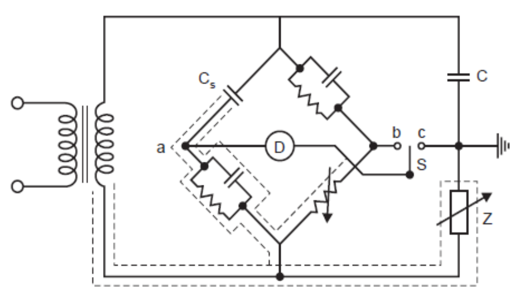


Fig. 4.8 Bridge incorporating Wagner earth

This method is, however, now rarely used. Instead an auxiliary arm using automatic guard potential regulator is used. The basic circuit is shown in Fig. 6.9.

The guard potential regulator keeps the shield potential at the same value as that of the detector diagonal terminals *a* and *b* for the bridge balance considered. Since potentials of *a*, *b* and shield are held at the same value the stray capacitances are eliminated. During the process of balancing the bridge the points *a* and *b* attain different values of potential in magnitude and phase with respect to ground. As a result, the guard potential regulator should be able to adjust the voltage both in magnitude and phase. This is achieved with a voltage divider arrangement provided with coarse and fine controls, one of them fed with in-phase and the other quadrature component of voltage. The control voltage is then the resultant of both components which can be adjusted either in positive or in negative polarity as desired. The comparison between the shielding potential adjusted by means of the Guard potential regulator and the bridge voltage is made in the null indicator oscilloscope as mentioned earlier. Modifying the potential, it is easy to bring the reading of the null detector to a horizontal straight line which shows a balance between the two voltages both in magnitude and phase.

The automatic guard potential regulator adjusts automatically the guard potential of the bridge making this equal in magnitude and phase to the potential of the point *a* or *b* with respect to ground. The regulator does not use any external source of voltage to achieve this objective. It is rather connected to the bridge corner point between *a* or *b* and *c* and is taken as a reference voltage and this is then transmitted to the guard circuit with unity gain both in magnitude and phase. The shields of the leads to *Cs* and *Cp* are not grounded but connected to the output of the regulator which, in fact, is an operational amplifier. The input impedance of the amplifier is more than 1000 Megaohms and the output impedance is less than 0.5 ohm. The high input impedance and very low output impedance of the amplifier does not load the detector and keeps the shield potential at any instant at an artificial ground.

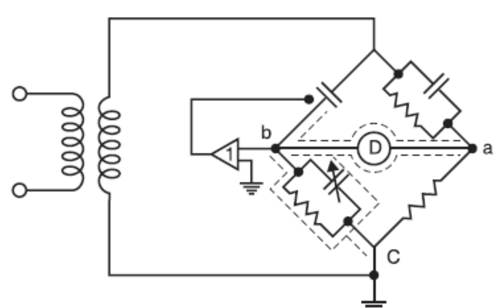


Fig. 4.9 Automatic Wagner earth or automatic guard potential regulator

Balancing the Bridge:

For ready reference Fig.4.5 is reproduced here and its phasor diagram under balanced condition

is drawn in Fig. 4.10 (*b*)

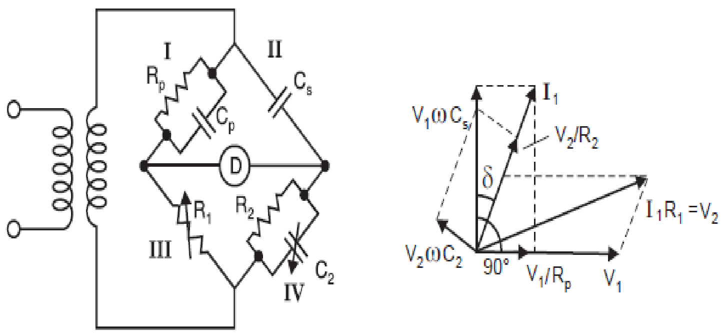


Fig. 4.10 (a) Schering bridge (b) Phasor diagram

The bridge is balanced by successive variation of *R*1 and *C*2 until on the oscilloscope (Detector) a horizontal straight line is observed:

At balance $$\frac{Z_I}{Z_{II}} = \frac{Z_{III}}{Z_{IV}}$$

Now $$Z_I = \frac{R_p}{1 + j\,\omega\,C_p R_p}$$

$$Z_{II} = \frac{1}{j\,\omega\,C_s}$$

$$Z_{III} = R_I \text{ and } Z_{IV} = \frac{R_2}{1 + j\,\omega\,C_2 R_2}$$

From balance equation we have

$$\frac{R_p}{R_1\,(1 + i\omega\,C_p R_p)} = \frac{1/j\,\omega\,C_s\,(1 + j\omega\,C_2 R_2)}{R_2}$$

or $$\frac{R_p\,(1 - j\,\omega\,C_p R_p)}{R_1\left(1 + \omega^2 C_p^2 R_p^2\right)} = \frac{1 + j\,\omega\,C_2 R_2}{j\,\omega\,C_s R_2}$$

or $$\frac{R_p}{R_1\left(1 + \omega^2 C_p^2 R_p^2\right)} - \frac{j\,\omega\,C_p R_p^2}{R_1\left(1 + \omega^2 C_p^2 R_p^2\right)} = -\frac{j}{\omega C_s R_2} + \frac{C_2}{C_s}$$

Equating real part, we have

$$\frac{R_p}{R_1\left(1 + \omega^2 C_p^2 R_p^2\right)} = \frac{C_2}{C_s}$$

and equating imaginary part, we have

$$\frac{\omega\ C_p R_p^2}{R_1\left(1+\omega^2\ C_p^2 R_p^2\right)} = \frac{1}{\omega C_s R_2}$$

Now tan δ from the phasor diagram

$$\tan\delta = \frac{V_1/R_p}{V_1 \omega C_p} = \frac{1}{\omega C_p R_p} = \frac{V_2\ \omega\ C_2}{V_2/R_2} = \omega C_2 R_2$$

Also $$\cos\delta = \frac{V_1 \omega C_p}{V_1\sqrt{\left(1/R_p^2\right)+\omega^2 C_p^2}}$$

or $$\cos^2\delta = \frac{\omega^2 C_p^2 R_p^2}{1+\omega^2 C_p^2 R_p^2}$$

or $$\frac{\omega C_p R_p}{1+\omega^2 C_p^2 R_p^2} = \cos^2\delta \cdot \frac{1}{\omega\ C_p R_p} = \frac{R_1}{\omega\ C_s R_2 R_p}$$

or $$C_p = \cos^2\delta\ C_s\ \frac{R_2}{R_1}$$

Since δ is usually very small cos δ = 1

Therefore $$C_p \approx C_s\ \frac{R_2}{R_1}$$

and $$\tan\delta_p = \omega\ C_2 R_2$$

and since $$\frac{1}{\omega\ C_p R_p} = \omega\ C_2 R_2$$

or $$\omega^2 C_p R_p C_2 R_2 = 1$$

or $$R_p = \frac{1}{\omega^2 R_2 C_2 C_p} \approx \frac{R_1}{\omega^2 R_2 C_2 C_s R_2} \approx \frac{R_1}{\omega^2 C_2 C_s R_2^2}$$

If, however, the specimen is replaced by *a* series equivalent circuit, then at balance

$$Z_I = R_s - \frac{j}{\omega C_s}$$

and the equation becomes

$$\frac{R_s - j/\omega C_s}{R_1} = \frac{1 + j\omega C_2 R_2}{j\omega C_s' R_2}$$

or $$\frac{R_s}{R_1} - \frac{j}{\omega C_s R_1} = -\frac{j}{\omega C_s' R_2} + \frac{C_2}{C_s'}$$

Equating real parts, we have

$$\frac{R_s}{R_1} = \frac{C_2}{C_s'}$$

or $$R_s = R_1 \frac{C_2}{C_s'}$$

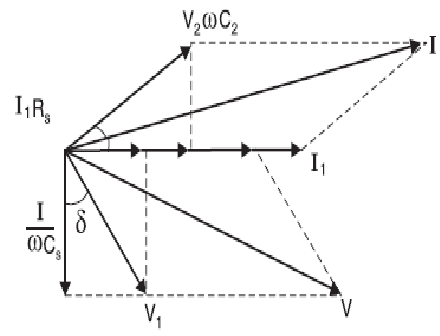


Fig. 4.11 Phasor diagram of S.B. for series equivalent of specimen

Similarly equating imaginary part, we have

$$\omega C_s R_1 = \omega C_s' R_2$$

or $$C_s = C_s' \frac{R_2}{R_1}$$

To find out tan δ, we draw the phasor diagram of the bridge circuit (Fig. 4.11).

$$\tan \delta_s = \frac{I_1 R_s}{I_1/\omega C_s} = \omega C_s R_s$$

MEASUREMENT OF LARGE CAPACITANCE:

In order to measure a large capacitance, the resistance *R*1 should be able to carry large value of current and resistance *R*1 should be of low value. To achieve this, a shunt of *S* ohm is connected across *R*1 as shown in Fig. 4.12. It is desirable to connect a fixed resistance *R* in series with variable resistance *R*1 so as to protect *R*1 from excessive current, should it accidentally be set to a very low value.

We know that under balanced condition for series equivalent representation of specimen

$$C_s = C_s' \frac{R_2}{R_1}$$

But here R_1 is to be replaced by the equivalent of $(R + R_1) \parallel S$.

or $$\frac{(R+R_1)\,S}{R+R_1+S}$$

or $$\frac{1}{R_{en}} = \frac{R+R_1+S}{(R+R_1)\,S}$$

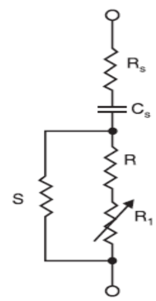


Fig. 6.12 Shunt arrangement for measurement of large capacitance

Therefore, $$C_s = C_s' R_2 \cdot \frac{R+R_1+S}{(R+R_1)S} \cdot \frac{R_1}{R_1} = C_s' \frac{R_2}{R_1} \cdot \frac{R_1\,(R+R_1+S)}{(R+R_1)\,S}$$

usually $R << R_1$

Therefore $$C_s = C_s' \frac{R_2}{R_1} \frac{R_1\,(R+R_1+S)}{R_1 S} = C_s' \frac{R_2}{R_1}\left[\frac{R}{S} + \frac{R_1}{S} + 1\right]$$

and $$\tan \delta = \omega\, C_s' R_2 .\, R/R_1$$

If circuit elements of Schering bridge are suitably designed, the bridge principle can be used upto to 100 kHz of frequency. However, common schering bridge can be used upto about 10 kHz only.

4.2.1.1 SCHERING BRIDGE METHOD FOR GROUNDED TEST SPECIMEN

A dielectric material which is to be tested, one side of this is usually grounded *e.g.* underground cables or bushings with flanges grounded to the tank of a transformer etc. There are two well known methods used for such measurement. One is the inversion of a Schering bridge shown in Fig. 4.13 with the operator, ratio arms and null detector inside a Faraday Cage at high potential.

The system requires the cage to be insulated for the full test voltage and with suitable design may be used up to maximum voltage available. However, there are difficulties in inverting physically the standard capacitor and it becomes necessary to mount it on a platform insulated for full voltage. Second method requires grounding of detector as shown in Fig. 4.14. In this arrangement, stray capacitances of the high voltage terminal *Cq* and of the source, leads etc. come in parallel with the test object. Hence, balancing is carried out in two steps: First step: The test specimen is disconnected and the capacitance *Cq* and loss factor tan δ*q* are measured. Second step: The test object is connected in the bridge and new balance is obtained. The second balance gives net capacitance of the parallel combination *i.e.,*

$$C_s' = C_s + C_q$$

and $$\tan \delta_q' = \frac{C_s \tan \delta_s + C_q \tan \delta_q}{C_s + C_q}$$

Hence the capacitance and loss factor of the specimen are

$$C_s = C_s'' - C_q$$

and $$\tan \delta_s = \frac{C_s'' \tan \delta'' - C_q \tan \delta_q}{C_s}$$

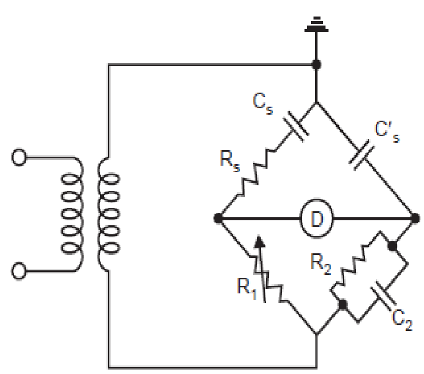


Fig. 4.13 Inverted Schering Bridge

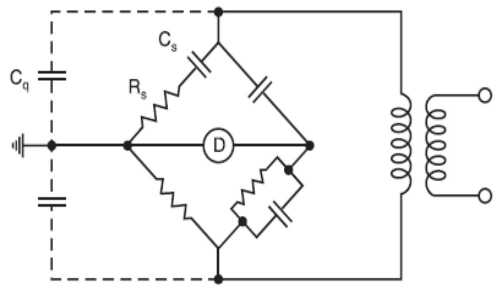


Fig. 4.14 Grounded specimen

If the stray capacitances are large as compared to the capacitance of the specimen, the accuracy of measurement is poor.

4.2.1.2 SCHERING BRIDGE FOR MEASUREMENT OF HIGH LOSS FACTOR:

If the loss factor tan δ□of a specimen is large, the bridge arm containing resistance *R*2 is modified. Resistance *R*2 is made as a slide wire along with a decade resistor and a fixed capacitance *C*2 is connected across the resistance *R*2 as shown in Fig. 4.15 (*a*). This modification can be used for test specimen having loss factor of the order of 1.0. If it is more than one and up to 10 or greater *C*2, *R*2 arm is not made a parallel combination, rather it is made a series combination as shown in Fig. 4.15 (*b*) Here, of course *R*2 is made variable.

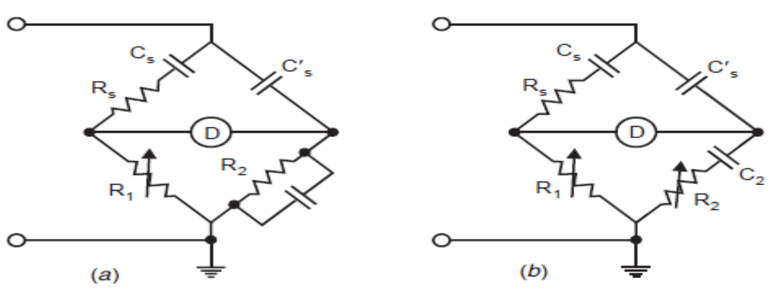


Fig. 4.15 Schering bridges for large loss factor

4.2.2 TRANSFORMER RATIO ARM BRIDGE:

For measurement of various parameters like resistance, inductance, capacitance, usually four arm bridges are used. For high frequency measurements, the arm with high resistances leads to difficulties due to their residual inductance capacitance and skin effect. Also if length of the leads is large, shielding is difficult. Hence at high frequencies the transformer ratio arm bridge which eliminates at least two arms, are preferred. These bridges provide more accurate results for small capacitance measurements. There are two types of transformer ratio arm bridges (*i*) Voltage ratio; (*ii*) Current ratio. The voltage ratio type is used for high frequency low voltage application. Fig. 6.16 shows schematic diagram of a voltage ratio arm bridge. Assuming ideal transformer, under balance condition:

$$\frac{V_b}{V_s} = \frac{N_b}{N_s} = \frac{C_s}{C_s'} \text{ and } \frac{R_s}{R_a} = \frac{N_s}{N_a}$$

However, in practical situation due to the presence of magnetizing current and the load currents, the voltage ratio slightly differs from the turns ratio and therefore, the method involves certain errors. The errors are classified as ratio error and load error which can be calculated before hand for a transformer. A typical bridge has a useful range from a fraction of a *pF* to about 100 □*F* and is accurate over a wide range of frequency from 100 Hz to 100 kHz, the accuracy being better than □□□0.5%. The current ratio arm bridge is used for high voltage low frequency applications. The main advantage of the method is that the test specimen is subjected to full system voltage. Fig. 4.17 shows schematic diagram of the bridge. The main component of the bridge is a three winding current transformer with very low losses and leakage (core of high permeability). The transformer is carefully shielded against stray magnetic fields and protected against mechanical vibrations.

