Lecture Notes in

High Voltage Engineering

Dr. Sabah I Mohamed

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1
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. The principal media of insulation used are gases, vacuum, solid, and liquid, or a combination of these. For achieving reliability and economy, a knowledge of the causes of deterioration is essential, and the tendency to increase the voltage stress for optimum design calls for judicious selection of insulation in relation to the dielectric strength, corona discharges, and other relevant factors. In this chapter some of the general principles used in high voltage technology are discussed.

1.1 ELECTRIC FIELD STRESSES

Like in mechanical designs where the criterion for design depends on the mechanical strength of the materials and the stresses that are generated during their operation, in high voltage applications, the dielectric strength of insulating materials and the electric field stresses developed in them when subjected to high voltages are the important factors in high voltage systems. In a high voltage apparatus the important materials used are conductors and insulators. While the conductors carry the current, the insulators prevent the flow of currents in undesired paths. The electric stress to which an insulating material is subjected to is numerically equal to the voltage gradient, and is equal to the electric field intensity,

$$\mathbf{E} = -\nabla \varphi \tag{1.1}$$

where $\mathbf{E}$ is the electric field intensity, φ is the applied voltage, and ∇ (read del) operator is defined as

$$\nabla \equiv a_x \frac{\partial}{\partial x} + a_y \frac{\partial}{\partial y} + a_z \frac{\partial}{\partial z}$$

where a_x, a_y, and a_z are components of position vector $\mathbf{r} = a_x\, x + a_y\, y + a_z\, z$.

As already mentioned, the most important material used in a high voltage apparatus is the insulation. The dielectric strength of an insulating material can be defined as the maximum dielectric stress which the material can withstand. It can also be defined as the voltage at which the current starts increasing to very high values unless controlled by the external impedance of the circuit. The electric breakdown strength of insulating materials depends on a variety of parameters, such as pressure, temperature, humidity, field configurations, nature of applied voltage, imperfections in dielectric materials, material of electrodes, and surface conditions of electrodes, etc. An understanding of the failure of the insulation will be possible by the study of the possible mechanisms by which the failure can occur.

The most common cause of insulation failure is the presence of discharges either within the voids in the insulation or over the surface of the insulation. The probability of failure will be greatly reduced if such discharges could be eliminated at the normal working voltage. Then, failure can occur as a result of thermal or electrochemical deterioration of the insulation.

1.2 GAS/VACUUM AS INSULATOR

Air at atmospheric pressure is the most common gaseous insulation. The breakdown of air is of considerable practical importance to the design engineers of power transmission lines and power apparatus. Breakdown occurs in gases due to the process of collisional ionization. Electrons get multiplied in an exponential manner, and if the applied voltage is sufficiently large, breakdown occurs. In some gases, free electrons are removed by attachment to neutral gas molecules; the breakdown strength of such gases is substantially large. An example of such a gas with larger dielectric strength is sulphur hexaflouride (SF_6).

The breakdown strength of gases increases steadily with the gap distance between the electrodes; but the breakdown voltage gradient reduces from 3 MV/m for uniform fields and small distances to about 0.6 MV/m for large gaps of several metres. For very large gaps as in lightning, the average gradient reduces to 0.1 to 0.3 MV/m.

High pressure gas provides a flexible and reliable medium for high voltage insulation. Using gases at high pressures, field gradients up to 25 MV/m have been realized. Nitrogen (N_2) was the gas first used at high pressures because of its inertness and chemical stability, but its dielectric strength is the same as that of air. Other important practical insulating gases are carbon-dioxide (CO_2), dichlorodifluoromethane (CCl_2F_2) (popularly known as freon), and sulphur hexafluoride (SF_6). Investigations are continuing with more complex and heavier gases to be adopted as possible insulators. SF_6 has been found to maintain its insulation superiority, about 2.5 times over N_2 and CO_2 at atmospheric pressure, the ratio increasing at higher pressures. SF_6 gas was also observed to have superior arc quenching properties over any other gas. The breakdown voltage at higher pressures in gases shows an increasing dependence on the nature and smoothness of the electrode material. It is relevant to point out that, of the gases examined to-date, SF_6 has probably the most attractive overall dielectric and arc quenching properties for gas insulated high voltage systems.

Ideally, vacuum is the best insulator with field strengths up to 10^7 V/cm, limited only by emissions from the electrode surfaces. This decreases to less than 10^5

V/cm for gaps of several centimetres. Under high vacuum conditions, where the pressures are below 10^{-4} torr*, the breakdown cannot occur due to collisional processes like in gases, and hence the breakdown strength is quite high. Vacuum insulation is used in particle accelerators, x-ray and field emission tubes, electron microscopes, capacitors, and circuit breakers.

1.3 LIQUID BREAKDOWN

Liquids are used in high voltage equipment to serve the dual purpose of insulation and heat conduction. They have the advantage that a puncture path is self-healing. Temporary failures due to overvoltages are reinsulated quickly by liquid flow to the attacked area. However, the products of the discharges may deposit on solid insulation supports and may lead to surface breakdown over these solid supports.

Highly purified liquids have dielectric strengths as high as 1 MV/cm. Under actual service conditions, the breakdown strength reduces considerably due to the presence of impurities. The breakdown mechanism in the case of very pure liquids is the same as the gas breakdown, but in commercial liquids, the breakdown mechanisms are significantly altered by the presence of the solid impurities and dissolved gases.

Petroleum oils are the commonest insulating liquids. However, askarels, fluorocarbons, silicones, and organic esters including castor oil are used in significant quantities. A number of considerations enter into the selection of any dielectric liquid. The important electricial properties of the liquid include the dielectric strength, conductivity, flash point, gas content, viscosity, dielectric constant, dissipation factor, stability, etc. Because of their low dissipation factor and other excellent characteristics, polybutanes are being increasingly used in the electrical industry. Askarels and silicones are particularly useful in transformers and capacitors and can be used at temperatures of 200°C and higher. Castor oil is a good dielectric for high voltage energy storage capacitors because of its high corona resistance, high dielectric constant, non-toxicity, and high flash point.

In practical applications liquids are normally used at voltage stresses of about 50-60 kV/cm when the equipment is continuously operated. On the other hand, in applications like high voltage bushings, where the liquid only fills up the voids in the solid dielectric, it can be used at stresses as high as 100-200 kV/cm.

1.4 SOLID BREAKDOWN

If the solid insulating material is truly homogeneous and is free from imperfections, its breakdown stress will be as high as 10 MV/cm. This is the 'intrinsic breakdown strength', and can be obtained only under carefully controlled laboratory conditions. However, in practice, the breakdown fields obtained are very much lower than this value. The breakdown occurs due to many mechanisms. In general, the breakdown occurs over the surface than in the solid itself, and the surface insulation failure is the most frequent cause of trouble in practice.

*1 torr = 1 mm of Hg.

The breakdown of insulation can occur due to mechanical failure caused by the mechanical stresses produced by the electrical fields. This is called "electromechanical" breakdown.

On the other hand, breakdown can also occur due to chemical degradation caused by the heat generated due to dielectric losses in the insulating material. This process is cumulative and is more severe in the presence of air and moisture.