The main feature of the arrangement is that under balance condition, there is no net *mmf* across the windings 1 and 2. Also the stray capacitances between the windings and the screened low voltage leads do not enter in the balance expression as there is no voltage developed between them. This feature makes this bridge possible to use long leads without using Wagner's earth. The sensitivity of the bridge is higher than that of the Schering bridge. The balance is obtained by varying *N*1, *N*2 and *R*. Under balance condition, the voltage across the detector coil is zero an

$$I_s N_1 = I_2 N_2$$

Voltage across the *R*-*C* arm is

$$V = \frac{I_s' R}{1 + j\omega CR}$$

Current I_2 through coil 2 is

$$I_2 = \frac{I_s' \dfrac{1}{j\,\omega C}}{R + \dfrac{1}{j\,\omega c}} = \frac{I_s'}{1 + J\omega CR}$$

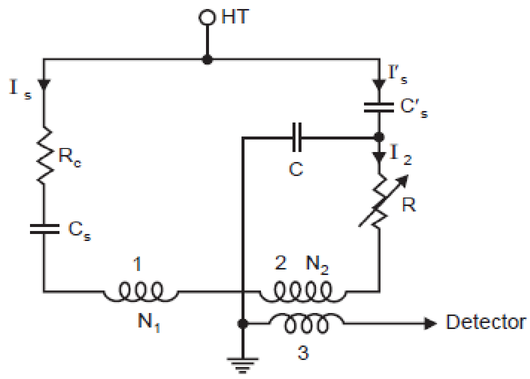


Fig. 4.17 Transformer current ratio arm bridge

Now total impedance of the branch consisting of C_s' and R and C.

$$Z = \left[\frac{1}{j\omega C_s'} + \frac{R}{1 + j\omega CR}\right]$$

Therefore, if unity voltage is applied, the current through this branch.

$$I_s' = \frac{1}{\dfrac{1}{j\omega C_s'} + \dfrac{R}{1 + j\omega CR}} = \frac{j\omega C_s'(1 + j\omega CR)}{1 + j\omega CR + j\omega C_s' R}$$

or

$$I_2 = \frac{j\omega C_s'(1 + j\omega CR)}{1 + j\omega R(C + C_s')} \cdot \frac{1}{1 + j\omega CR} = \frac{j\omega C_s'}{1 + j\omega R(C + C_s')}$$

Now again with unity voltage

$$I_s = \frac{1}{R_s + \dfrac{1}{j\omega C}} = \frac{j\omega C_s'}{1 + j\omega C_s R_s}$$

$$\frac{I_s}{I_2} = \frac{[1 + j\omega R(C + C_s')]C_s}{(1 + j\omega C_s R_s)C_s'} = \frac{N_2}{N_1}$$

Therefore, $$\frac{C_s}{C_s'} = \frac{N_2}{N_1}$$

or $$C_s = C_s' \frac{N_2}{N_1}$$

and $$\tan \delta_s = \omega R (C_s' + C)$$

4.2.3 Loss measurement on complete equipment:

It is often required to measure the dielectric loss on specimen's one side of which is permanently earthed. There are two established methods used for such measurement. One is the inversion of a Schering bridge, shown in Fig. 4.18, with the operator, ratio arms and null detector inside a Faraday cage at high potential. The system requires the cage to be insulated for the full test voltage and with suitable design may be used up to the maximum voltage available. There are, however, difficulties in inverting physically the h.v. standard capacitor and it becomes necessary to mount it on a platform insulated for full voltage.

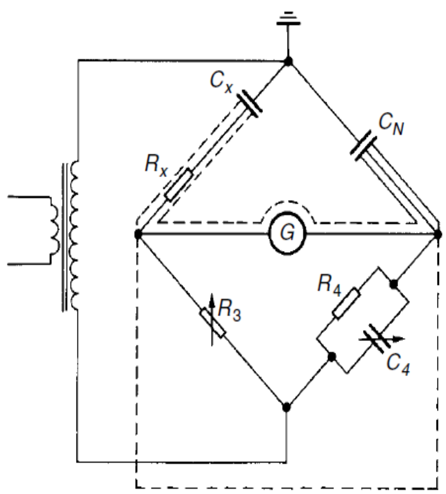


Fig:4.18 *High-voltage bridge with Faraday cage*

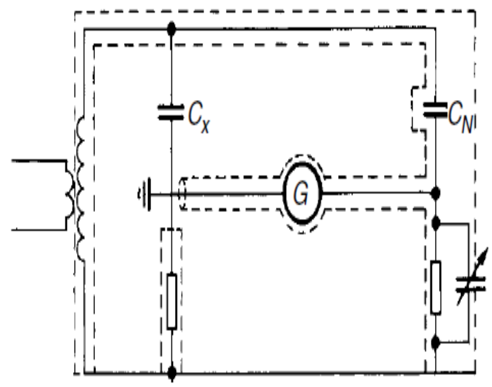


Fig : 4.19 *Fully screened bridge*

An alternative method, though limited to lower voltages, employs an artificial earth which differs in potential from a true earth by the voltage developed across each of the l.v. arms as shown in Fig.4.20 The artificial earth screen intercepts all the field from high potential to earth except in the specimen. It thus requires screening of the h.v. lead and presents difficulties at voltages in Excess of about 5 KV.

4.2.4 Null detectors:

The null detector _G_ for ancient bridges was simply a vibration galvanometer of high mechanical Q factor. Although their application is well justified, the sensitivity to mechanical noise (if present) and the limited electrical sensitivity present some disadvantages. Since a few decades more sensitive electronic null detectors are commonly used. The possible high sensitivity, however, cannot be utilized in general, as noise voltages from the circuit, or electromagnetically induced voltages from the stray fields of the h.v. circuit, disturb the balance.

This electronic null detector reads the voltage across the detector branch. As the balance equations of the bridge are only valid for a particular fixed frequency, the unavoidable harmonic content of the high input voltage of the bridge results in higher harmonic voltages across the null detector, for which the bridge is not balanced. A very pronounced pass-band characteristic is therefore necessary to attenuate these harmonics.

A very much improved balance is possible using electronic null detectors, which are also sensitive to the phase. Bridges may only slowly converge, i.e. the magnitude of the detector branch voltage may only slightly change within the individual settings of R3 and C4 in the Schering bridge or R in the transformer ratio-arm bridge. In the use of phase-sensitive null detectors, the balance condition is indicated in terms of magnitude and phase. With a reference voltage in phase with the (high) source voltage, these values describe Lissajou figures at the screen of a CRO used for the display. In this way the balancing procedure is always known and the balance is obtained much faster.

4.3. Partial-discharge measurements:

What is a 'partial discharge'? Let us use the definition given in the International Standard of the IEC (International Electro technical Commission) related to partial discharge measurements, see reference 31: Partial discharge (PD) is a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor. This definition is supplemented by three notes, from which only notes 1 and 2 shall be cited:

NOTE 1 – Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation.

Generally such discharges appear as pulses of duration of much less than 1 μs. More continuous forms may, however, occur, as for example the so called pulse-less discharges in gaseous dielectrics. This kind of discharge will normally not be detected by the measurement methods described in this standard.

NOTE 2 – 'Corona' is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation.

'Corona' should not be used as a general term for all forms of PD.

No further explanations are necessary to define this kind of phenomena: PDs are thus localized electrical discharges within any insulation system as applied in electrical apparatus, components or systems. In general PDs are restricted to a part of the dielectric materials used, and thus only partially bridging the electrodes between which the voltage is applied. The insulation may consist of solid, liquid or gaseous materials, or any combination of these. The term 'partial discharge' includes a wide group of discharge phenomena: (i) internal discharges occurring in voids or cavities within solid or liquid dielectrics; (ii) surface discharges appearing at the boundary of different insulation materials; (iii) corona discharges occurring in gaseous dielectrics in the presence of in homogeneous fields; (iv) continuous impact of discharges in solid dielectrics forming discharge channels (treeing).

The significance of partial discharges on the life of insulation has long been recognized. Every discharge event causes a deterioration of the material by the energy impact of high energy electrons or accelerated ions, causing chemical transformations of many types. As will be shown later, the number of discharge events during a chosen time interval is strongly dependent on the kind of voltage applied and will be largest for a.c. voltages. It is also obvious that the actual deterioration is dependent upon the material used. Corona discharges in air will have no influence on the life expectancy of an overhead line; but PDs within a thermoplastic dielectric, e.g. PE, may cause breakdown within a few days. It is still the aim of many investigations to relate partial discharge to the lifetime of specified materials. Such a quantitatively defined relationship is, however, difficult to ensure. PD measurements have nevertheless gained great importance during the last four decades and large number publications are concerned either with the measuring techniques involved or with the deterioration effects of the insulation.

The detection and measurement of discharges is based on the exchange of energy taking place during the discharge. These exchanges are manifested as: (i) electrical pulse currents (with some exceptions, i.e. some types of glow discharges); (ii) dielectric losses; (iii) e.m. radiation (light); (iv) sound (noise); (v) increased gas pressure; (vi) chemical reactions. Therefore, discharge detection and measuring techniques may be based on the observation of any of the above phenomena.

The oldest and simplest method relies on listening to the acoustic noise from the discharge, the 'hissing test'. The sensitivity is, however, often low and difficulties arise in distinguishing between discharges and extraneous noise sources, particularly when tests are carried out on factory premises. It is also well known that the energy released by PD will increase the dissipation factor; a measurement of tan υ in dependency of voltage applied displays an 'ionization knee', a bending of the otherwise straight dependency. This knee, however, is blurred and not pronounced, even with an appreciable amount of PD, as the additional losses generated in very localized sections can be very small in comparison to the volume losses resulting from polarization processes. The use of optical techniques is limited to discharges within transparent media and thus not applicable in most cases. Only modern acoustical detection methods utilizing ultrasonic transducers can successfully be used to localize the discharges. These very specialized methods are not treated here.

The most frequently used and successful detection methods are the electrical ones, to which the new IEC Standard is also related. These methods aim to separate the impulse currents linked with partial discharges from any other phenomena. The adequate application of different PD detectors which became now quite well defined and standardized within, presupposes a fundamental knowledge about the electrical phenomena within the test samples and the test circuits. Thus an attempt is made to introduce the reader to the basics of these techniques without full treatment, which would be too extensive. Not treated here, however, are non-electrical methods for PD detection.

4.3.1 The basic PD test circuit:

Electrical PD detection methods are based on the appearance of a 'PD (current or voltage) pulse' at the terminals of a test object, which may be either a simple dielectric test specimen for fundamental investigations or even a large h.v. apparatus which has to undergo a PD test. For the evaluation of the fundamental quantities related to a PD pulse we simulate the test object, as usual, by the simple capacitor arrangement as shown in Fig. 4.20(a), comprising solid or fluid dielectric materials between the two electrodes or terminals A and B, and a gas-filled cavity. The electric field distribution within this test object is here simulated by some partial capacitances, which is possible as long as no space charges disturb this distribution. Electric field lines within the cavity are represented by C'_c and those starting or ending at the cavity walls form the two capacitances C'_b and C''_b within the solid or fluid dielectric. All field lines outside the cavity are represented by $Ca = C'_a + C_a''$. Due to realistic geometric dimensions involved, and as $C'_b = C'_b C''_b / (C'_b + C''_b)$, the magnitude of the capacitances will then be controlled by the inequality

Ca>> Cc >> Cb.

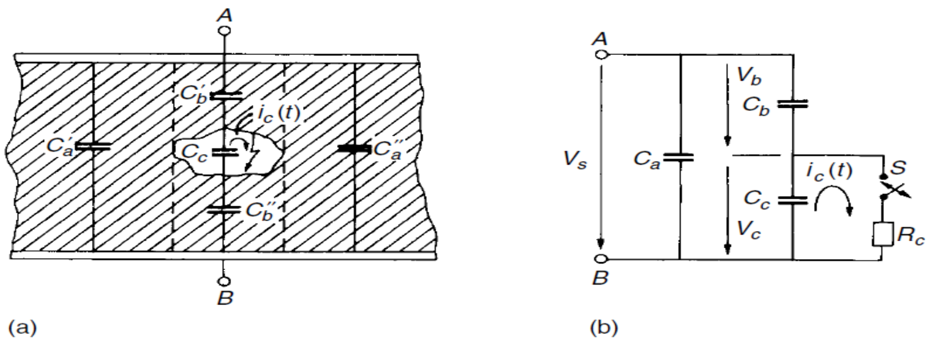


Fig 4.20 Simulation of a PD test object. (a) Scheme of an insulation system comprising a cavity. (b) Equivalent circuit

This void will become the origin of a PD if the applied voltage is increased, as the field gradients in the void are strongly enhanced by the difference in permittivity's as well as by the shape of the cavity. For an increasing value of an a.c. voltage the first discharge will appear at the crest or rising part of a half-cycle. This discharge is a gas discharge creating electrons as well as negative and positive ions, which are driven to the surfaces of the void thus forming dipoles or additional polarization of the test object. This physical effect reduces the voltage across the void significantly. Within our model, this effect is causing the cavity capacitance Cc to discharge to a large extent. If the voltage is still increasing or decreasing by the negative slope of an a.c. voltage, new field lines are built up and hence the discharge phenomena are repeated during each cycle If increasing d.c. voltages are applied, one or only a few partial discharges will occur during the rising part of the voltage. But if the voltage remains constant, the discharges will stop as long as the surface charges as deposited on the walls of the void do not recombine or diffuse into the surrounding dielectric. These phenomena can now be simulated by the equivalent circuit of this scheme as shown in Fig. 4.21(b). Here, the switch S is controlled by the voltage Vc across the void capacitance Cc, and S is closed only for a short time, during which the flow of a current $i_c(t)$takes place. The resistor Rc simulates the time period during which the discharge develops and is completed. This discharge current $i_c(t)$, which cannot be measured, would have a shape as governed by the gas discharge process and would in general be similar to a Dirac function, i.e. this discharge current is generally a very short pulse in the nanosecond range. Let us now assume that the sample was charged to the voltage Va but the terminals A, B are no longer connected to a voltage source. If the switch S is closed and C_c becomes completely discharged, the current $i_c(t)$ releases a charge $\delta q_c = C_c \delta V_c$ from C_c, a charge which is lost in the whole system as assumed for simulation. By comparing the charges within the system before and after this discharge, we receive the voltage drop across the terminal δV_a as

$$\delta V_a = \frac{C_b}{C_a + C_b} \delta V_c$$

This voltage drop contains no information about the charge δq_c, but it is proportional to ($C_c \delta V_c$), a magnitude vaguely related to this charge, as Cb will increase with the geometric dimensions of the cavity. δV_a is clearly a quantity which could be measured. It is a negative voltage step with a rise time depending upon the duration of $i_c(t)$. The magnitude of the voltage step, however, is quite small, although δV_c is in a range of some 102 to 103 V; but the ratio C_b/C_a will always be very small and unknown according to eqn (7.42). Thus a direct detection of this voltage step by a measurement of the whole input voltage would be a tedious task. The detection circuits are therefore based upon another quantity, which can immediately be derived from a nearly complete circuit shown in Fig. 4.21. The test object, Fig. 4.20(a), is now connected to a voltage source V, in general an a.c. power supply. An impedance Z, comprising either only the natural impedance of the lead between voltage source and the parallel arrangement of C_K and C_t or enlarged by a PD-free inductance or filter, may disconnect the 'coupling capacitor' C_K and the test specimen Ct from the voltage source during the short duration PD phenomena only. Then C_K is a storage capacitor or quite a stable voltage source during the short period of the partial discharge.