When breakdown occurs on the surface of an insulator, it can be a simple flashover or formation of a conducting path on the surface. When the conducting path is formed, it is called "tracking", and results in the degradation of the material. Surface flashover normally occurs when the solid insulator is immersed in a liquid dielectric. Surface flashover, as already mentioned, is the most frequent cause of trouble in practice. Porcelain insulators for use on transmission lines must therefore be designed to have a long path over the surface. Surface contamination of electrical insulation exists almost everywhere to some degree. In porcelain high voltage insulators of the suspension type, the length of the path over the surface will be 20 to 30 times greater than that through the solid. Even there, surface breakdown is the commonest form of failure.

The failure of solid insulation by discharges which may occur in the internal voids and cavities of the dielectric, called partial discharges, is receiving much attention today, mostly because it determines the life versus stress characteristics of the material. The energy dissipated in the partial discharges causes further deterioration of the cavity walls and gives rise to further evolution of gas. This is a cumulative process eventually leading to breakdown. In practice, it is not possible to completely eliminate partial discharges, but a level of partial discharges is fixed depending on the expected operating life of the equipment. Also, the insulation engineer should attempt to raise the discharge inception level, by carefully choosing electric field distributions and eliminating voids, particularly from high field systems. This requires a very high quality control during manufacture and assembly. In some applications, the effect of the partial discharges can be minimized by vacuum impregnation of the insulation. For high voltage applications, cast epoxy resin is solving many problems, but great care should be exercised during casting. High voltage switchgear, bushings, cables, and transformers are typical devices for which partial discharge effects should be considered in design.

So far, the various mechanisms that cause breakdown in dielectrics have been discussed. It is the intensity of the electric field that determines the onset of breakdown and the rate of increase of current before breakdown. Therefore, it is very essential that the electric stress should be properly estimated and its distribution known in a high voltage apparatus. Special care should be exercised in eliminating the stress in the regions where it is expected to be maximum, such as in the presence of sharp points.

1.5 ESTIMATION AND CONTROL OF ELECTRIC STRESS

The electric field distribution is governed by the Poisson's equation:

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon_0} \tag{1.2}$$

where φ is the the potential at a given point, ρ is the space charge density in the region, and ε_0 is the electric permittivity of free space (vacuum). However, in most of the high

voltage apparatus, space charges are not normally present, and hence the potential distribution is governed by the Laplace's equation:

$$\nabla^2 \varphi = 0 \tag{1.3}$$

In Eqs. (1.2) and (1.3) the operator ∇^2 is called the Laplacian and is a scalar with properties

$$\nabla \cdot \nabla = \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

There are many methods available for determining the potential distribution, the most commonly used methods being,

(*i*) the electrolytic tank method, and
(*ii*) the method using digital computers.

The potential distribution can also be calculated directly. Howevei, this is very difficult except for simple geometries. In many practical cases, a good understanding of the problem is possible by using some simple rules to sketch the field lines and equipotentials. The important rules are

(*i*) the equipotentials cut the field lines at right angles,
(*ii*) when the equipotentials and field lines are drawn to form curvilinear squares, the density of the field lines is an indication of the electric stress in a given region, and
(*iii*) in any region, the maximum electric field is given by dv/dx, where dv is the voltage difference between two successive equipotentials dx apart.

Considerable amount of labour and time can be saved by properly choosing the planes of symmetry and shaping the electrodes accordingly. Once the voltage distribution of a given geometry is established, it is easy to refashion or redesign the electrodes to minimize the stresses so that the onset of corona is prevented. This is a case normally encountered in high voltage electrodes of the bushings, standard capacitors, etc. When two dielectrics of widely different permittivities are in a series, the electric stress is very much higher in the medium of lower permittivity. Considering a solid insulation in a gas medium, the stress in the gas becomes ε_r times that in the solid dielectric, where ε_r is the relative permittivity of the solid dielectric. This enhanced stress occurs

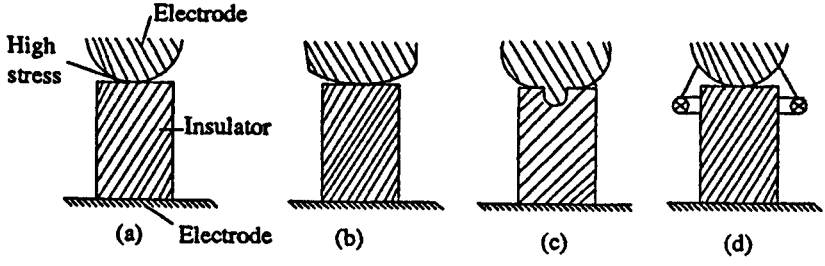


Fig. 1.1 Control of stress at an electrode edge

at the electrode edges and one method of overcoming this is to increase the electrode diameter. Other methods of stress control are shown in Fig. 1.1.

1.5.1 Electric Field

A brief review of the concepts of electric fields is presented, since it is essential for high voltage engineers to have a knowledge of the field intensities in various media under electric stresses. It also helps in choosing proper electrode configurations and economical dimensioning of the insulation, such that highly stressed regions are not formed and reliable operation of the equipment results in its anticipated life.

The field intensity **E** at any location in an electrostatic field is the ratio of the force on an infinitely small charge at that location to the charge itself as the charge decreases to zero. The force **F** on any charge q at that point in the field is given by

$$\mathbf{F} = q\,\mathbf{E} \tag{1.4}$$

The electric flux density **D** associated with the field intensity **E** is

$$\mathbf{D} = \varepsilon\,\mathbf{E} \tag{1.5}$$

where ε is the permittivity of the medium in which the electric field exists. The work done on a charge when moved in an electric field is defined as the potential. The potential φ is equal to

$$\varphi = -\int_l \mathbf{E}\ \ d\mathbf{l} \tag{1.6}$$

where l is the path through which the charge is moved.

Several relationships between the various quantities in the electric field are summarized as follows:

$$\mathbf{D} = \varepsilon\,\mathbf{E} \tag{1.5}$$

$$\varphi = -\int_l \mathbf{E} \cdot d\mathbf{l} \ (\text{or } \mathbf{E} = -\nabla\varphi) \tag{1.6}$$

$$\mathbf{E} = \frac{\mathbf{F}}{q} \tag{1.7}$$

$$\iint_S \mathbf{E} \cdot d\mathbf{S} = \frac{q}{\varepsilon_0} \text{ (Gauss theorem)} \tag{1.8}$$

$$\nabla \cdot \mathbf{D} = \rho \text{ (Charge density)} \tag{1.9}$$

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon_0} \text{ (Poisson's equation)} \tag{1.10}$$

$$\nabla^2 \varphi = 0 \text{ (Laplace's equation)} \tag{1.11}$$

where **F** is the force exerted on a charge q in the electric field **E**, and **S** is the closed surface contianing charge q.

1.5.2 Electric Field in a Single Dielectric Medium

When several conductors are situated in an electric field with the conductors charged, a definite relationship exists among the potentials of the conductors, the charges on them, and the physical location of the conductors with respect to each other.

In a conductor, electrons can move freely under the influence of an electric field. This means that the charges are distributed inside the substance and over the surface such that, $\mathbf{E} = 0$ everywhere inside the conductor. Since $\mathbf{E} = -\nabla\varphi = 0$, it is necessary that φ is constant inside and on the surface of the conductor. Thus, the conductor is an equipotential surface.

A dielectric material contains an array of charges which remain in equilibrium when an electric field is not zero within the substance. Therefore, a non-conductor or dielectric material is one that does contain free electrons or charges in appreciable number.

A simple capacitor consists of two conductors which are separated by a dielectric. If the two conductors contain a charge $+Q$ and $-Q$ and the potential difference between them is φ_{12}, the capacitance of such a capacitor is defined as the ratio of charge Q to the potential difference φ_{12}. Thus $C = Q/\varphi_{12}$. If the charge is not distributed uniformly over the two conductor surfaces, and if the charge density is ρ and the electric field in the dielectric is E,

then,
$$C = \iint_S \rho dS / \int_1^2 \mathbf{E} \cdot dl \tag{1.12}$$

When several conductors are present with charges $Q_1, Q_2, \ldots Q_n$ on them and their respective potentials are $\varphi_1, \varphi_2, \ldots \varphi_n$ the relationships between the charges and the potentials are given by

$$\begin{bmatrix} Q_1 \\ Q_2 \\ \cdot \\ \cdot \\ \cdot \\ Q_n \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & \ldots & C_{1n} \\ C_{21} & C_{22} & \ldots & C_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ C_{n1} & C_{n2} & & C_{nn} \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \cdot \\ \cdot \\ \cdot \\ \varphi_n \end{bmatrix} \tag{1.13}$$

where $C_{11}, C_{22}, \ldots, C_{ii}, \ldots, C_{nn}$ are called capacitance coefficients, and $C_{12}, C_{21}, \ldots, C_{ij}, C_{ji}$ are called induction coefficients. Here C_{ij} is the quantity of charge on the ith conductor, which will charge the jth conductor to unity potential when all other conductors are kept at zero potential.

These coefficients are geometric factors, and can be estimated from the configuration of the conductors. The reciprocity property holds good for coefficients of induction and $C_{ij} = C_{ji}$. The self-capacitance of a conductor i is

$$C_{ii} = \sum_{j=1}^{n} C_{ij} \tag{1.14}$$

The mutual capacitance between two conductors i and j is

$$C_{ij} = C_{ji} \tag{1.15}$$

This concept is very useful in the calculation of either potentials or charges in an electric field with known potential or charge distributions. In simple cases the electric field problems are solved, using Laplace or Poisson equation for the potential φ with the given boundary conditions. The electric field is estimated from the potential φ, and hence the charge distribution is obtained.

1.5.3 Electric Field in Mixed Dielectrics

When more than one dielectric material is present in any region of an electric field, the boundary conditions satisfied by the electric field intensity E at the dielectric boundary are

$$E_{t1} = E_{t2};\ \varepsilon_1 E_{n1} = \varepsilon_2 E_{n2};\ \text{and}\ \frac{\tan\alpha_1}{\tan\alpha_2} = \frac{\varepsilon_1}{\varepsilon_2} \tag{1.16}$$

where E_{t1} and E_{t2} are the tangential components of the electric field, E_{n1} and E_{n2} are the normal components of the electric field, α_1 and α_2 are the angle of incidence and angle of refraction with the normal direction at the boundary, and ε_1 and ε_2 are the permittivities of the two dielectrics at the boundary.

Normally, all dielectrics are good insulators at lower magnitudes of field intensities. But as the electric field increases, the electrons bound to the molecules of the dielectric will be subjected to higher forces, and some of them are freed from their molecular bonding. The electrons move in the opposite direction to the electric field and thus create conduction current. This dissociation is temporary in gases in which a combination occurs when the field is removed, whereas it is a partial or permanent feature in liquids and solids. Also, this phenomenon depends on a number of factors like impurities present in the substance, temperature, humidity, length of time for which an electric field is present, etc. The phenomenon is called dielectric breakdown, and the magnitude of an electric field that gives rise to the dielectric breakdown and destroys the property of insulation in dielectric materials is called the dielectric breakdown strength. Breakdown strength is usually expressed in kV/cm or MV/metre. Detailed study of the breakdown phenomena in various dielectric media is presented in the following chapters.

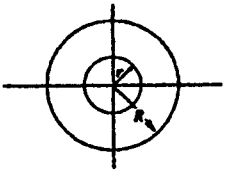
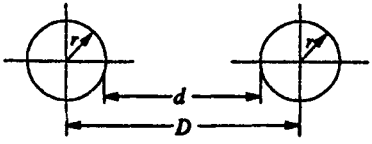
1.5.4 Estimation of Electric Field in Some Geometric Boundaries

It has been shown that the maximum electric field E_m in a given electric field configuration is of importance. The mean electric field over a distance d between two conductors with a potential difference of V_{12} is

$$E_{av} = \frac{V_{12}}{d} \tag{1.17}$$

In field configurations of non-uniform fields, the maximum electric field E_m is always higher than the average value. For some common field configurations, the maximum value of E_m and the field enhancement factor f given by E_m / E_{av} are presented in Table 1.1.

Table 1.1 Some Geometrical Configurations and the Field Factors

Geometrical configuration	Maximum electric field E_m	Field enhancement factor $f = E_m/E_{av}$
 Parallel plates	$\frac{V}{r}$	1.0
 Concentric cylinders	$\frac{V}{r \ln \frac{R}{r}}$	$\frac{(R-r)}{r \ln \frac{R}{r}}$
Figure same as above Concentric spheres	$\frac{VR}{r\,(R-r)}$	$\frac{R}{r}$
 Parallel cylinders of equal diameter	$\frac{V\sqrt{D^2-4r^2}}{2r(D-r)\cosh^{-1}(D/2r)} \approx \frac{V}{2r} \ln \frac{D}{r} \approx \frac{d}{2r \ln \frac{d}{r}}$ if $D \gg r$ if $d \gg r$	
Equal spheres with dimensions as above	$\approx \frac{V}{d} f$ $\approx \frac{V}{2r}$, if $d \gg r$	$f = \frac{\left(\frac{d}{r}+1\right) + \sqrt{\left(\frac{d}{r}+1\right)^2 + 8}}{4}$ $\approx \frac{d}{2r}$, if $d \gg r$

For other configurations like sphere-plane and cylinder-plane f is approximately given by

$$f = 0.94 \frac{d}{r} + 0.8 \text{ (sphere-plane)}$$

$$f = 0.25 \frac{d}{r} + 1.0 \text{ (cylinder-plane)}$$

Many electric conductors are normally either plane, cylindrical, or spherical in shape or can be approximated to these shapes. In other situations the conductors may be approximated into spheroidal, elliptical, toroidal, and other geometrical shapes, and thus estimation of E_m can be made.

2

Conduction and Breakdown in Gases

2.1 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 (CCl_2F_2) and sulphur hexafluoride (SF_6) are also used.