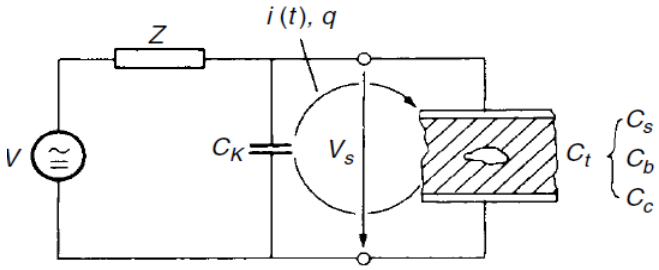


Fig .4.21: The PD test object Ct *within a PD test circuit*

It releases a charging current or the actual 'PD current pulse' i(t) between C_K and C_t and tries to cancel the voltage drop δV_a across $C_t \approx (C_a + C_b)$. If $C_K >> C_t$, δV_a is completely compensated and the charge transfer provided by the current pulse i(t) is given by

$$q = \int i(t) = (C_a + C_b)\delta V_a$$

With eqn (7.43), this charge becomes

$$q = C_b \delta V_c$$

and is the so-called *apparent charge of a PD pulse*, which is the most fundamental quantity of all PD measurements. The word 'apparent' was introduced because this charge again is not equal to the amount of charge locally involved at the site of the discharge or cavity Cc. This PD quantity is much more realistic than δV_a in eqn (7.43), as the capacitance Ca of the test object, its main part of Ct, has no influence on it. And even the amount of charge as locally involved during a discharge process is of minor interest, as only the number and magnitude of their dipole moments and their interaction with the electrodes or terminals determine the magnitude of the PD current pulse.

The condition $C_K >> C_a$ ($\approx C_t$) is, however, not always applicable in practice, as either C_t is quite large, or the loading of an a.c. power supply becomes high and the cost of building such a large capacitor, which must be free of any PD, is not economical. For a finite value of C_K the charge q or the current i(t)is reduced, as the voltage across C_K will also drop during the charge

transfer. Designating this voltage drop by δVŁa , we may compute this value by assuming that the same charge $C_b\delta V_c$ has to be transferred in the circuits of Figs 7.20(b) and 7.21. Therefore

$$\delta V_a(C_a + C_b) = \delta V^*(C_a + C_b + C_K).$$

Introducing eqn (7.43) as well as eqn (7.45), we obtain

$$\delta V^* = \frac{C_b}{C_a + C_b + C_K}\delta V_c = \frac{q}{C_a + C_b + C_K}.$$

Again, δV^* is a difficult quantity to be measured. The charge transferred from C_K to C_t by the reduced current i(t) is, however, equal to $C_K\delta V^*$it is related to the real value of the apparent charge q which then can be measured by an integration procedure, If we designate this measured quantity as q_m, then

$$q_m = C_K\delta V^* = \frac{C_K}{C_a + C_b + C_K}q \approx \frac{C_K}{C_a + C_K}q$$

or

$$\frac{q_m}{q} \cong \frac{C_K}{C_a + C_K} \approx \frac{C_K}{C_t + C_K}.$$

The relationship q_m/q indicates the difficulties arising in PD measurements for test objects of large capacitance values C_t. Although C_K and C_t may be known, the ability to detect small values of q will decrease as all instruments capable of integrating the currents i(t) will have a lower limit for quantifying q_m. Equation (7.48) therefore sets limits for the recording of 'pico coulombs' in large test objects. During actual measurements, however, a calibration procedure is needed during which artificial apparent charge q of well-known magnitude is injected to the test object,

Apparent charge q of a *PD pulse* is that unipolar charge which, if injected within a very short time between the terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the PD current pulse itself. The *apparent charge* is usually expressed in pico coulombs. This definition ends with:

NOTE – The *apparent charge* is not equal to the amount of charge locally involved at the site of the discharge and which cannot be measured directly.

This definition is an indication of the difficulties in understanding the physical phenomena related to a PD event. As one of the authors of this book has been chairman of the International Working Group responsible for setting up this new standard, he is familiar with these difficulties and can confirm that the definition is clearly a compromise which could be accepted by the international members of the relevant Technical Committee of IEC. The definition is correct. It relates to a calibration procedure of a PD test and measuring circuit, as already mentioned above. The 'NOTE', however, is still supporting the basically wrong assumption that a certain amount or number of charges at the site of the discharge should be measured. As already mentioned it is not the number of charges producing the PD currents, but the number of induced dipole moments which produce a sudden increase in the capacitance of the test object.

4.3.1 PD currents:

Before discussing the fundamentals of the measurement of the apparent charge some remarks concerning the PD currents i_t_ will be helpful, as much of the research work has been and is still devoted to these currents, which are difficult to measure with high accuracy. The difficulties arise for several reasons.

If V is an a.c. voltage, the main contribution of the currents flowing within the branches C_K and C_t of Fig. 7.17 are displacement currents C(dV/dt), and both are nearly in phase. The PD pulse currents i(t) with crest values in the range of sometimes smaller than 10^{-4} A, are not only small in amplitude, but also of very short duration.

If no stray capacitance in parallel to C_K were present, i(t)would be the same in both branches, but of opposite polarity. For accurate measurements, a shunt resistor with matched coaxial cable may be introduced in the circuit as shown in Fig. 4.22. The voltage across the CRO (or transient recorder) input is then given by $V_m(t) = (i_t + i)\, Z_0R/(R + Z0)$. Only if the capacitance of the test object is small, which is a special case, will the voltages referring to the PD currents i(t) be clearly distinguished from the displacement currents $i_t(t)$.

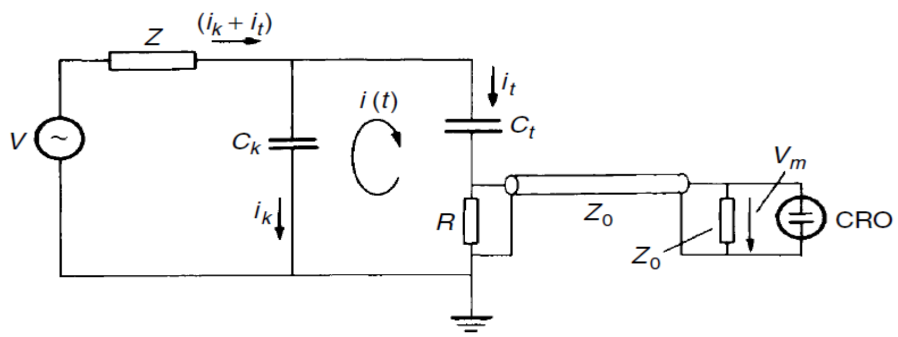


Fig : 4.22 Measurement of PD current i(t) *– low sensitivity circuit*

Improvements are possible by inserting an amplifier (e.g. active voltage probe) of very high bandwidth at the input end of the signal cable. In this way the signal cable is electrically disconnected from R. High values of R, however, will introduce measuring errors, which are explained with Fig. 4.33. A capacitance C of some 10 pF, which accounts for the lead between Ct and earth as well as for the input capacitance of the amplifier or other stray capacitances, will shunt the resistance R and thus bypass or delay the very high-frequency components of the current i(t). Thus, if i_t_ is a very short current pulse, its shape and crest value is heavily distorted, as C will act as an integrator. Furthermore, with R within the discharge circuit, the current pulse will be lengthened, as the charge transfer even with C = 0 will be delayed by a time constant $RC_tC_K/(C_t + C_K)$. Both effects are influencing the shape of the original current pulse, and thus the measurement of i(t) is a tedious task and is only made for research purposes.

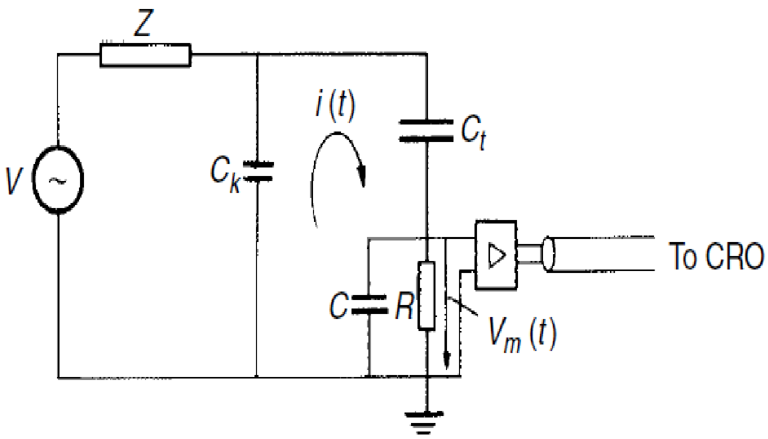


Fig: 4.33 Measurement of PD currents – high sensitivity circuit

All measured data on current shapes published in many papers are suffering from this effect. One may, however, summarize the results by the following statements. Partial discharge currents originated in voids within solids or liquids are very short current pulses of less than a few nanoseconds duration. This can be understood, as the gas discharge process within a very limited space is developed in a very short time and is terminated by the limited space for movement of the charge carriers. Discharges within a homogeneous dielectric material, i.e. a gas, produce PD currents with a very short rise time (≈<5 n sec) and a longer tail. Whereas the fast current rise is produced by the fast avalanche processes the decay of the current can be attributed to the drift velocity of attached electrons and positive ions within the dielectric. Discharge pulses in atmospheric air provide in general current pulses of less than about 100 nsec duration. Longer current pulses have only been measured for partial discharges in fluids or solid materials without pronounced voids, if a number of consecutive discharges take place within a short time. In most of these cases the total duration of i(t) is less than about 1 μsec, with only some exceptions e.g. the usual bursts of discharges in insulating fluids.

All these statements refer to test circuits with very low inductance and proper damping effects within the loop C_K - C_t. The current i(t), however, may oscillate, as oscillations are readily excited by the sudden voltage drop across Ct. Test objects with inherent inductivity or internal resonant circuits, e.g. transformer or reactor/generator windings, will always cause oscillatory PD current pulses. Such distortions of the PD currents, however, do not change the transferred charge magnitudes, as no discharge resistor is in parallel to CK or Ct. If the displacement currents $i_t(t)$ or $i_K(t)$ are suppressed, the distorted PD currents can also be filtered, integrated and displayed.

PD measuring systems within the PD test circuit:

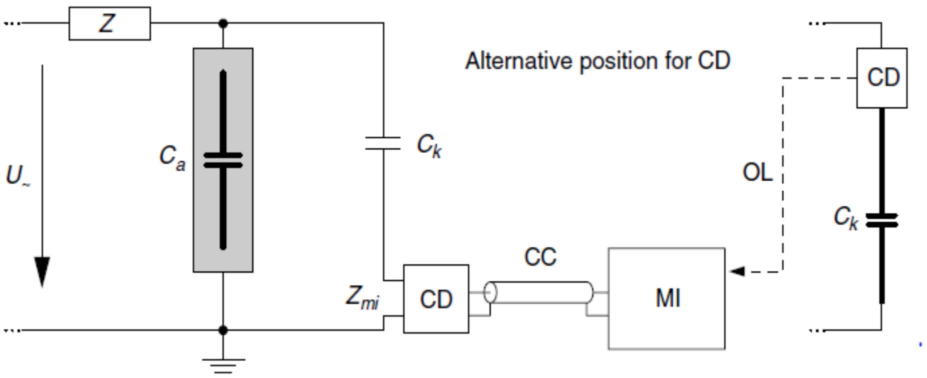
To quantify the individual apparent charge magnitudes' qi for the repeatedly occurring PD pulses which may have quite specific statistical distributions, a measuring system must be integrated into the test circuit which fulfils specific requirements. Already at this point it shall be mentioned that under practical environment conditions quite different kinds of disturbances (background noise) are present.

Most PD measuring systems applied are integrated into the test circuit in accordance with schemes shown in Figs 4.24(a) and (b), which are taken from the new IEC Standardwhich replaces the former one as issued in 1981.Within these 'straight detection circuits', the coupling device 'CD' with its input impedance Z_{mi} forms the input end of the measuring system. As indicated in Fig. 4.24(a), this device may also be placed at the high-voltage terminal side, which may be necessary if the test object has one terminal earthed. Optical links are then used to connect the CD with an instrument instead of a connecting cable 'CC'.

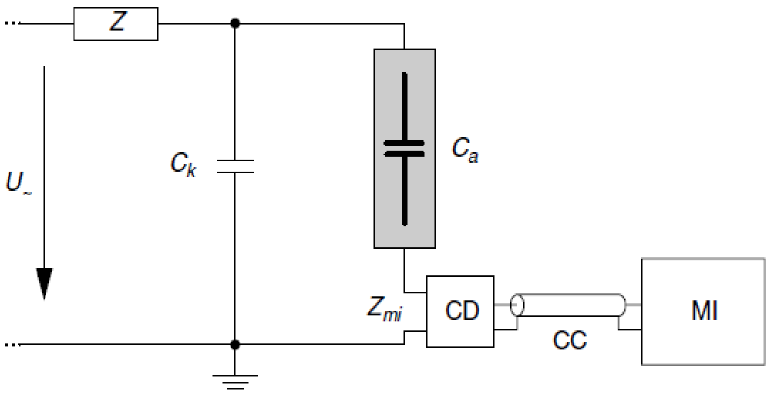
The coupling capacitor Ck shall be of low inductance design and should exhibit a sufficiently low level of partial discharges at the specified test voltage to allow the measurement of the specified partial discharge magnitude. A higher level of partial discharges can be tolerated if the measuring system is capable of separating the discharges from the test object and the

coupling capacitor and measuring them separately; The high-voltage supply shall have sufficiently low level of *background noise* to allow the specified partial discharge magnitude to be measured at the specified test voltage; high-voltage connections shall have sufficiently low level of *background noise* to allow the specified partial discharge magnitude to be measured at the specified test voltage; an impedance or a filter may be introduced at high voltage to reduce *background noise* from the power supply.

The main difference between these two types of PD detection circuits is related to the way the measuring system is inserted into the circuit. In Fig. 4.24(a), the CD is at ground potential and in series to the coupling capacitor C_k as it is usually done in praxis. In Fig. 4.24(b), CD is in series with the test object C_a. Here the stray capacitances of all elements of the high-voltage side to ground potential will increase the value of Ck providing a somewhat higher sensitivity for this circuit according to eqn (7.48). The disadvantage is the possibility of damage to the PD measuring system, if the test object fails. The new IEC Standard defines and quantifies the *measuring system characteristics*. The most essential ones will again be cited and further explained below:



(a) Coupling device CD in series with the coupling capacitor



(b) Coupling device CD in series with the test object

U~ high-voltage supply

Zmi input impedance of measuring system

CC connecting cable

OL optical link

Ca test object

Ck coupling capacitor

CD coupling device

MI measuring instrument

Z filter

Fig4.24 :Basic partial discharge test circuits – 'straight detection'

The *transfer impedance* Z_f_ is the ratio of the output voltage amplitude to a constant input current amplitude, as a function of frequency f, when the input is sinusoidal.

This definition is due to the fact that any kind of output signal of a measuring instrument (MI) as used for monitoring PD signals is controlled by a voltage, whereas the input at the CD is a current.

The *lower and upper limit frequencies* f1 *and* f2 are the frequencies at which the transfer *impedance* Z_f_ has fallen by 6 dB from the peak passband value.

Midband frequency fm *and bandwidth* 1f: for all kinds of measuring systems, the midband frequency is defined by:

$$f_m = \frac{f_1 + f_2}{2}$$

and the bandwidth by:

$$\Delta f = f_2 - f_1;$$

The *superposition error* is caused by the overlapping of transient output pulse responses when the time interval between input current pulses is less than the duration of a single output response pulse. Superposition errors may be additive or subtractive depending on the *pulse repetition rate* n of the input pulses. In practical circuits both types will occur due to the random nature of the pulse repetition rate.

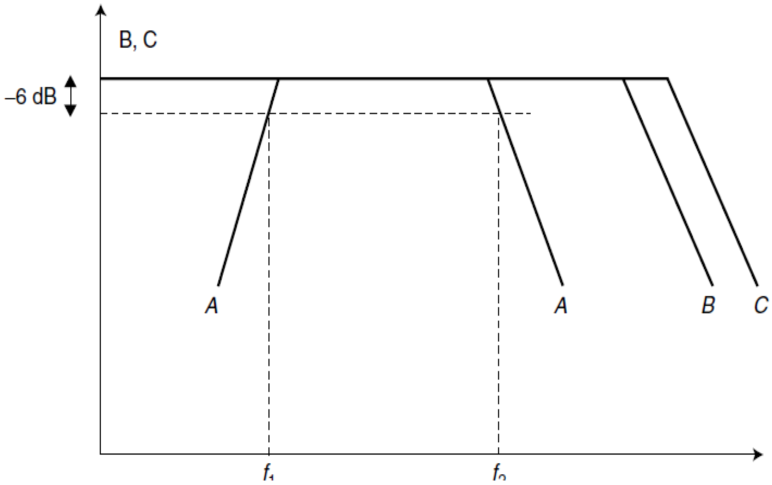
`This rate 'n' is defined as the ratio between the total number of PD pulses recorded in a selected time interval and the duration of the time interval.

The pulse resolution time T_r is the shortest time interval between two consecutive input pulses of very short duration, of same shape, polarity and charge magnitude for which the peak value of the resulting response will change by not more than 10 per cent of that for a single pulse.

The pulse resolution time is in general inversely proportional to the bandwidth 1f of the measuring system. It is an indication of the measuring system's ability to resolve successive PD events.

The integration error is the error in apparent charge measurement which occurs when the upper frequency limit of the PD current pulse amplitude spectrum is lower than (i) the upper cut-off frequency of a wideband measuring system or (ii) the mid-band frequency of a narrow-band measuring system.

The last definition of an 'integration error' will need some additional explanation. PD measuring systems quantifying apparent charge magnitudes are band-pass systems, which predominantly are able to suppress the high power frequency displacement currents including higher harmonics. The lower frequency limit of the band-pass f1 and the kind of 'roll-off' of the band-pass control this ability. Adequate integration can thus only be made if the 'pass-band' or the flat part of the filter is still within the constant part of the amplitude frequency spectrum of the PD pulse to be measured. Figure 4.25, again taken from the new standard, provides at least formal information about correct relationships.



A band-pass of the measuring system

B amplitude frequency spectrum of the PD pulse

C amplitude frequency spectrum of calibration pulse

f1 lower limit frequency

f2 upper limit frequency

Figure 4.25 *correct relationships between amplitude and frequency to minimize integration errors for a wide-band system.*

More fundamental information may be found within some specific literature. Now we can proceed to explain the basic types of PD instruments to see how the requirements can be fulfilled.

4.3.4 Measuring systems for apparent charge

The following types of measuring systems all comprise the already mentioned subsystems: coupling device (CD), transmission system or connecting cable (CC), and a measuring instrument (MI), see Fig. 7.20. In general the transmission system, necessary to transmit the output signal of the CD to the input of the MI, does not contribute to the measuring system characteristics as both ends are matched to the characteristics of both elements. The CC will thus not be considered further. The input impedance Z_{mi} of the CD or measuring system respectively will have some influence on the wave shape of the PD current pulse i(t) as already mentioned in the explanation of Fig. 4.24. A too high input impedance will delay the charge transfer between C_a and C_k to such an extent that the upper limit frequency of the amplitude frequency spectrum would drop to unacceptable low values. Adequate values of Z_{mi} are in the range of 100’Ω.

In common with the first two measuring systems for apparent charge is a *newly* defined ‘pulse train response’ of the instruments to quantify the ‘largest repeatedly occurring PD magnitude’, which is taken as a measure of the ‘specified partial discharge magnitude’ as permitted in test objects during acceptance tests under specified test conditions. Sequences of partial discharges follow in general unknown statistical distributions and it would be useless to quantify only one or very few discharges of large magnitude within a large array of much smaller events as a specified PD magnitude. For further information on quantitative requirements about this pulse train response, which was not specified up to now and thus may not be found within in earlier instruments, reference is made to the standard.

4.3.5 Sources and reduction of disturbances:

Within the informative Annex G of the IEC Standard sources and suggestions regarding the reduction of disturbances are described in detail. A citation of some of the original text together with some additional information is thus adequate. Quantitative measurements of PD magnitudes are often obscured by interference caused by disturbances which fall into two categories:

Disturbances which occur even if the test circuit is not energized. They may be caused, for example, by switching operations in other circuits, commutating machines, high-voltage tests in the vicinity, radio transmissions, etc., including inherent noise of the measuring instrument itself. They may also occur when the high-voltage supply is connected but at zero voltage.

Disturbances which only occur when the test circuit is energized but which do not occur in the test object. These disturbances usually increase with increasing voltage. They may include, for example, partial discharges in the testing transformer, on the high-voltage conductors, or in bushings (if not part of the test object). Disturbances may also be caused by sparking of imperfectly earthed objects in the vicinity or by imperfect connections in the area of the high voltage, e.g. by spark discharges between screens and other high-voltage conductors, connected with the screen only for testing purposes. Disturbances may also be caused by higher harmonics of the test voltage within or close to the bandwidth of the measuring system. Such higher harmonics are often present in the low-voltage supply due to the presence of solid state switching devices (thyristors, etc.) and are transferred, together with the noise of sparking contacts, through the test transformer or through other connections, to the test and measuring circuit.

Some of these sources of disturbances have already been mentioned in the preceding sections and it is obvious that up to now numerous methods to reduce disturbances have been and still are a topic for research and development, which can only be mentioned and summarized here.

The most efficient method to reduce disturbances is *screening and filtering*, in general only possible for tests within a shielded laboratory where all electrical connections running into the room are equipped with filters. This method is expensive, but inevitable if sensitive measurements are required, i.e. if the PD magnitudes as specified for the test objects are small, e.g. for h.v. cables.

Straight PD-detection circuits as already shown in Fig. 7.20 are very sensitive to disturbances: any discharge within the entire circuit, including h.v. source, which is not generated in the test specimen itself, will be detected by the coupling device CD. Therefore, such 'external' disturbances are not rejected. Independent of screening and filtering mentioned above, the testing transformer itself should be PD free as far as possible, as h.v. filters or inductors as indicated in Fig. 7.20 are expensive. It is also difficult to avoid any partial discharges at the h.v. leads of the test circuit, if the test voltages are very high. A basic improvement of the straight detection circuit may therefore become necessary by applying a 'balanced circuit', which is similar to a Schering bridge. In Fig. 7.30 the coupling capacitor C_K and test specimen Ct form the h.v. arm of the bridge, and the l.v. arms are basically analogous to a Schering bridge. As C_K is not a standard capacitor but should be PD free, the dissipation factor tan δ_K may also be higher than that of Ct, and therefore the capacitive branch of the l.v. arm may be switched to any of the two arms. The bridge can then be adjusted for balance for all frequencies at which tan δ_K = tan δ_t. This condition is best fulfilled if the same insulation media are used within both capacitors. The use of a partial discharge-free sample for C_K of the same type as used in C_t is thus advantageous. If the frequency dependence of the dissipation factors is different in the two capacitors, a complete balance within a larger frequency range is not possible. Nevertheless, a fairly good balance can be reached and therefore most of the sinusoidal or transient voltages appearing at the input ends of C_K and Ct cancel out between the points 1 and 2. A discharge within the test specimen, however, will contribute to voltages of opposite polarity across the l.v. arms, as the PD current is flowing in opposite directions within C_K and Ct.

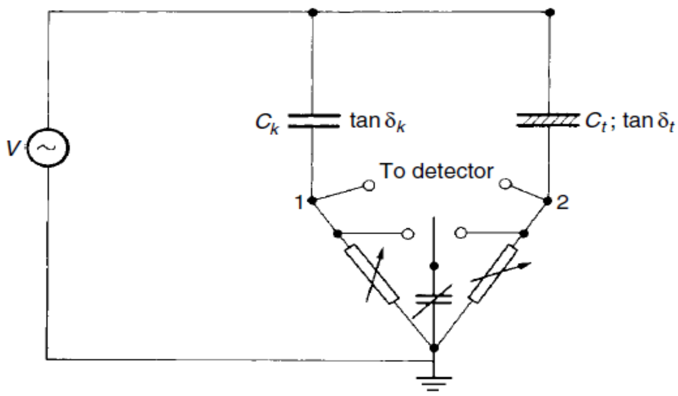


Figure 4.26 *Differential PD bridge (balanced circuit)*

Polarity discrimination methods take advantage of the effect of opposite polarities of PD pulses within both arms of a PD test circuit. Two adequate coupling devices CD and CD1 as shown in Fig. 4.27 transmit the PD signals to the special measuring instrument MI, in which a logic system performs the comparison and operates a gate for pulses of correct polarity. Consequently only those PD pulses which originate from the test object are recorded and quantified. This method was proposed by I.A. Black.

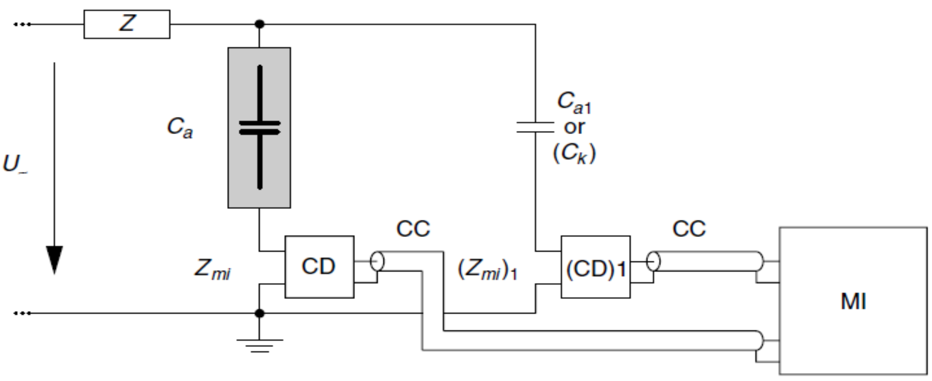


Figure 4.28 *Polarity discrimination circuit*

Another extensively used method is the *time window method* to suppress interference pulses. All kinds of instruments may be equipped with an electronic gate which can be opened and closed at preselected moments, thus either passing the input signal or blocking it. If the disturbances occur during regular intervals the gate can be closed during these intervals. In tests with alternating voltage, the real discharge signals often occur only at regularly repeated intervals during the cycles of test voltage. The time window can be phase locked to open the gate only at these intervals.

4.3.6Other PD quantities:

The measurement of the 'apparent charge q' as the fundamental PD quantity is widely acknowledged and used today, and only the 'largest repeatedly occurring magnitudes' of this kind are usually specified. Individual charge magnitudes q_i are different, however, as well as the number of partial discharges recorded within a selected reference time interval. But the deterioration process within an insulation system is certainly a result of all discharges and is not

limited to the maximum values only. Much research work has been related to the measurement of all single PD impulses and to the evaluation of the results on a statistical basis. Such measuring systems are known as PD pulse analysers and depending on the performance of the detection and analyzing systems, the number of pulses, the pulse intervals or the amplitudes of the individual pulses may be recorded and stored.

Such additional quantities related to PD pulses, although already mentioned in earlier standards, will be much more used in future and thus their definitions are given below with brief comments only:

(a) The phase angle _i and time ti of occurrence of a PD pulse is

$$\phi_i = 360(t_i/T)$$

where t_i is the time measured between the preceding positive going transition of the test voltage through zero and the PD pulse. Here T is the period of the test voltage.

(b)The *average discharge current I* is the sum of the absolute values of individual apparent charge magnitudes qi during a chosen reference time interval Tref divided by this time interval, Tref divided by this time interval, i.e.:

$$I = \frac{1}{T_{\text{ref}}}(|q_1| + |q_2| + \ldots + |q_i|)$$

This current is generally expressed in coulombs per second or in amperes. By this definition a quantity is available which includes all individual PD pulses as well as the pulse repetition rate n. The measurement of this quantity is possible based upon both linear amplification and rectification of the PD discharge currents, by processing the output quantities of the apparent charge detectors by integration and averaging or by digital post processing. This average discharge current has not been investigated extensively up to now, although early investigations show quite interesting additional information about the impact on the lifetime of insulation.

(c) *The discharge power* P is the average pulse power fed into the terminals of the test object due to apparent charge magnitudes qi during a chosen reference time interval Tref, i.e.:

$$P = \frac{1}{T_{\text{ref}}}(q_1 u_1 + q_2 u_2 + \ldots + q_i u_i)$$

Where u_1, u_2, . . . , u_i are instantaneous values of the test voltage at the instants of occurrence t_i of the individual apparent charge magnitudes q_i. This quantity is generally expressed in watts. In this equation the sign of the individual values must be strictly observed, which is often difficult to fulfill. Narrow-band PD instruments are not able to quantify the polarity of PD events and even the response of wide-band instruments may not be clear, see Fig. 7.26. In the vicinity of the test voltage zero PD pulses and instantaneous voltage are often different in polarity! As discharge energy is directly related to discharge power, this quantity is always directly related to insulation decomposition.

(d) The *quadratic rate* D is the sum of the squares of the individual apparent charge magnitudes qi during a chosen reference time interval Tref divided by this time interval, i.e.:

$$D = \frac{1}{T_{\text{ref}}}(q_1^2 + q_2^2 + \ldots + q_m^2)$$

and is generally expressed in (coulombs)2 per second. Although this quantity appears to have no advantages compared to the measurement of the maximum values of q only, some commercially available, special instruments record this quantity.

4.3.7 Calibration of PD detectors in a complete test circuit:

Even the definition of the 'apparent charge q' is based on a routine calibration procedure, which shall be made with each new test object. Calibration procedures are thus firmly defined within the standard.

A calibration of measuring systems intended for the measurement of the fundamental quantity q is made by injecting short duration repetitive current pulses of well-known charge magnitudes q0 across the test object, whatever test circuit is used. For an example, see Fig. 7.29. These current pulses are generally derived from a calibrator which comprises a generator producing step voltage pulses (see ‘G’) of amplitude V0 in series with a precision capacitor C0. If the voltages V_0 also remain stable and are exactly known, repetitive calibration pulses with charge magnitudes of $\boldsymbol{q_0=V_0C_0}$ are injected. A short rise time of 60 ns is now specified for the voltage generator to produce current pulses with amplitude frequency spectra which fit the requirements set by the bandwidth of the instruments and to avoid integration errors if possible.

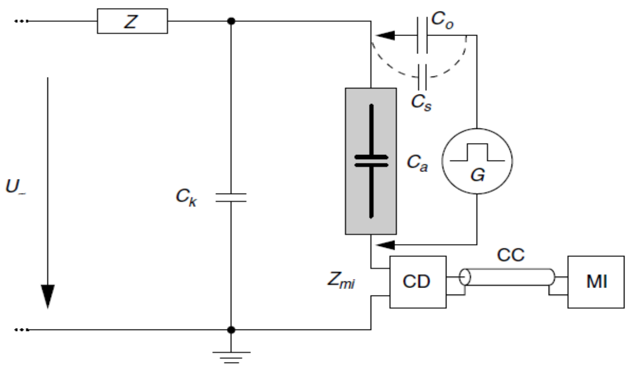


Fig: 4.29 The usual circuit for the calibration of a PD measuring instrument MI within the complete test circuit.