Various phenomena occur in gaseous dielectrics when a voltage is applied. When the applied voltage is low, small currents flow between the electrodes 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 maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage. In order to understand the breakdown phenomenon in gases, a study of the electrical properties of gases and the processes by which high currents are produced in gases is essential.

The electrical discharges in gases are of two types, i.e. (*i*) non-sustaining discharges, and (*ii*) self-sustaining types. The breakdown in a gas, called spark breakdown is the transition of a non-sustaining discharge into a self-sustaining discharge. The build-up of high currents in a breakdown is due to the process known as ionization in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents. At present two types of theories, 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.

2.2 IONIZATION PROCESSES

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

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

2.2.1 Ionization by Collision

The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionisation. In the process of ionisation by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion. If we consider a low pressure gas column in which an electric field E is applied across two plane parallel electrodes, as shown in Fig. 2.1 then, any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel towards the anode. If the energy (ε) gained during this travel between collisions exceeds the ionisation potential, V_i, which is the energy required to dislodge an electron from its atomic shell, then ionisation takes place. This process can be represented as

$$e^- + A \xrightarrow{\varepsilon > V_i} e^- + A^+ + e^- \tag{2.1}$$

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

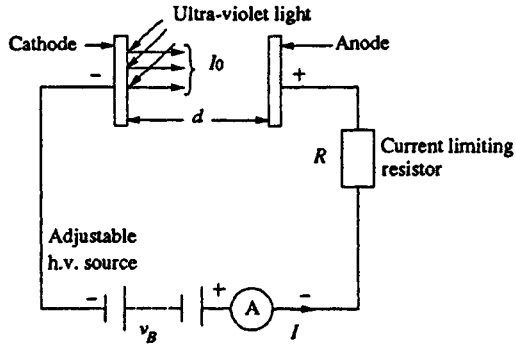


Fig. 2.1 Arrangement for study of a Townsend discharge

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

2.2.2 Photo-ionization

The phenomena associated with ionisation by radiation, or photo-ionisation, involves the interaction of radiation with matter. Photo-ionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionisation 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 ionisation etc.

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

$$h\nu + A \rightleftharpoons A^* \tag{2.2}$$

Ionisation occurs when

$$\lambda \leq c \cdot \frac{h.}{V_i} \tag{2.3}$$

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 ionisation 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 ionisation energy, the shorter will be the wavelength of the radiation capable of causing ionisation. It was observed experimentally that a radiation having a wavelength of 1250 $A°$ is capable of causing photo-ionisation of almost all gases.

2.2.3 Secondary Ionisation Processes

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

They are briefly described below.

(a) Electron Emission due to Positive Ion Impact

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

A positive ion approaching a metallic cathode can cause emission of electrons from the cathode by giving up its kinetic energy on impact. If the total energy of the positive ion, namely, the sum of its kinetic energy and the ionisation energy, is greater than twice the work function of the metal, then one electron will be ejected and a second electron will neutralise the ion. The probability of this process is measured as γ_i which is called the Townsend's secondary ionisation coefficient due to positive

ions and is defined as the net yield of electrons per incident positive ion. γ_i increases with ion velocity and depends on the kind of gas and electrode material used.

(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 (see Eq. 2.3)

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

where φ is the work function of the metallic electrode. The frequency (ν) is given by the relationship

$$\nu = \frac{\varphi}{h} \tag{2.4}$$

is known as the threshold frequency. For a clean nickel surface with $\varphi = 4.5$ eV, the threshold frequency will be that corresponding to a wavelength $\lambda = 2755\ \mathring{A}$. If the incident radiation has a greater frequency than the threshold frequency, then the excess energy goes partly as the kinetic energy of the emitted electron and partly to heat the surface of the electrode. Since φ is typically a few electron volts, the threshold frequency lies in the far ultra-violet region of the electromagnetic radiation spectrum.

(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. This process is most easily observed with metastable atoms, because the lifetime of other excited states is too short for them to reach the cathode and cause electron emission, unless they originate very near to the cathode surface. Therefore, the yields can also be large nearly 100%, for the interactions of excited *He* atom with a clean surface of molybdenum, nickel or magnesium. Neutral atoms in the ground state also give rise to secondary electron emission if their kinetic energy is high (≈ 1000 eV). At low energies the yield is considerably less.

2.2.4 Electron Attachment Process

The types of collisions in which electrons may become attached to atoms or molecules to form negative ions are called attachment collisions. Electron attachment process depends on the energy of the electron and the nature of the gas and is a very important process from the engineering point of view. All electrically insulating gases, such as O_2, CO_2, Cl_2, F_2, C_2F_6, C_3F_8, C_4F_{10}, CCl_2F_2, and SF_6 exhibit this property. An electron attachment process can be represented as:

$$\text{Atom} + e^- + k \longrightarrow \text{negative atomic ion} + (E_a + K) \tag{2.5}$$

The energy liberated as a result of this process is the kinetic energy K plus the electron affinity E_a. In the attaching or insulating gases, the atoms or molecules have vacancies in their outermost shells and, therefore, have an affinity for electrons. The attachment process plays a very important role in the removal of free electrons from an ionised gas when arc interruption occurs in gas-insulated switchgear. The effect of attachment on breakdown in gases is discussed in sec. 2.7 of this chapter.

2.3 TOWNSEND'S CURRENT GROWTH EQUATION

Referring to Fig. 2.1 let us assume that n_0 electrons are emitted from the cathode. When one electron collides with a neutral particle, a positive ion and an electron are formed. This is called an ionizing collision. Let α be the average number of ionizing collisions made by an electron per centimetre travel in the direction of the field (α depends on gas pressure p and E/p, and is called the Townsend's first ionization coefficient). At any distance x from the cathode, let the number of electrons be n_x. When these n_x electrons travel a further distance of dx they give rise to ($\alpha n_x dx$) electrons.

At $$x = 0, n_x = n_0 \tag{2.6}$$

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

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

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

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

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

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

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

where I_0 is the initial current at the cathode.

2.4 CURRENT GROWTH IN THE PRESENCE OF SECONDARY PROCESSES

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

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

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

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

The electrons produced by these processes are called secondary electrons. The secondary ionization coefficient γ is defined in the same way as α, as the net number of secondary electrons produced per incident positive ion, photon, excited particle, or metastable particle, and the total value of γ is the sum of the indlvidual coefficients due to the three different processes, i.e., $\gamma = \gamma_1 + \gamma_2 + \gamma_3$. γ is called the Townsend's secondary ionization coefficient and is a function of the gas pressure p and E/p.

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

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

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

Then
$$n_0'' = n_0 + n_0 \tag{2.11}$$

The total number of electrons n reaching the anode becomes,

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

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

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

or
$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma [\exp(\alpha d) - 1]} \tag{2.12}$$

2.5 TOWNSEND'S CRITERION FOR BREAKDOWN

Equation (2.12) 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 $d = d_s$.

$$1 - \gamma [\exp(\alpha d) - 1] = 0 \tag{2.13}$$

For values of $d < d_s$, I is approximately equal to I_0, and if the external source for the supply of I_0 is removed, I becomes zero. If $d = d_s$, $I \to \infty$ 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

$$\gamma \exp(\alpha d) = 1 \tag{2.14}$$

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 $p \times d$ (gas pressure $\times$ gap distance) values of 1000 torr-cm and below.

2.8 TIME LAGS FOR BREAKDOWN

In the previous section, the mechanism of spark breakdown is considered as a function of ionization processes under uniform field conditions. But in practical engineering designs, the breakdown due to rapidly changing voltages or impulse voltages is of great importance. Actually, there is a time difference between the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself. This time difference is called the time lag.

The Townsend criterion for breakdown is satisfied, only if at least one electron is present in the gap between the electrodes. In the case of applied d.c. or slowly varying (50 Hz a.c) voltages, there is no difficulty in satisfying this condition. However, with rapidly varying voltages of short duration ($\simeq 10^{-6}$ s), the initiatory electron may not be present in the gap, and in the absence of such an electron breakdown cannot occur. The time t which lapses between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag (t_s) of the gap. The appearance of electrons is usually statistically distributed. After the appearance of the electron, a time t_t is required for the ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag (t_t). The total time $t_s + t_t = t$ is called the total time lag.

Time lags are of considerable practical importance. For breakdown to occur the applied voltage V should be greater than the static breakdown voltage V_s as shown in Fig. 2.9. The difference in voltage $\Delta V = V - V_s$ is called the overvoltage, and the ratio V/V_s is called the impulse ratio. The variation of t_t with overvoltage (ΔV) is shown in Fig. 2.10. The volt-time characteristics of different electrical apparatus, which are very important in insulation co-ordination, are shown in Fig. 2.11. It can be seen from the Fig. 2.11 that a rod gap will protect a bushing, whereas a sphere gap is required for the complete protection of a transformer against high voltage surges (see also Chapter 8).

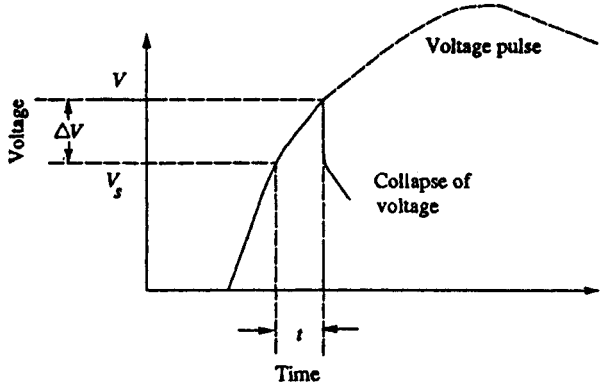


Fig. 2.9 Breakdown on the front of the applied impulse voltage wave

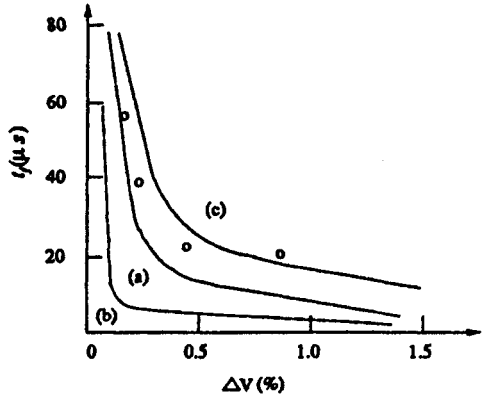


Fig. 2.10 Formative time lag (t_f) as a function of ΔV. *a*, *b*, *c* are for different gap spacings
0 experimental point, — calculated
ref: F. Llewellyn Jones, ionization and breakdown in gases, Methuen, London (1957)

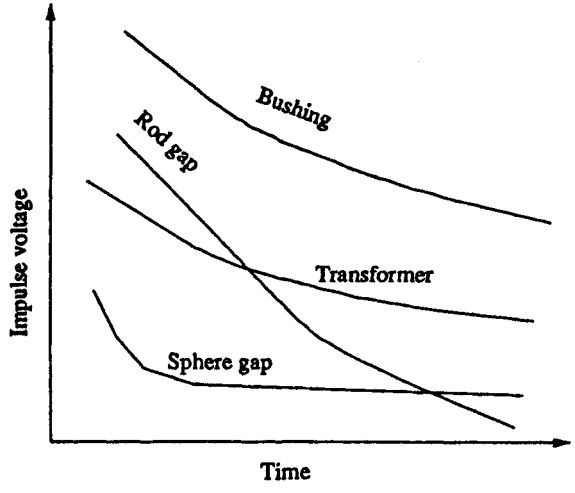


Fig. 2.11 Impulse voltage-time to flashover characteristics

2.9 STREAMER THEORY OF BREAKDOWN IN GASES

Townsend mechanism when applied to breakdown at atmospheric pressure was found to have certain drawbacks. Firstly, according to the Townsend theory, current growth occurs as a result of ionization processes only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap. Secondly, the

mechanism predicts time lags of the order of 10^{-5}s, while in actual practice breakdown was observed to occur at very short times of the order of 10^{-8}s. Also, while the Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular. The Townsend mechanism failed to explain all these observed phenomena and as a result, around 1940, Raether and, Meek and Loeb independently proposed the Streamer theory.

The theories predict the development of a spark discharge directly from a single avalanche in which the space charge developed by the avalanche itself is said to transform the avalanche into a plasma streamer. Consider Fig. 2.12. A single electron starting at the cathode by ionization builds up an avalanche that crosses the gap. The electrons in the avalanche move very fast compared with the positive ions. By the time the electrons reach the anode the positive ions are virtually in their original positions and form a positive space charge at the anode. This enhances the field, and the secondary avalanches are formed from the few electrons produced due to photo-ionization in the space charge region. This occurs first near the anode where the space charge is maximum. This results in a further increase in the space charge. This process is very fast and the positive space charge extends to the cathode very rapidly resulting in the formation of a streamer. Comparatively narrow lumimous tracks occurring at breakdown at high pressures are called streamers. As soon as the streamer tip approaches the cathode, a cathode spot is formed and a stream of electrons rush from the cathode to neutralize the positive space charge in the streamer; the result is a spark, and the spark breakdown has occurred. The three successive stages in the development of the streamer are shown diagrammatically in Fig. 2.13 in which (*a*) shows the stage when avalanche has crossed the gap, (*b*) shows that the streamer has crossed half the gap length, and (*c*) shows that the gap has been bridged by a conducting channel.