For identification of circuit elements see text and Fig. 4.20. Whereas further details for the calibration procedures shall not be discussed here, the new philosophy in reducing measuring errors during PD tests will be presented.

It has been known for some time that measuring uncertainties in PD measurements are large. Even today, PD tests on identical test objects performed with different types of commercially available systems will provide different results even after routine calibration performed with the same calibrator. The main reasons for this uncertainty are the different transfer impedances (bandwidth) of the measuring systems, which up to 1999 have never been well defined and quantified. The new but not very stringent requirements related to this property will improve the situation; together with other difficulties related to disturbance levels measuring uncertainties of more than about 10 per cent may, however, exist.

The most essential part of the new philosophy concerns the calibrators, for which – up to now – no requirements for their performance exist. Tests on daily used commercial calibrators sometimes display deviations of more than 10 per cent of their nominal values. Therefore routine type, and performance tests on calibrators have been introduced with the new standard. At least the first of otherwise periodic performance tests should be traceable to national standards; this means they shall be performed by an accredited calibration laboratory. With the introduction of this requirement it can be assumed that the uncertainty of the calibrator charge magnitudes q0 can be assessed to remain within ±5 per cent or 1 pC, whichever is greater, from its nominal values. Very recently executed inter comparison tests on calibrators performed by accredited calibration laboratories showed that impulse charges can be measured with an uncertainty of about 3 per cent.

Digital PD instruments and measurements

Between 1970 and 1980 the state of the art in computer technology and related techniques rendered the first application of digital acquisition and processing of partial discharge magnitudes.Since then this technology was applied in numerous investigations generally made with either instrumentation set up by available components or some commercial instruments equipped with digital techniques. One task for the working group evaluating the new IEC Standard was thus concerned with implementing some main requirements for this technology. It is again not the aim of this section to go into details of digital PD instruments, as too many variations in designing such instruments exist. Some hints may be sufficient to encourage further reading.

Digital PD instruments are in general based on analogue measuring systems or instruments for the measurement of the apparent charge q followed by a digital acquisition and processing system. These digital parts of the system are then used to process analogue signals for further evaluation, to store relevant quantities and to display test results. It is possible that in the near future a digital PD instrument may also be based on a high-pass coupling device and a digital acquisition system without the analogue signal processing front end. The availability of cheap but extremely fast flash A/D converters and digital signal processors (DSPs) performing signal integration is a prerequisite for such solutions.

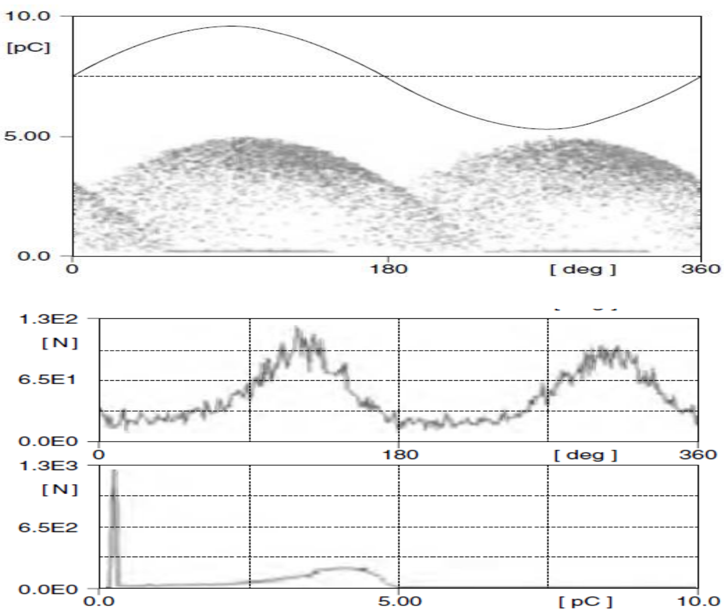


Figure: 4.30 The pattern of a phase-resolved PD measurement for a moving metal particle within a GIS. Further details see text (courtesy FKH, Zurich, Switzerland)

The main objective of applying digital techniques to PD measurements is based on recording in real time at least most of consecutive PD pulses quantified by its apparent charge q_i occurring at time instant t_i and its instantaneous values of the test voltage u_i occurring at this time instant t_i or, for alternating voltages, at phase angle of occurrence φi within a voltage cycle of the test voltage. As, however, the quality of hard- and software used may limit the accuracy and resolution of the measurement of these parameters, the new standard provides some recommendations and requirements which are relevant for capturing and registration of the discharge sequences.

One of the main problems in capturing the output signals of the analogue front end correctly may well be seen from Figs 7.29 and 7.30, in which three output signals as caused by two consecutive PD events are shown. Although none of the signals is distorted by superposition errors, several peaks of each signal with different polarities are present. For the wideband signals, only the first peak value shall be captured and recorded including polarity, which is not easy to do. For the narrow-band response for which polarity determination is not necessary, only the largest peak is proportional to the apparent charge. For both types of signals therefore only one peak value shall be quantified, recorded and stored within the pulse resolution time of the analogue measuring system. Additional errors can well be introduced by capturing wrong peak values which add to the errors of the analogue front end.

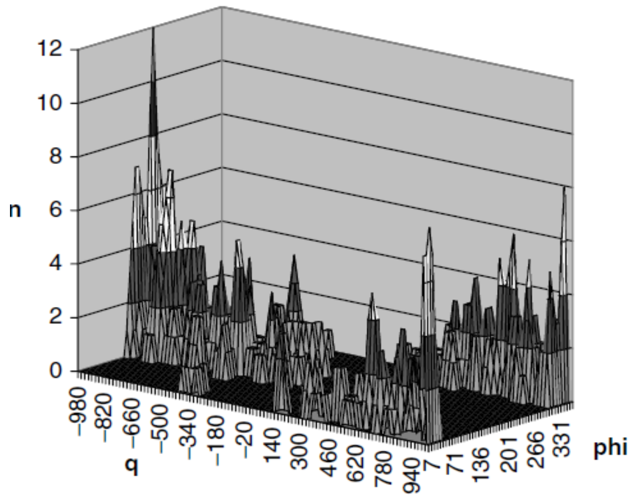


Fig: 4.31 An example of φ - q - n *diagram. On-site PD measurements performed on an h.v. cable, heavy partial discharges at a terminator(courtesy Presco AG, Weiningen, Switzerland)*

Further aims of PD instruments are related to post-processing of the recorded values. Firstly, the so-called 'φi -qi-ni' patterns as available from the recorded and stored data in which ni is the number of identical or similar PD magnitudes recorded within short time (or phase) intervals and an adequate total recording duration can be used to identify and localize the origin of the PDs based on earlier experience and/or even to establish physical models for specific PD processes._60 and cited references_ If recorded raw data are too much obscured by disturbances, quite different numerical methods may also be applied to reduce the disturbance levels.

UNIT – 5

High Voltage Testing of Electrical Apparatus

Syllabus:

High Voltage Testing of Electrical Apparatus

Testing of Insulators and bushings, Testing of Isolators and circuit breakers, testing of cables, Testing of Transformers, Testing of Surge Arresters, Radio Interference measurements.

5. INTRODUCTION

In modern times the world has seen phenomenal increase in demand for energy, of which an important component is that of electrical energy. The production of electrical energy in big plants under the most economic condition makes it necessary that more and more energy be transported over longer and longer distances. Therefore, transmission at extra high voltages and the erection of systems which may extend over whole continents has become the most urgent problems to be solved in the near future. The very fast development of systems is followed by studies of equipment and the service conditions they have to fulfill. These conditions will also determine the values for testing at alternating, impulse and d.c. voltages under specific conditions.

As we go for higher and higher operating voltages (say above 1000 kV) certain problems are associated with the testing techniques. Some of these are:

(*i*) Dimension of high voltage test laboratories.

(*ii*) Characteristics of equipment for such laboratories.

(*iii*) Some special aspects of the test techniques at extra high voltages.

The dimensions of laboratories for test equipments of 750 kV and above are fixed by the following main considerations:

(*i*) Figures (values) of test voltages under different conditions.

(*ii*) Sizes of the test of equipments in a.c., d.c. and impulse voltages.

(*iii*) Distances between the objects under high voltage during the test period and the earthed surroundings such as floors, walls and roofs of the buildings. The problems associated with the characteristics of the equipments used for testing are summarised here.

In alternating voltage system, a careful choice of the characteristics of the testing transformer is essential. It is known that the flash over voltage of the insulator in air or in any insulating fluid depends upon the capacitance of the supply system. This is due to the fact that a voltage drop may not maintain preliminary discharges or breakdown. It is, therefore, suggested that a capacitance of at least 1000 Pf must be connected across the insulator to obtain the correct flash over or puncture voltage and also under breakdown condition (a virtual short circuit) the supply system should be able to supply at least 1 amp for clean and 5 amp for polluted insulators at the test voltage. There are some difficult problems with impulse testing equipments also especially when testing large power transformers or large reactors or large cables operating at very high voltages. The equivalent capacitance of the impulse generator is usually about 40 nano farads independent of the operating voltage which gives a stored energy of about 1/2 × 40 10–9 × 36 × 109 = 720 KJ for 6 MV generators which is required for testing equipments operating at 150 kV. It is not at all difficult to pile up a large number of capacitances to charge them in parallel and then discharge in series to obtain a desired impulse wave. But the difficulty exists in reducing the internal reactance of the circuit so that a short wave front with minimum oscillation can be obtained. For example for a 4 MV circuit the inductance of the circuit is about 140 μH and it is impossible to test an equipment with a capacitance of 5000 pF with a front time of 1.2 μ sec. and less than 5% overshoot on the wave front.

Cascaded rectifiers are used for high voltage d.c. testing. A careful consideration is necessary when test on polluted insulation is to be performed which requires currents of 50 to 200 mA but extremely predischarge streamer of 0.5 to 1 amp during milliseconds occur. The generator must have an internal reactance in order to maintain the test voltage without too high a voltage drop.

High Voltage Testing of Electrical Apparatus

It is essential to ensure that the electrical equipment is capable of withstanding the over voltages that are met with in service. The over voltages may be either due to natural causes like lightning or system originated ones such as switching or power frequency transient voltages. Hence, testing for over voltages is necessary.

5.1 TESTING OF INSULATORS AND BUSHINGS

Various types of overhead line insulators are (*i*) Pin type (*ii*) Post type (*iii*) String insulator unit (*iv*) Suspension insulator string (*v*) Tension insulator.

5.1.1 Arrangement of Insulators for Test

String insulator unit should be hung by a suspension eye from an earthed metal cross arm. The test voltage is applied between the cross arm and the conductor hung vertically down from the metal part on the lower side of the insulator unit. Suspension string with all its accessories as in service should be hung from an earthed metal cross arm. The length of the cross arm should be at least 1.5 times the length of the string being tested and should be at least equal to 0.9 m on either side of the axis of the string. No other earthed object should be nearer to the insulator string then 0.9 m or 1.5 times the length of the string whichever is greater. A conductor of actual size to be used in service or of diameter not less than 1 cm and length 1.5 times the length of the string is secured in the suspension clamp and should lie in a horizontal plane. The test voltage is applied between the conductor and the cross arm and connection from the impulse generator is made with a length of wire to one end of the conductor. For higher operating voltages where the length of the string is large, it is advisable to sacrifice the length of the conductor as stipulated above. Instead, it is desirable to bend the ends of the conductor over in a large radius.

For tension insulators the arrangement is more or less same as in suspension insulator except that it should be held in an approximately horizontal position under a suitable tension (about 1000 Kg.). For testing pin insulators or line post insulators, these should be mounted on the insulator pin or line post shank with which they are to be used in service. The pin or the shank should be fixed in a vertical position to a horizontal earthed metal cross arm situated 0.9 m above the floor of the laboratory.

A conductor of 1 cm diameter is to be laid horizontally in the top groove of the insulator and secured by at least one turn of tie-wire, not less than 0.3 cm diameter in the tie-wire groove. The length of the wire should be at least 1.5 times the length of the insulator and should over hang the insulator at least 0.9 m on either side in a direction at right angles to the cross arm. The test voltage is applied to one end of the conductor. High voltage testing of electrical equipment requires two types of tests: (*i*) Type tests, and (*ii*) Routine test. Type tests involves quality testing of equipment at the design and development level *i.e.* samples of the product are taken and are tested when a new product is being developed and designed or an old product is to be redesigned and developed whereas the routine tests are meant to check the quality of the individual test piece. This is carried out to ensure quality and reliability of individual test objects. High voltage tests include (*i*) Power frequency tests and (*ii*) Impulse tests. These tests are carried out on all insulators.

(*i*) 50% dry impulse flash over test.

(*ii*) Impulse withstand test.

(*iii*) Dry flash over and dry one minute test.

(*iv*) Wet flash over and one minute rain test.

(*v*) Temperature cycle test.

(*vi*) Electro-mechanical test.

(*vii*) Mechanical test.

(*viii*) Porosity test.

(*ix*) Puncture test.

(*x*) Mechanical routine test.

The tests mentioned above are briefly described here.

(*i*) The test is carried out on a clean insulator mounted as in a normal working condition. An impulse voltage of 1/50 μsec. wave shape and of an amplitude which can cause 50% flash over of the insulator, is applied, *i.e.* of the impulses applied 50% of the impulses should cause flash over. The polarity of the impulse is then reversed and procedure repeated. There must be at least 20 applications of the impulse in each case and the insulator must not be damaged. The magnitude of the impulse voltage should not be less than that specified in standard specifications.

(*ii*) The insulator is subjected to standard impulse of 1/50 μ sec. wave of specified value under dry conditions with both positive and negative polarities. If five consecutive applications do not cause any flash over or puncture, the insulator is deemed to have passed the impulse withstand test. If out of five, two applications cause flash over, the insulator is deemed to have filed the test.

(*iii*) Power frequency voltage is applied to the insulator and the voltage increased to the specified value and maintained for one minute. The voltage is then increased gradually until flash over occurs. The insulator is then flashed over at least four more times, the voltage is raised gradually to reach flash over in about 10 seconds. The mean of at least five consecutive flash over voltages must not be less than the value specified in specifications.

(*iv*) If the test is carried out under artificial rain, it is called wet flash over test. The insulator is subjected to spray of water of following characteristics:

Precipitation rate	3±10% mm/min.
Direction	45° to the vertical
Conductivity of water	100 micro Siemens ± 10%
Temperature of water Ambient	+15°C

The insulator with 50% of the one-min. rain test voltage applied to it, is then sprayed for two minutes, the voltage raised to the one minute test voltage in approximately 10 sec. and maintained there for one minute. The voltage is then increased gradually till flash over occurs and the insulator is then flashed at least four more times, the time taken to reach flash over voltage being in each case about 10 sec. The flash over voltage must not be less than the value specified in specifications.

(*v*) The insulator is immersed in a hot water bath whose temperature is 70° higher than normal water bath for *T* minutes. It is then taken out and immediately immersed in normal water bath for *T* minutes. After *T* minutes the insulator is again immersed in hot water bath for *T* minutes. The cycle is repeated three times and it is expected that the insulator should withstand the test without damage to the insulator or glaze. Here $T = (15 + W/1.36)$ where W is the weight of the insulator in kgs.

(*vi*) The test is carried out only on suspension or tension type of insulator. The insulator is subjected to a 2½ times the specified maximum working tension maintained for one minute. Also, simultaneously 75% of the dry flash over voltage is applied. The insulator should withstand this test without any damage.

(*vii*) This is a bending test applicable to pin type and line-post insulators. The insulator is subjected to a load three times the specified maximum breaking load for one minute. There should be no damage to the insulator and in case of post insulator the permanent set must be less than 1%. However, in case of post insulator, the load is then raised to three times and there should not be any damage to the insulator and its pin.

(*viii*) The insulator is broken and immersed in a 0.5% alcohol solution of fuchsin under a pressure of 13800 kN/m2 for 24 hours. The broken insulator is taken out and further broken. It should not show any sign of impregnation.

(*ix*) An impulse over voltage is applied between the pin and the lead foil bound over the top and side grooves in case of pin type and post insulator and between the metal fittings in case of suspension type insulators. The voltage is 1/50 μ sec. wave with amplitude twice the 50% impulse flash over voltage and negative polarity. Twenty such applications are applied. The procedure is repeated for 2.5, 3, 3.5 times the 50% impulse flash over voltage and continued till the insulator is punctured. The insulator must not puncture if the voltage applied is equal to the one specified in the specification.

(*x*) The string in insulator is suspended vertically or horizontally and a tensile load 20% in excess of the maximum specified working load is applied for one minute and no damage to the string should occur.

TESTING OF BUSHINGS

Bushings are an integral component of high voltage machines. A bushing is used to bring high voltage conductors through the grounded tank or body of the electrical equipment without excessive potential gradients between the conductor and the edge of the hole in the body. The bushing extends into the surface of the oil at one end and the other end is carried above the tank to a height sufficient to prevent breakdown due to surface leakage. Following tests are carried out on bushings.

5.1.2 ***Power Factor Test***

The bushing is installed as in service or immersed in oil. The high voltage terminal of the bushing is connected to high voltage terminal of the Schering Bridge and the tank or earth portion of the bushing is connected to the detector of the bridge. The capacitance and p.f. of the bushing is measured at different voltages as specified in the relevant specification and the capacitance and p.f. should be within the range specified.

5.1.3 ***Impulse Withstand Test***

The bushing is subjected to impulse waves of either polarity and magnitude as specified in the standard specification. Five consecutive full waves of standard wave form (1/50 μ sec.) are applied and if two of them cause flash over, the bushing is said to be defective. If only one flash over occurs, ten additional applications are made. If no flash over occurs, bushing is said to have passed the test.

5.1.4 ***Chopped Wave and Switching Surge Test***

Chopped wave and switching surge of appropriate duration tests are carried out on high voltage bushings. The procedure is identical to the one given in (*ii*) above.

5.1.5 ***Partial Discharge Test***

In order to determine whether there is deterioration or not of the insulation used in the bushing, this test is carried out. The shape of the discharge is an indication of nature and severity of the defect in the bushing. This is considered to be a routine test for high voltage bushings.

5.1.6 ***Visible Discharge Test at Power Frequency***

The test is carried out to ascertain whether the given bushing will give rise to ratio interference or not during operation. The test is carried out in a dark room. The voltage as specified is applied to the bushing .No discharge other than that from the grading rings or arcing horns should be visible.

5.1.7 ***Power Frequency Flash Over or Puncture Test***

(*Under Oil*): The bushing is either immersed fully in oil or is installed as in service condition. This test is carried out to ascertain that the internal breakdown strength of the bushing is 15% more than the power frequency momentary dry withstand test value.

5.2 TESTING OF ISOLATORS AND CIRCUIT BREAKERS

The testing of isolators and circuit breakers is covered, giving common characteristics for both. While these characteristics are directly relevant to the testing of circuit breakers, they are not much relevant as far as the testing of isolators are concerned since isolators are not used for interrupting high currents. At best, they interrupt small currents of the order of 0.5 A (for rated voltages of 420 k V and below) which may be the capacitive currents of bushings, bus bars etc. In fact, the definition of an Isolator or a Disconnector.

An isolator or a disconnector is a mechanical switching device, which provides in the open position, an isolating distance in accordance with special requirements. An isolator is capable of opening and closing a circuit when either negligible current is broken or made or when no significant change in the voltage across the terminals of each of the poles of the isolator occurs. It is also capable of carrying currents under normal circuit conditions, and carrying for a specified time, currents under abnormal conditions such as those of a short circuit.

Thus, most of the discussion here refers to the testing of circuit breakers. Testing of circuit breakers is intended to evaluate (a) the constructional and operational characteristics, and (b) the electrical characteristics of the circuit which the switch or the breaker has to interrupt or make. The different characteristics of a circuit breaker or a switch may be summarized as per the following groups.

(i) (a) The electrical characteristics which determine the arcing voltage, the current chopping characteristics, the residual current, the rate of decrease of conductance of the arc space and the plasma, and the shunting effects in interruption.

(b) Other physical characteristics including the media in which the arc is extinguished, the pressure developed or impressed at the point of interruption, the speed of the contact travel, the number of breaks, the size of the arcing chamber, and the materials and configuration of the circuit interruption.

(ii) The charateristics of the circuit include the degree of electrical loading, the normally generated or applied voltage, the type of fault in the system which the breaker has to clear, the time of interruption, the time constant, the natural frequency and the power factor of the circuit, the rate of rise of recovery voltage, the restriking voltage, the decrease in the a.c. component of the short circuit current, and the degree of asymmetry and the d.c. component of the short circuit current, To assess the above factors, the main tests conducted on the circuit breakers and isolator switches are *(i)* the dielectric tests or overvoltage tests,

*(*ii*)* the temperature rise tests,

(iii) the mechanical tests, and

(iv) the short circuit tests

(i)Dielectric tests consist of overvoltage withstand tests of power frequency, lightning and switching impulse voltages. Tests are done for both internal and external insulation with the switch or circuit breaker in both the open and closed positions. In the open position, the test voltage levels are 15% higher than the test voltages used when the breaker is in closed position. As such there is always the possibility of line to ground flashover. To avoid this, the circuit breaker is mounted on insulators above the ground, and hence the insulation level of the body of the circuit breaker is raised.

(ii)The impulse tests with the lightning impulse wave of standard shape are done in a similar manner as in the case of insulators. In addition, the switching surge tests with switching over voltages are done on circuit breakers and isolators to assess their performance under over voltages due to switching operations.

(iii)Temperature rise and mechanical tests are tube tests on circuit breakers and are done according to the specifications.

TESTING OF CIRCUIT BREAKERS

An equipment when designed to certain specification and is fabricated, needs testing for its performance. The general design is tried and the results of such tests conducted on one selected breaker and are thus applicable to all others of identical construction. These tests are called the type tests. These tests are classified as follows:

1. Short circuit tests:

(*i*) Making capacity test.

(*ii*) Breaking capacity test.

(*iii*) Short time current test.

(*iv*) Operating duty test

2. Dielectric tests:

(*i*) Power frequency test:

(*a*) One minute dry withstand test.

(*b*) One minute wet withstand test.

(*ii*) Impulse voltage dry withstand test.

3. Thermal test.

4. Mechanical test

Once a particular design is found satisfactory, a large number of similar C.Bs. are manufactured for marketing. Every piece of C.B. is then tested before putting into service. These tests are known as routine tests. With these tests it is possible to find out if incorrect assembly or inferior quality material has been used for a proven design equipment. These tests are classified as (*i*) operation tests,

(*ii*) Milli voltdrop tests, (*iii*) power frequency voltage tests at manufacturer's premises, and (*iv*) power frequency voltage tests after erection on site.

We will discuss first the type tests. In that also we will discuss the short circuit tests after the other three tests.

5.2.1 SHORT CIRCUIT TESTS

These tests are carried out in short circuit testing stations to prove the ratings of the C.Bs. Before discussing the tests it is proper to discuss about the short circuit testing stations. There are two types of testing stations; (*i*) field type, and (*ii*) laboratory type.

In case of field type stations the power required for testing is directly taken from a large power system. The breaker to be tested is connected to the system. Whereas this method of testing is economical for high voltage C.Bs. it suffers from the following drawbacks:

1. The tests cannot be repeatedly carried out for research and development as it disturbs the whole network.

2. The power available depends upon the location of the testing stations, loading conditions, installed capacity, etc.

3. Test conditions like the desired recovery voltage, the RRRV etc. cannot be achieved conveniently.

In case of laboratory testing the power required for testing is provided by specially designed generators. This method has the following advantages:

1. Test conditions such as current, voltage, power factor, restriking voltages can be controlled accurately.

2. Several indirect testing methods can be used.

3. Tests can be repeated and hence research and development over the design is possible.

The limitations of this method are the cost and the limited power availability for testing the breakers.

Short Circuit Test Plants

The essential components of a typical test plant are represented in Fig. 5.2.1. The short-circuit power is supplied by specially designed short-circuit generators driven by induction motors. The magnitude of voltage can be varied by adjusting excitation of the generator or the transformer ratio. A plant master breaker is available to interrupt the test short circuit current if the test breaker should fail. Initiation of the short circuit may be by the master breaker, but is always done by a making switch which is specially designed for closing on very heavy currents but never called upon to break currents. The generator winding may be arranged for either star or delta connection according to the voltage required; by further dividing the winding into two sections which may be connected in series or parallel, a choice of four voltages is available. In addition to this the use of resistors and reactors in series gives a wide range of current and power factors. The generator, transformer and reactors are housed together, usually in the building accommodating the test cells.

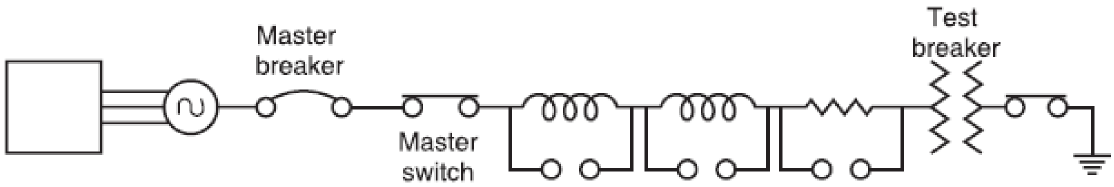


Fig : 5.2.1 schematic diagram of a typical test plant

Generator

The short circuit generator is different in design from the conventional power station. The capacity of these generators may be of the order of 2000 MVA and very rigid bracing of the conductors and coil ends is necessary in view of the high electromagnetic forces possible. The limiting factor for the maximum output current is the electromagnetic force. Since the operation of the generator is intermittent, this need not be very efficient.

The reduction of ventilation enables the main flux to be increased and permits the inclusion of extra coil end supports. The machine reactance is reduced to a minimum. Immediately before the actual closing of the making switch the generator driving motor is switched out and the short circuit energy is taken from the kinetic energy of the generator set. This is done to avoid any disturbance to the system during short circuit. However, in this case it is necessary to compensate for the decrement in generator voltage corresponding to the diminishing generator speed during the test. This is achieved by adjusting the generator field excitation to increase at a suitable rate during the short circuit period.

Resistors and Reactors

The resistors are used to control the p.f. of the current and to control the rate of decay of d.c. component of current. There are a number of coils per phase and by combinations of series and parallel connections, desired value of resistance and/or reactance can be obtained.

Capacitors

These are used for breaking line charging currents and for controlling the rate of re-striking voltage.

Short Circuit Transformers

The leakage reactance of the transformer is low so as to withstand repeated short circuits. Since they are in use intermittently, they do not pose any cooling problem. For voltage higher than the generated voltages, usually banks of single phase transformers are employed. In the short circuit station at Bhopal there are three single phase units each of 11 kV/76 kV. The normal rating is 30 MVA but their short circuit capacity is 475 MVA.

Master C.Bs.

These breakers are provided as back up which will operate, should the breaker under test fail to operate. This breaker is normally air blast type and the capacity is more than the breaker under test. After every test, it isolates the test breaker from the supply and can handle the full short circuit of the test circuit.

Make Switch

The make switch is closed after other switches are closed. The closing of the switch is fast, sure and without chatter. In order to avoid bouncing and hence welding of contacts, a high air pressure is maintained in the chamber. The closing speed is high so that the contacts are fully closed before the short circuit current reaches its peak value.

Test Procedure

Before the test is performed all the components are adjusted to suitable values so as to obtain desired values of voltage, current, rate of rise of restriking voltage, p.f. etc. The measuring circuits are connected and oscillograph loops are calibrated. During the test several operations are performed in a sequence in a short time of the order of 0.2 sec. This is done with the help of a drum switch with several pairs of contacts which is rotated with a motor. This drum when rotated closes and opens several control circuits according to a certain sequence.

In one of the breaking capacity tests the following sequence was observed:

(*i*) After running the motor to a speed the supply is switched off.

(*ii*) Impulse excitation is switched on.

(*iii*) Master C.B. is closed.

(*iv*) Oscillograph is switched on.

(*v*) Make switch is closed.

(*vi*) C.B. under test is opened.

(*vii*) Master C.B. is opened.

(*viii*) Exciter circuit is switched off.

The circuit for direct test is shown in Fig. 5.2.1.1

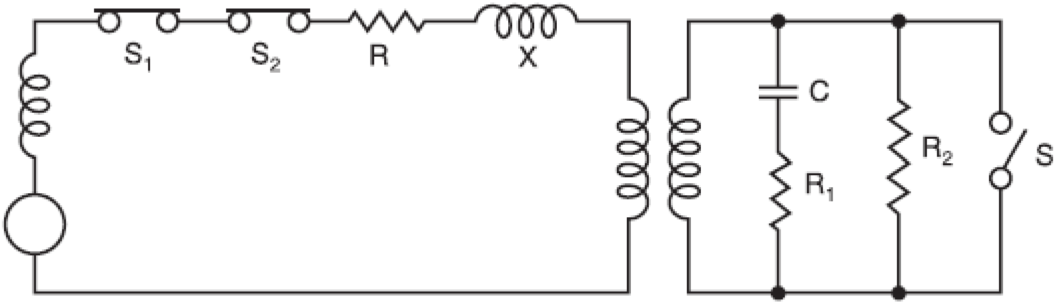


Fig : 5.2.1.1 Circuit For Direct Testing

Here *XG* = generator reactance, S_1 and S_2 are master and make switches respectively. *R* and *X* are the resistance and reactance for limiting the current and control of p.f., *T* is the transformer, *C*, R_1 and R_2 is the circuit for adjusting the restriking voltage. For testing, breaking capacity of the breaker under test, master and breaker under test are closed first. Short circuit is applied by closing the making switch. The breaker under test is opened at the desired moment and breaking current is determined from the oscillograph as explained earlier. For making capacity test the master and the make switches are closed first and short circuit is applied by closing the breaker under test. The making current is determined from the oscillograph as

explained earlier.

5.2.1.1 Short-Time Current Test

The current is passed through the breaker for a short-time say 1 second and the oscillograph is taken as shown in Fig. 5.2.1.2. From the oscillogram the equivalent r.m.s. value of short-time current is obtained as follows. The time interval 0 to *T* is divided into 10 equal parts marked as 0, 1, 2 ..., 9, 10. Let the r.m.s. value of currents at these instants be I_0, I_1, I_2, ..., I_9, I_{10} (asymmetrical values). From these values, the r.m.s. value of short-time current is calculated using Simpson formula.