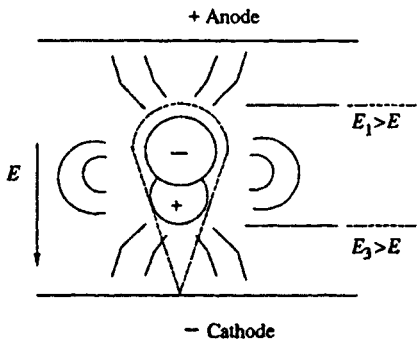


Fig. 2.12 Effect of space charge produced by an avalanche on the applied electric field

Meek proposed a simple quantitative criterion to estimate the electric field that transforms an avalanche into a streamer. The field E_r produced by the space charge, at the radius r, is given by

$$E_r = 5.27 \times 10^{-7} \frac{\alpha \exp(\alpha x)}{(x/p)^{1/2}} \text{ V/cm} \qquad (2.20)$$

where α is Townsend's first ionization coefficient, p is the gas pressure in torr, and x is the distance to which the streamer has extended in the gap. According to Meek, the minimum breakdown voltage is obtained when $E_r = E$ and $x = d$ in the above equation.

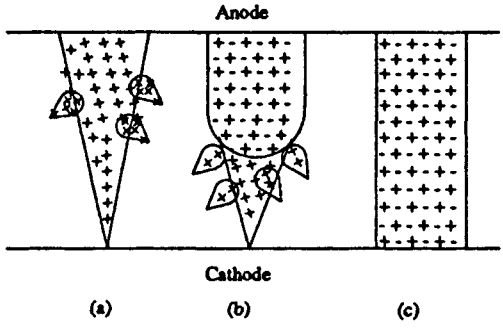


Fig. 2.13 Cathode directed streamer

The equation simplifies into,

$$\alpha d + \ln\left(\frac{\alpha}{p}\right) = 14.5 + \ln\left(\frac{E}{p}\right) + \frac{1}{2}\ln\left(\frac{d}{p}\right) \tag{2.21}$$

This equation is solved between α/p and E/p at which a given p and d satisfy the equation. The breakdown voltage is given by the corresponding product of E and d.

The above simple criterion enabled an agreement between the calculated and the measured breakdown voltages. This theory also neatly fits in with the observed filamentary, crooked channels and the branching of the spark channels, and cleared up many ambiguities of the Townsend mechanism when applied to breakdown in a high pressure gas across a long gap.

It is still controversial as to which mechanism operates in uniform field conditions over a given range of *pd* values. It is generally assumed that for *pd* values below 1000 torr-cm and gas pressures varying from 0.01 to 300 torr, the Townsend mechanism operates, while at higher pressures and *pd* values the Streamer mechanism plays the dominant role in explaining the breakdown phenomena. However, controversies still exist on these statements.

2.10 PASCHEN'S LAW

It has been shown earlier (refer Sec. 2.5) that the breakdown criterion in gases is given as

$$\gamma\,[\exp(\alpha d) - 1] = 1 \tag{2.22}$$

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

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

and

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

Also

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

Substituting for E in the expressions for α and γ and rewriting Eq. (2.18) we have

$$f_2\left(\frac{V}{pd}\right)\left[\exp\left\{pdf_1\left(\frac{V}{pd}\right)\right\} - 1\right] = 1 \tag{2.23}$$

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 Eq. (2.22) as,

$$V = f(pd) \tag{2.24}$$

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 Paschen's curve, the relationship between V and pd is shown in Fig. 2.14 for three gases CO_2, air and H_2. It is seen that the relationship between V and pd is not linear and has a minimum value for any gas. The minimum breakdown voltages for various gases are given in Table 2.1

Table 2.1 Minimum Sparking Potential For Various Gases

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

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

For values of $pd > (pd)_{min}$, electrons crossing the gap make more frequent collisions with gas molecules than at $(pd)_{min}$, but the energy gained between collisions is lower. Hence, to maintain the desired ionization more voltage has to be applied. For $pd < (pd)_{min}$, electron may cross the gap without even making a collision or making only less number of collisions. Hence, more voltage has to be applied for breakdown to occur.

However, in some gases Paschen's law is not strictly obeyed, and sparking potentials at larger spacings for a given value of pd are higher than at lower spacings for the same pd value. This is attributed to the loss of electrons from the gap due to diffusion.

The sparking potentials for uniform field gaps in air, CO_2 and H_2 at 20°C are shown in Fig. 2.14. It has been observed that the cathode materials also affect the breakdown values. This is shown in Fig. 2.15 for cathodes made of barium, magnesium and aluminium.

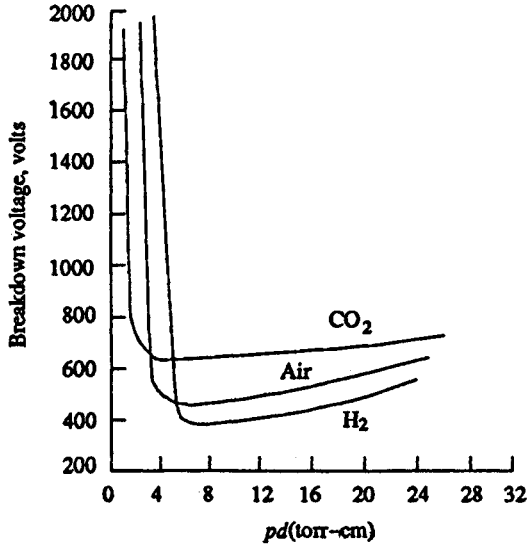


Fig. 2.14 Breakdown voltage-*pd* characteristics for air, CO_2 and hydrogen

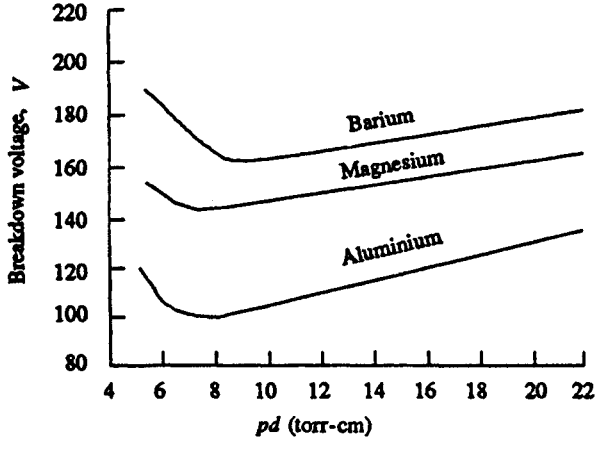


Fig. 2.15 Dependence of breakdown voltage on the cathode materials

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

$$V = 24.22\left[\frac{293\,pd}{760T}\right] + 6.08\left[\frac{293\,pd}{760T}\right]^{1/2} \tag{2.25}$$

It may be noted from the above formula that the breakdown voltage at constant pressure and temperature is not constant.

At 760 torr and 293°K.

$$E = V/d = 24.22 + \left[\frac{6.08}{\sqrt{d}}\right] \text{kV/cm} \tag{2.26}$$

This equation yields a limiting value for E of 24 kV/cm for long gaps and a value of 30 kV/cm for $\left(\frac{293pd}{760T}\right) = 1$, which means a pressure of 760 torr at 20°C with 1 cm gap. This is the usually quoted breakdown strength of air at room temperature and at atmospheric pressure.

2.11 BREAKDOWN IN NON-UNIFORM FIELDS AND CORONA DISCHARGES

2.11.1 Corona Discharges

If the electric field is uniform, a gradual increase in voltage across a gap produces a breakdown of the gap in the form of a spark without any preliminary discharges. On the other hand, if the field is non-uniform, an increase in voltage will first cause a discharge in the gas to appear at points with highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission lines. This form of discharge is called a corona discharge and can be observed as a bluish luminiscence. This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone. Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges. Corona also gives rise to radio interference.

The voltage gradient required to produce visual a.c. corona in air at a conductor surface, called the corona inception field, can be approximately given for the case of parallel wires of radius r as

$$E_v = 30md\left[1 + \frac{0.301}{\sqrt{dr}}\right] \tag{2.27}$$

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

$$E_c = 31md\left[1 + \frac{0.308}{\sqrt{dr}}\right] \tag{2.28}$$

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

$$d = \frac{0.392b}{(273 + t)} \tag{2.29}$$

where b is the atmospheric pressure in torr, and t is the temperature in °C, $d = 1$ at 760 torr and 25°C. The expressions were found to hold good from atmospheric pressure down to a pressure of several torr.

On the high voltage conductors at high pressures there is a distinct difference in the visual appearance of the corona under positive and negative polarities of the applied voltage. When the voltage is positive, corona appears as a uniform bluish white sheath over the entire surface of the conductor. On the other hand, when the voltage is negative, the corona will appear like reddish glowing spots distributed along the length of the wire. Investigations with point-plane gaps in air showed that when point is negative, corona appears as current pulses called Trichel pulses, and the repetition frequency of these pulses increases as the applied voltage is increased and decreases with decrease in pressure. On the other hand, observations when the point is positive in air showed that the corona current increases steadily with voltage. At sufficiently high voltage, current amplification increases rapidly with voltage, up to a current of about 10^{-7}A, after which the current becomes pulsed with repetition frequency of about 1 kHz composed of small bursts. This form of corona is called burst corona. The average current then increases steadily with applied voltage leading to breakdown.

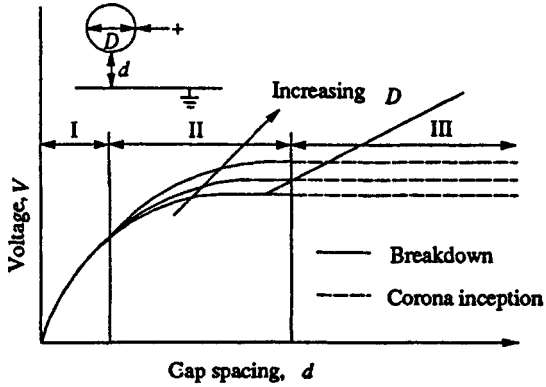


Fig. 2.16 Breakdown and corona inception characteristics for spheres of different diameters in sphere-plane gap geometry

The corona inception and breakdown voltages of the sphere-plane arrangement are shown in Fig. 2.16. From this figure it can be seen that

(*a*) at small spacings (region I), the field is uniform, and the breakdown voltage mainly depends on the spacing;

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

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

The actual breakdown characteristics of the sphere-plane gap in air is shown in Fig. 2.17. It may be summarized that the study of corona and non-uniform field breakdown is very complicated and investigations are still under progress.

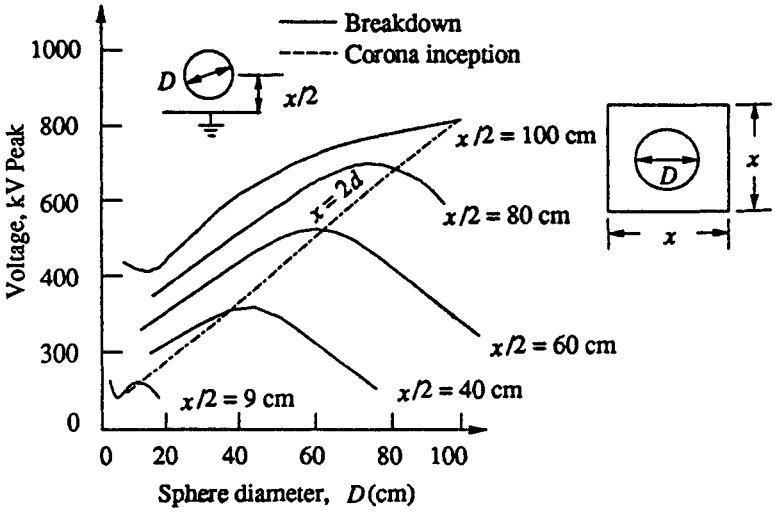


Fig. 2.17 Breakdown and corona inception characteristics of sphere-plane geometry in air, x is the fixed overall dimension of a system as shown

ref: B.L. Goodlet, F.S. Edwards and F.R. Perry, Journal of the Institution of Electrical Engineers; vol. 69, 695 (1931)

2.11.2 Breakdown in Non-uniform Fields

In non-uniform fields, such as coaxial cylinders, point-plane and sphere-plane gaps, the applied field varies across the gap. Similarly, Townsend's first ionization coefficient (α) also varies with the gap. Hence αd in Townsend's criterion [refer to Eq. (2.14)] is rewritten by replacing αd by $\int_0^d \alpha\, dx$. Townsend's criterion for breakdown now becomes

$$\gamma\left\{\exp\left[\int_0^d \alpha dx\right] - 1\right\} = 1 \qquad (2.30)$$

Meek and Raether also discussed the non-uniform field breakdown process as applied to their Streamer theory, and the Meek's equation [Eq. (2.19)] for the radial field at the head of an avalanche when it has crossed a distance x is modified as

$$E_r = \frac{5.27 \times 10^{-7} \alpha_x \exp\left(\int_0^x \alpha dx\right)}{(x/p)^{1/2}} \text{ V/cm} \qquad (2.31)$$

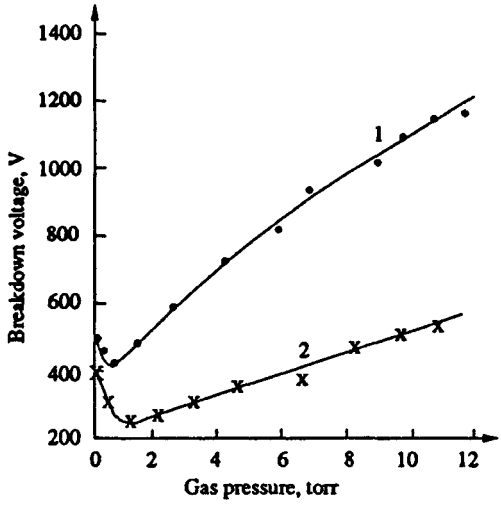


Fig. 2.18 Breakdown characteristics for nitrogen between a wire and a coaxial cylinder of radii 0.083 and 2.3 cm. 1-wire positive, 2-wire negative

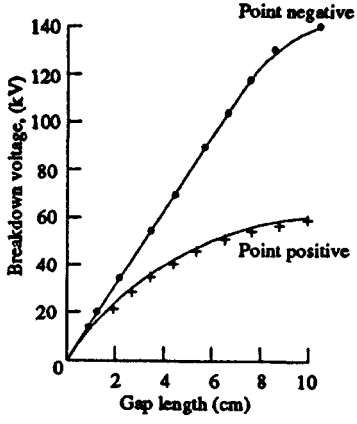


Fig. 2.19 d.c. breakdown characteristics for air between 30° conical point and a plane

where α_x is the value of α at the head of the avalanche, and p is the gas pressure. The criterion for the formation of the streamer is reached when the space charge field E_r approaches a value equal to the applied field at the head of the avalanche.