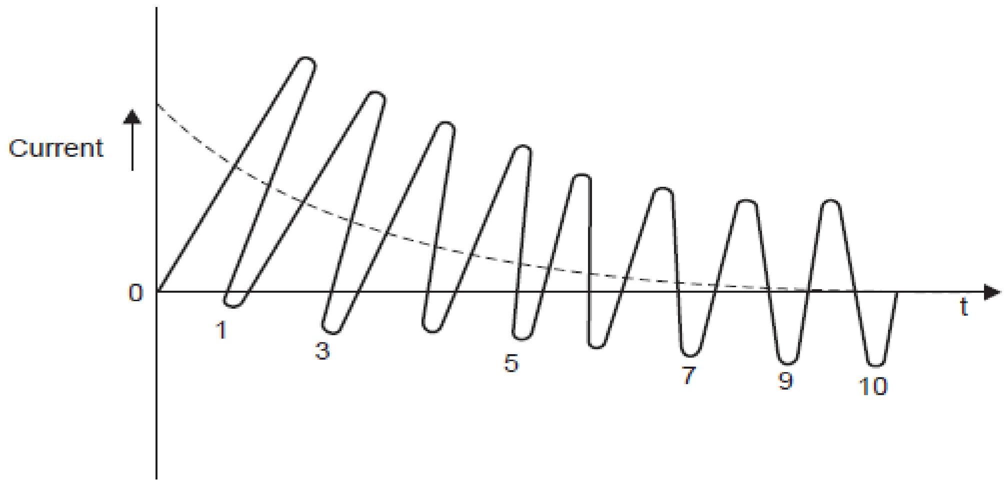


Fig : 5.2.1.2 Determination of short-time current

$$I = \sqrt{\frac{1}{3}\left[K_0^2 + 4\,(I_1^2 + I_3^2 + I_5^2 + \ldots + I_9^2) + 2\,(I_2^2 + I_4^2 + \ldots + I_{10}^2)\right]}$$

Operating duty tests are performed according to standard specification unless the duty is marked on the rating plate of the breaker. The tests according to specifications are:

(*i*) B—32—B—32—B at 10% of rated symmetrical breaking capacity;

(*ii*) B—32—B—32—B at 30% of rated symmetrical breaking capacity;

(*iii*) B—32—B—32—B at 60% of rated symmetrical breaking capacity;

(*iv*) B—32—MB—32—MB at not less than 100% of rated symmetrical breaking capacity and not less than 100% of rated making capacity. Test duty (*iv*) may be performed as two separate duties as follows:

(*a*) M—32—M (Make test);

(*b*) B—32—B—32—B (Break test)

(*v*) B—32—B—32—B at not less than 100% rated asymmetrical breaking capacity.

Here B and M represent breaking and making operations respectively. MB denotes the making operation followed by breaking operation without any international time-lag.32 denotes the time in minutes between successive operations of an operating duty.

5.2.2 DIELECTRIC TESTS

The general dielectric characteristics of any circuit breaker or switchgear unit depend upon the basic design *i.e.* clearances, bushing materials, etc. upon correctness and accuracy in assembly and upon the quality of materials used. For a C.B. these factors are checked from the viewpoint of their ability to withstand over voltages at the normal service voltage and abnormal voltages during lightning or other phenomenon.

The test voltage is applied for a period of one minute between (*i*) phases with the breaker closed,(*ii*) phases and earth with C.B. open, and (*iii*) across the terminals with breaker open. With this the breaker must not flash over or puncture. These tests are normally made on indoor switchgear. For such C.Bs the impulse tests generally are unnecessary because it is not exposed to impulse voltage of a very high order. The high frequency switching surges do occur but the effect of these in cable systems used for indoor switchgear are found to be safely withstood by the switchgear if it has withstood the normal frequency test. Since the outdoor switchgear is electrically exposed, they will be subjected to over voltages caused by lightning. The effect of these voltages is much more serious than the power frequency voltages in service. Therefore, this class of switchgear is subjected in addition to power frequency tests, the impulse voltage tests.

5.2.2.1 Power Frequency Test

The test voltage should be a standard 1/50 μ sec wave, the peak value of which is specified according to the rated voltage of the breaker. A higher impulse voltage is specified for non-effectively grounded system than those for solidly grounded system. The test voltages are applied between (*i*) each pole and earth in turn with the breaker closed and remaining phases earthed, and (*ii*) between all terminals on one side of the breaker and all the other terminals earthed, with the breaker open. The specified voltages are withstand values *i.e.* the breaker should not flash over for 10 applications of the wave. Normally this test is carried out with waves of both the polarities. The wet dielectric test is used for outdoor switchgear. In this, the external insulation is sprayed for two minutes while the rated service voltage is applied; the test overvoltage is then maintained for 30 seconds during which no flash over should occur. The effect of rain on external insulation is partly beneficial, insofar as the surface is thereby cleaned, but is also harmful if the rain contains impurities.

5.2.2.2 Thermal Test

These tests are made to check the thermal behaviour of the breakers. In this test the rated current through all three phases of the switchgear is passed continuously for a period long enough to achieve steady state conditions. Temperature readings are obtained by means of thermocouples whose hot junctions are placed in appropriate positions. The temperature rise above ambient, of conductors, must normally not exceed 40°C when the rated normal current is less than 800 amps and 50°C if it is 800 amps and above. An additional requirement in the type test is the measurement of the contact resistances between the isolating contacts and between the moving and fixed contacts. These points are generally the main sources of excessive heat generation. The voltage drop across the breaker pole is measured for different values of d.c. current which is a measure of the resistance of current carrying parts and hence that of contacts.

5.2.2.3 Mechanical Test

A C.B. must open and close at the correct speed and perform such operations without mechanical failure. The breaker mechanism is, therefore, subjected to a mechanical endurance type test involving repeated opening and closing of the breaker. B.S. 116: 1952 requires 500 such operations without failure and with no adjustment of the mechanism. Some manufacture feel that as many as 20,000 operations may be reached before any useful information regarding the possible causes of failure may be obtained. A resulting change in the material or dimensions of a particular component may considerably improve the life and efficiency of the mechanism.

5.3 TESTING OF CABLES

High voltage power cables have proved quite useful especially in case of HV d.c. transmission. Underground distribution using cables not only adds to the aesthetic looks of a metropolitan city but it provides better environments and more reliable supply to the consumers.

Preparation of Cable Sample

The cable sample has to be carefully prepared for performing various tests especially electrical tests. This is essential to avoid any excessive leakage or end flash overs which otherwise may occur during testing and hence may give wrong information regarding the quality of cables. The length of the sample cable varies between 50 cms to 10 m. The terminations are usually made by shielding the ends of the cable with stress shields so as to relieve the ends from excessive high electrical stresses.

A cable is subjected to following tests:

(*i*) Bending tests.

(*ii*) Loading cycle test.

(*iii*) Thermal stability test.

(*iv*) Dielectric thermal resistance test.

(*v*) Life expectancy test.

(*vi*) Dielectric power factor test.

(*vii*) Power frequency withstand voltage test.

(*viii*) Impulse withstand voltage test.

(*ix*) Partial discharge test.

(i) It is to be noted that a voltage test should be made before and after a bending test. The cable is bent round a cylinder of specified diameter to make one complete turn. It is then unwound and rewound in the opposite direction. The cycle is to be repeated three times.

(ii) A test loop, consisting of cable and its accessories is subjected to 20 load cycles with a minimum conductor temperature 5°C in excess of the design value and the cable is energized to 1.5 times the working voltage. The cable should not show any sign of damage.

(*iii*) After test as at (*ii*), the cable is energized with a voltage 1.5 times the working voltage for a cable of 132 kV rating (the multiplying factor decreases with increases in operating voltage) and the loading current is so adjusted that the temperature of the core of the cable is 5°C higher than its specified permissible temperature. The current should be maintained at this value for six hours.

(*iv*) The ratio of the temperature difference between the core and sheath of the cable and the heat flow from the cable gives the thermal resistance of the sample of the cable. It should be within the limits specified in the specifications.

(*v*) In order to estimate life of a cable, an accelerated life test is carried out by subjecting the cable to a voltage stress higher than the normal working stress. It has been observed that the relation between the expected life of the cable in hours and the voltage stress is given by

$$g = \frac{K}{n\sqrt{t}}$$

where K is a constant which depends on material and n is the life index depending again on the material.

(*vi*) High Voltage Schering Bridge is used to perform dielectric power factor test on the cable sample. The power factor is measured for different values of voltages *e.g.* 0.5, 1.0, 1.5 and 2.0 times the rated operating voltages. The maximum value of power factor at normal working voltage does not exceed a specified value (usually 0.01) at a series of temperatures ranging from 15°C to 65°C. The difference in the power factor between rated voltage and 1.5 times the rated voltage and the rated voltage and twice the rated voltage does not exceed a specified value. Sometimes the source is not able to supply charging current required by the test cable, a suitable choke in series with the test cable helps in tiding over the situation.

(*vii*) Cables are tested for power frequency a.c. and d.c. voltages. During manufacture the entire cable is passed through a higher voltage test and the rated voltage to check the continuity of the cable. As a routine test the cable is subjected to a voltage 2.5 times the working voltage for 10 min without damaging the insulation of the cable. HV d.c. of 1.8 times the rated d.c. voltage of negative polarity for 30 min. is applied and the cable is said to have withstood the test if no insulation failure takes place.

(*viii*) The test cable is subjected to 10 positive and 10 negative impulse voltage of magnitude as specified in specification, the cable should withstand 5 applications without any damage. Usually, after the impulse test, the power frequency dielectric power factor test is carried out to ensure that no failure occurred during the impulse test.

(*ix*) Partial discharge measurement of cables is very important as it gives an indication of expected life of the cable and it gives location of fault, if any, in the cable.

When a cable is subjected to high voltage and if there is a void in the cable, the void breaks down and a discharge takes place. As a result, there is a sudden dip in voltage in the form of an impulse. The duration between the normal pulse and the discharge pulse is measured on the oscilloscope and this distance gives the location of the void from the test end of the cable. However, the shape of the pulse gives the nature and intensity of the discharge.

In order to scan the entire length of the cable against voids or other imperfections, it is passed through a tube of insulating material filled with distilled water. Four electrodes, two at the end and two in the middle of the tube are arranged. The middle electrodes are located at a stipulated distance and these are energized with high voltage. The two end electrodes and cable conductor are grounded. As the cable is passed between the middle electrode, if a discharge is seen on the oscilloscope, a defect in this part of the cable is stipulated and hence this part of the cable is removed from the rest of the cable.

5.4 TESTING OF TRANSFORMERS

Transformer is one of the most expensive and important equipment in power system. If it is not suitably designed its failure may cause a lengthy and costly outage. Therefore, it is very important to be cautious while designing its insulation, so that it can withstand transient over voltage both due to switching and lightning. The high voltage testing of transformers is, therefore, very important and would be discussed here. Other tests like temperature rise, short circuit, open circuit etc. are not considered here. However, these can be found in the relevant standard specification.

5.4.1 Partial Discharge Test

The test is carried out on the windings of the transformer to assess the magnitude of discharges. The transformer is connected as a test specimen similar to any other equipment and the discharge measurements are made. The location and severity of fault is ascertained using the travelling wave theory technique. The measurements are to be made at all the terminals of the transformer and it is estimated that if the apparent measured charge exceeds 104 pico-coulombs, the discharge magnitude is considered to be severe and the transformer insulation should be so designed that the discharge measurement should be much below the value of 104 pico-coulombs.

5.4.2 Impulse Testing of Transformer

The impulse level of a transformer is determined by the breakdown voltage of its minor insulation (Insulation between turn and between windings), breakdown voltage of its major insulation (insulation between windings and tank) and the flash over voltage of its bushings or a combination of these. The impulse characteristics of internal insulation in a transformer differs from flash over in air in two main respects. Firstly the impulse ratio of the transformer insulation is higher (varies from 2.1 to 2.2) than that of bushing (1.5 for bushings, insulators etc.). Secondly, the impulse breakdown of transformer.

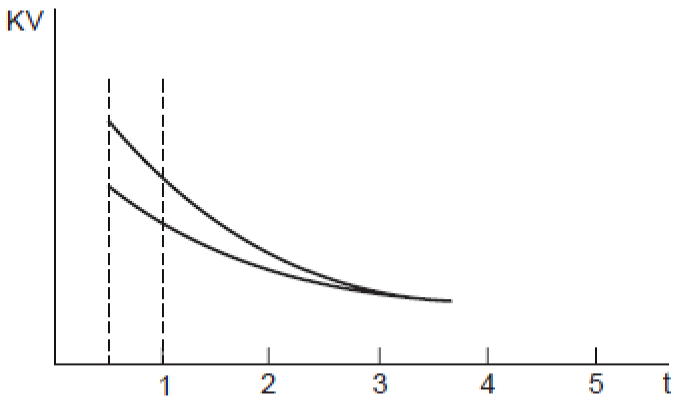


Fig : 5.4.1 Volt Time Curve of Typical Major Insulation In Transformer

Insulation in practically constant and is independent of time of application of impulse voltage. Fig. 5.4.1 shows that after three micro seconds the flash over voltage is substantially constant. The voltage stress between the turns of the same winding and between different windings of the transformer depends upon the steepness of the surge wave front. The voltage stress may further get aggravated by the piling up action of the wave if the length of the surge wave is large. In fact, due to high steepness of the surge waves, the first few turns of the winding are overstressed and that is why the modern practice is to provide extra insulation to the first few turns of the winding. Fig. 5.4.2 shows the equivalent circuit of a transformer winding for impulse voltage.

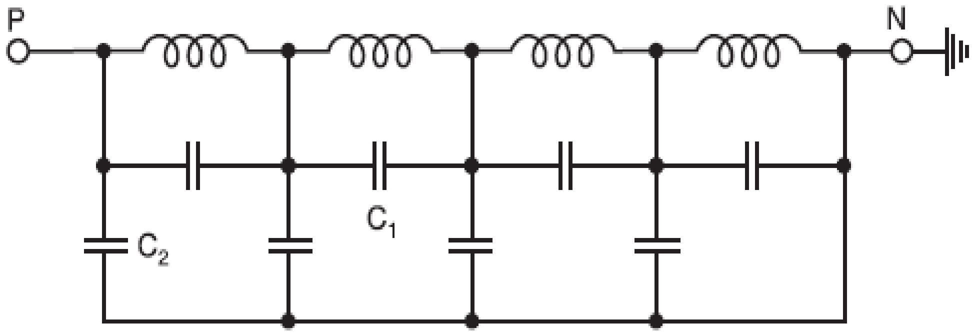


Fig : 5.4.2 Equivalent circuit of a Transformer for impulse voltage

Here *C*1 represents inter-turn capacitance and *C*2 capacitance between winding and the ground (tank). In order that the minor insulation will be able to withstand the impulse voltage, the winding is subjected to chopped impulse wave of higher peak voltage than the full wave. This chopped wave is produced by flash over of a rod gap or bushing in parallel with the transformer insulation. The chopping time is usually 3 to 6 micro seconds. While impulse voltage is applied between one phase and ground, high voltages would be induced in the secondary of the transformer. To avoid this, the secondary windings are short-circuited and finally connected to ground. The short circuiting, however, decreases the impedance of the transformer and hence poses problem in adjusting the wave front and wave tail timings of wave. Also, the minimum value of the impulse capacitance required is given by

$$C_0 = \frac{P \times 10^8}{Z \times V^2}\ \mu\text{F}$$

where *P* = rated MVA of the transformer Z = per cent impedance of transformer. *V* = rated voltage of transformer.

Fig. 5.4.3 shows the arrangement of the transformer for impulse testing. CRO forms an integral part of the transformer impulse testing circuit. It is required to record to wave forms of the applied voltage and current through the winding under test.

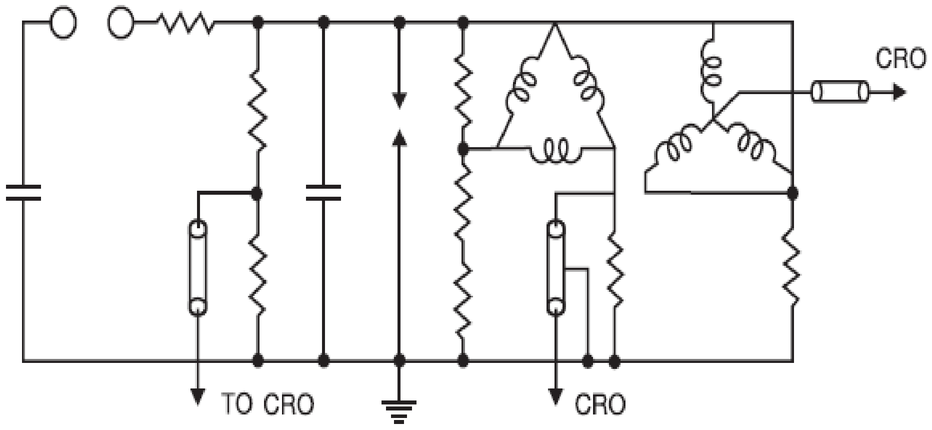


Fig : 5.4.3 Arrangement for impulse testing of transformer

Impulse testing consists of the following steps:

(*i*) Application of impulse of magnitude 75% of the Basic Impulse Level (BIL) of the transformer under test.

(*ii*) One full wave of 100% of BIL.

(*iii*) Two chopped wave of 115% of BIL.

(*iv*) One full wave of 100% BIL and

(*v*) One full wave of 75% of BIL.

During impulse testing the fault can be located by general observation like noise in the tank or smoke or bubble in the breather. If there is a fault, it appears on the Oscilloscope as a partial of complete collapse of the applied voltage. Study of the wave form of the neutral current also indicated the type of fault. If an arc occurs between the turns or form turn to the ground, a train of high frequency pulses are seen on the oscilloscope and wave shape of impulse changes. If it is a partial discharge only, high frequency oscillations are observed but no change in wave shape occurs.

The bushing forms an important and integral part of transformer insulation. Therefore, its impulse flash over must be carefully investigated. The impulse strength of the transformer winding is same for either polarity of wave whereas the flash over voltage for bushing is different for different polarity. The manufacturer, however, while specifying the impulse strength of the transformer takes into consideration the overall impulse characteristic of the transformer.

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5.5 TESTING OF SURGE ARRESTERS

Surge arresters are often "overlooked" when performing Power Factor tests on transformers, breakers and other apparatus in a substation. Often times, the testers are aware of how a transformer or a breaker functions, but are not aware of the intended purpose of the surge arresters. Since there are no "moving" parts to maintain or an oil sample to pull, it is often their policy not to perform any testing of the arrester.

Surge arresters are devices that help prevent damage to apparatus due to high voltages. The arrester provides a low-impedance path to ground for the current from a lightning strike or transient voltage and then restores to a normal operating conditions. A surge arrester may be compared to a relief valve on a boiler or hot water heater. It will release high pressure until a normal operating condition is reached. When the pressure is returned to normal, the safety valve is ready for the next operation.

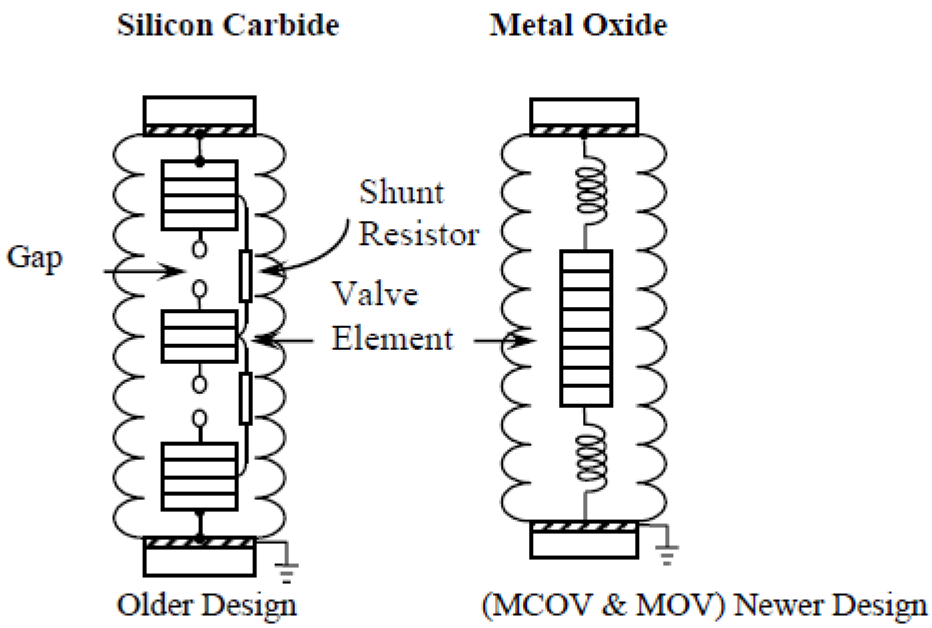
When a high voltage (greater than the normal line voltage) exists on the line, the arrester immediately furnishes a path to ground and thus limits and drains off the excess voltage. The arrester must provide this relief and then prevent any further flow of current to ground. The arrester has two functions, it must provide a point in the circuit at which an over-voltage pulse can pass to ground and second, to prevent any follow-up current from flowing to ground.

A great number of silicone carbide arresters are still in service. The silicone carbide arrester has some unusual electrical characteristics. It has a very high resistance to low voltage, but a very low resistance to high-voltage. When lightning strikes or a transient voltage occurs on the system, there is a sudden rise in voltage and current. The silicone carbide resistance breaks down allowing the current to be conducted to ground. After the surge has passed, the resistance of the silicone carbide blocks increases allowing normal operation. The silicone carbide arrester uses nonlinear resistors made of bonded silicone carbide placed in series with gaps. The function of the gaps is to isolate the resistors from the normal steady-state system voltage. One major drawback is the gaps require elaborate design to ensure consistent spark-over level and positive clearing (resealing) after a surge passes. It should be recognized that over a period of operations that melted particles of copper might form which could lead to a reduction of the breakdown voltage due to the pinpoint effect. Over a period of time, the arrester gap will break down at small over voltages or even at normal operating voltages. Extreme care should be taken on arresters that have failed but the over pressure relief valve did not operate. This pressure may cause the arrester to shatter.

This design is not as popular due to the emergence of the Metal Oxide Varistor (MOV) arrester. Silicon carbide arresters are vulnerable to moisture ingress that leads to failure due to reduction in spark over. Contamination can also upset voltage distribution resulting in spark over reduction. Over a period of time, excessive energy inputs can destroy the ability of the blocks and gaps to interrupt follow current leading to failure of the arrester. Transaction on Power Delivery, Dr. M Darveniza recommended that all silicon carbide arresters that have been in service for over 13 years be replaced due to moisture ingress. His tests revealed that degradation was evident in 75% of arresters tested.

To determine if a silicon carbide arrester warrants replacement, field-testing must be performed. The ideal method is to determine the protective level of the arrester, this is not practical since an impulse generator is required. An effective and more practical method is to determine the watts-loss of the arrester and compare to like arresters. Testing methods will be reviewed later.

The MOV arrester is the arrester usually installed today. Doble documentation reveals that MOV type arresters entered the market in the United States around 1976. The metal oxide arresters are without gaps, unlike the SIC arrester. This “gap-less” design eliminates the high heat associated with the arcing discharges. The MOV arrester has two-voltage rating: duty cycle and maximum continuous operating voltage, unlike the silicone carbide that just has the duty cycle rating. A metal-oxide surge arrester utilizing zinc-oxide blocks provides the best performance, as surge voltage conduction starts and stops promptly at a precise voltage level, thereby improving system protection. Failure is reduced, as there is no air gap contamination possibility; but there is always a small value of leakage current present at operating frequency.



It is important for the test personnel to be aware that when a metal oxide arrester is disconnected from an energized line a small amount of static charge can be retained by the arrester. As a safety precaution, the tester should install a temporary ground to discharge any stored energy.

Duty cycle rating: The silicon carbide and MOV arrester have a duty cycle rating in KV, which is determined by duty cycle testing. Duty cycle testing of an arrester is performed by subjecting an arrester to an AC rms voltage equal to its rating for 24 minutes. During which the arrester must be able to withstand lightning surges at 1-minute intervals. For station class arresters, the magnitude of this surge is 10kA (10,000 Amperes). For intermediate and distribution class arresters, this surge is 5 kA (5000 Amperes). The surge wave shape is an 8/20, which means the current wave reaches a crest in 8 milliseconds and diminishes to half the crest value in 20 milliseconds.

Maximum continuous operating voltage rating – MCOV. The MCOV rating is usually 80 to 90% of the duty cycle rating.

As one may guess, each class offers different levels of protection and energy diversion. The station class arrester offers the best level of protection and is capable of diverting the most energy. The intermediate class has the next best level; with a lower energy diversion capability than the station class arrester. The distribution class arrester offers the lowest level of protection with the lowest energy diversion capability. The secondary class arrester dose not overlap with any of the other classes that makes it difficult to compare with the other classes. The station class arresters offers the most protection, but the higher protection also results in higher costs per unit.

5.6 RADIO INTERFERENCE MEASUREMENTS

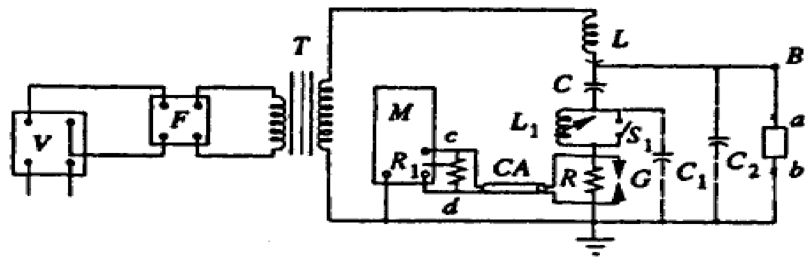
Many electrical apparatuses like transformers, line conductors, rotating machines, etc. produce unwanted electrical signals in the radio and high frequency (television band, microwave bands, etc.) ranges. These signals arise due to corona discharges in air, internal or partial discharges in the insulation, sparking at commutators and brush gear in rotating machines, etc. It is important to see that the noise voltages generated in the radio and other transmission bands are limited to acceptable levels, and hence the radio interference voltage measurements are of importance. It has been found that the surface conditions of the overhead conductors subjected t_d high voltage stresses and varying atmospheric conditions greatly influence the magnitude of the noise voltage produced. In case of solid insulators, the bonding between the porcelain and the metal pin, the binding of high voltage conductor and the insulator surface, and the surface pollution were found to be the sources of this noise.

5.6.1 MEASUREMENTS OF RADIO INTERFERENCE VOLTAGE

The noise generated in the radio frequency band as a result of corona or partial discharges in high voltage power apparatus may be measured

(i) By the radio frequency line to ground voltage known as the radio influence voltage or RIV, and

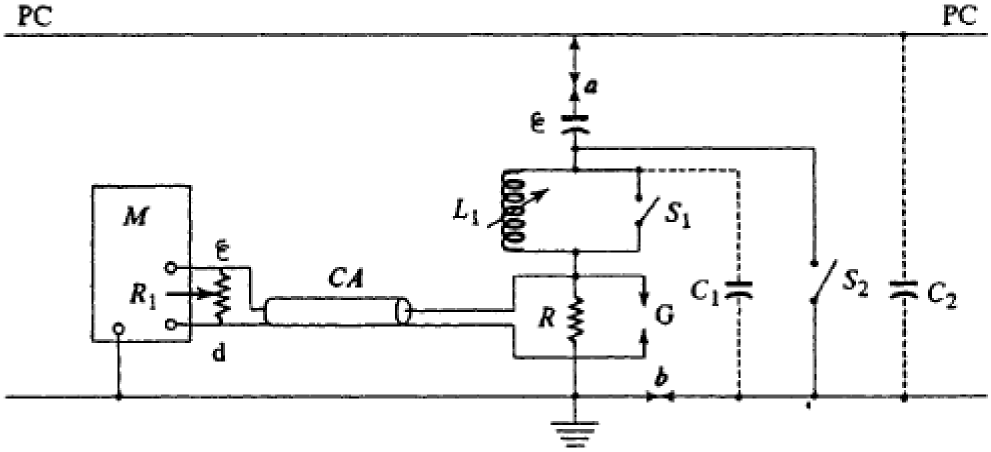
(ii) As an interfering field by means of an antenna known as the radiated radio interference voltage or RI. Normally, the tests and measurements done in the laboratories are RIV measurements, whereas field investigations with portable radio receivers are RI measurements.



F — Voltage control unit; *V* — Voltmeter; *T* — High voltage transformer; *L* — Radio frequency choke; *C* — Coupling condenser; R_1 — Meter input impedance; *M* — Radio noise meter; a-b — Test apparatus; CA — Coaxial cable; G — Protective gap; S_1 — Shorting switch, C_1, C_2 — Stray capacitances; L_1 — Tuning choke; *R* — Measuring impedance

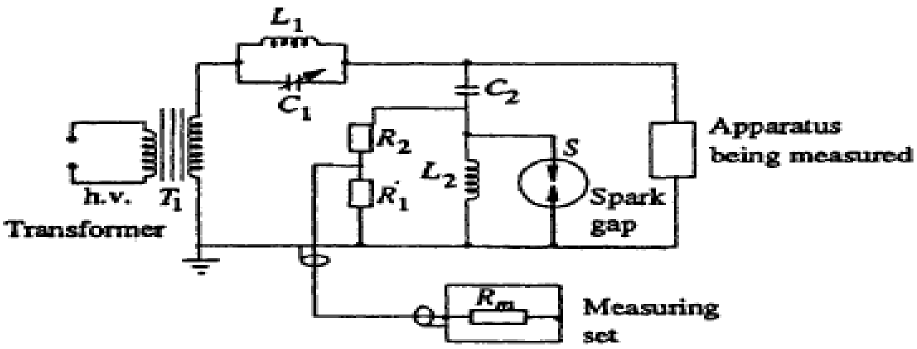
Fig : 5.6.1 Schematic Diagram of Circuit For The Measurement of RIV of A High Voltage Apparatus In 150kHz To 30 MHz Frequency Range

A radio noise meter used in the laboratory consists of a portable radio receiver with a local oscillator, a radio frequency amplifier, a mixer, an intermediate frequency amplifier, and a detector similar to that of a standard radio receiver and operates in the frequency range 150 kHz to 30 MHz. In addition, the radio noise meter has multi-input circuits to accommodate a number of pick-up devices, (calibrators, and output circuits containing special detectors and meters. The detector circuit consists of a diode detector in series with a series resistance *Rs*, charging a parallel *R-C* circuit. The detector circuit is provided with a measuring device to measure either (a) the average value, (b) the peak value, or (c) quasi-peak value (the quasi-peak value of the impulse noise is equal to the rms value of the sine wave at the centre frequency of the pass band which produces the same deflection in the meter scale as that of the impulse). The voltmeter provided at the end of the detector has an input impedance of 50 to 75Ω



€ — Coupling condenser; *M* — Radio noise meter; *a-b* — Test apparatus; *CA* — Coaxial cable; *O* — Protective gap; S_1 — Shorting switch; C_1, C_2 — Stray capacitances; L_1 — Tuning choke; *R* — Measuring impedance; R_1 — Meter input impedance; P.C. — Power system conductor

Fig : 5.6.2 Circuit for measurement of RIV from the conductors of an energized system



T_1 — High voltage transformers; L_1, C_1 — Filter; C_2 — Coupling condenser; L_2 — Measuring choke; R_1, R_2 — Potential divider; *S* — Protective spark gap; R_m — Input impedance of the meter

Fig : 5.6.3 Circuit for RIV measurement as given by British standards

TEST CIRCUITS FOR THE MEASUREMENTS

The schematic circuits used for RIV measurements are shown in Figs. The RIV meter is first calibrated as per standards. The important components of the circuits are:

(i)The radio frequency choke to limit the loss of the RIV voltage and to conduct energy from the sample. The choke itself should be free from noise, and its impedance should be less than 1500 Ω

(ii) The coupling capacitor *C* (< 0.001μ F); it should be free from noise in the operating range and the resistance 'R' should be equal to 800 **Ω**. The value indicated by the meter gives the conducted radio noise from the test sample.

(iii) Coaxial cable (CA): A coaxial cable of characteristic impedance 185 Ω shall be connected between the resistance 'R' and the radio noise meter. When the radio noise meter measurements are stated, the information regarding the specifications of the meter used, the frequency range of measurements, the band pass characteristics, and the open circuit and the detector characteristics have to be mentioned.

Now-a-days, for transmission systems of 400 kV and above, radio noise voltages are of importance, and corrective measures are to be adopted for various apparatus and hardware to minimize the radio and television band noise.