This equation has been successfully used for determining the corona onset voltages of many non-uniform geometries. However, the condition for the advancement of streamers has not been arrived at so far. Figures 2.18 and 2.19 show the d.c. breakdown characteristics for a wire-coaxial cylinder geometry in nitrogen and for a point-plane geometry in air, respectively.

From the practical engineering point of view, rod-rod gap and sphere-sphere gap are of great importance, as they are used for the measurement of high voltages and for the protection of electrical apparatus such as transformers. The breakdown characteristics of rod-rod gaps are shown n Fig. 2.20. From this figure it can be seen that the breakdown voltages are higher for negative polarity. The breakdown voltages were also observed to depend on humidity in air. In the case of rod gaps the field is non-uniform, while in the case of sphere gaps field is uniform, if the gap is small compared with the diameter. In the case of sphere gaps, the breakdown voltages do not depend on humidity and are also independent of the voltage waveform. The formative time lag is quite small (~ 0.5 μ s) even with 5% over voltage. Hence sphere gaps are used for breakdown voltage (peak value) measurements. These are further discussed in Chapter 7 (Sec. 7.2.6).

2.12 POST-BREAKDOWN PHENOMENA AND APPLICATIONS

This is the phenomenon which occurs after the actual breakdown has taken place and is of technical importance. Glow and arc discharges are the post-breakdown phenomena, and there are many devices that operate over these regions. In a Townsend discharge (see Fig. 2.21) the current increases gradually as a function of the applied voltage. Further to this point (B) only the current increases, and the discharge changes from the Townsend type to Glow type (BC). Further increase in current results in a very small reduction in voltage across the gap (CD) corresponding to the normal glow region. The gap voltage again increases (DE), when the current is increased more, but eventually leads to a considerable drop in the applied voltage. This is the region of the arc discharge (EG). The phenomena that occur in the region CG are the post-breakdown phenomena consisting of glow discharge (CE) and the arc discharge (EG):

Glow Discharge

A glow discharge is characterized by a diffused luminous glow. The colour of the glow discharge depends on the cathode material and the gas used. The glow discharge covers the cathode partly and the space between the cathode, and the anode will have intermediate dark and bright regions. This is called normal glow. If the current in the normal glow is increased such that the discharge covers the entire cathode surface, then it becomes abnormal glow. In a glow discharge, the voltage drop between the electrodes is substantially constant, ranging from 75 to 300 V over a current range of 1 mA to 100 mA depending on the type of the gas. The properties of the glow discharge are used in many practical applications, such as cold cathode gaseous voltage stabilized tubes (voltage regulation tubes or VR tubes), for rectification, as a relaxation oscillator, and as an amplifier.

Arc Discharge

If the current in the gap is increased to about 1 A or more, the voltage across the gap suddenly reduces to a few volts (20-50 V). The discharge becomes very luminous and noisy (region EG in Fig. 2.21). This phase is called the arc discharge and the current

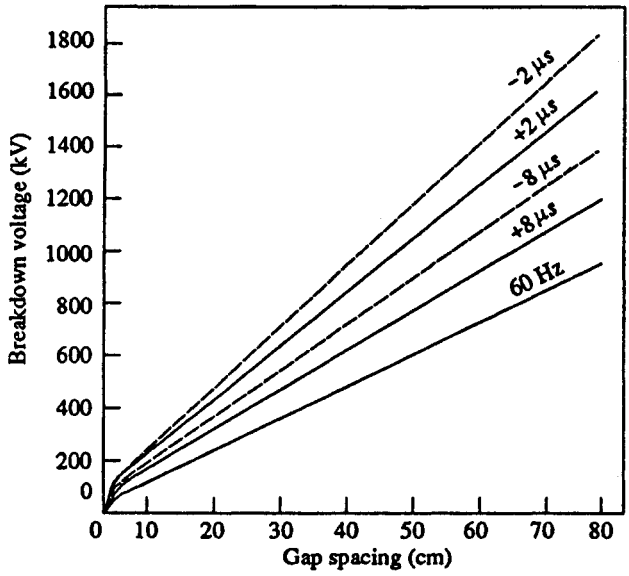


Fig. 2.20 Power frequency (60 Hz) and impulse breakdown voltage curves for a rod-rod gap in air at n.t.p. One rod is earthed. Absolute humidity is 6.5 gms/ft^2. impulse breakdown curves are for various times of breakdown on the wave tail
ref.: B.S.S. 171: 1959, power transformers

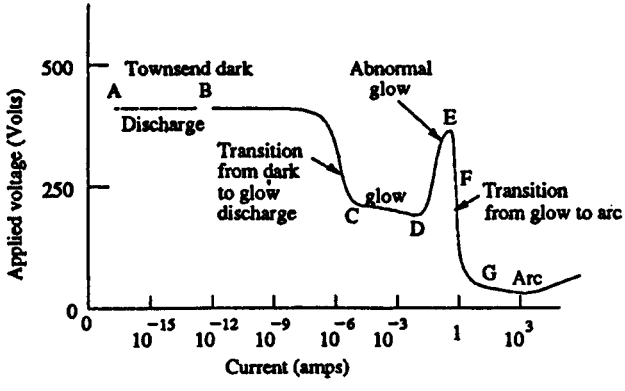


Fig. 2.21 d.c. voltage-current characteristic of an electrical discharge with electrodes having no sharp points or edges

density over the cathode region increases to very high values of 10^3 to 10^7 A/cm^2. Arcing is associated with high temperatures, ranging from 1000°C to several thousand degrees celsius. The discharge will contain a very high density of electrons and positive ions, called the arc plasma. The study of arcs is important in circuit breakers

and other switch contacts. It is a convenient high temperature high intensity light source. It is used for welding and cutting of metals. It is the light source in lamps such as carbon arc lamp. High temperature plasmas are used for generation of electricity through magneto-hydro dynamic (MHD) or nuclear fusion processes.

2.13 PRACTICAL CONSIDERATIONS IN USING GASES FOR INSULATION PURPOSES

In recent years, considerable amount of work has been done to adopt a specific gas for practical use. Before adopting a particular gas for a practical purpose, it is useful to gain a knowledge of what the gas does, what its composition is, and what the factors that influence its performance are. The greater the versatility of the operating performance demanded from an insulating gas, the more rigorous would be the requirements which the gas should meet. These requirements needed by a good dielectric gas do not exist in a majority of the gases. Generally, the preferred properties of a gaseous dielectric for high voltage applications are:

(*a*) high dielectric strength,
(*b*) thermal stability and chemical inactivity towards materials of construction,
(*c*) non-flammability and physiological intertness,
(*d*) low temperature of condensation,

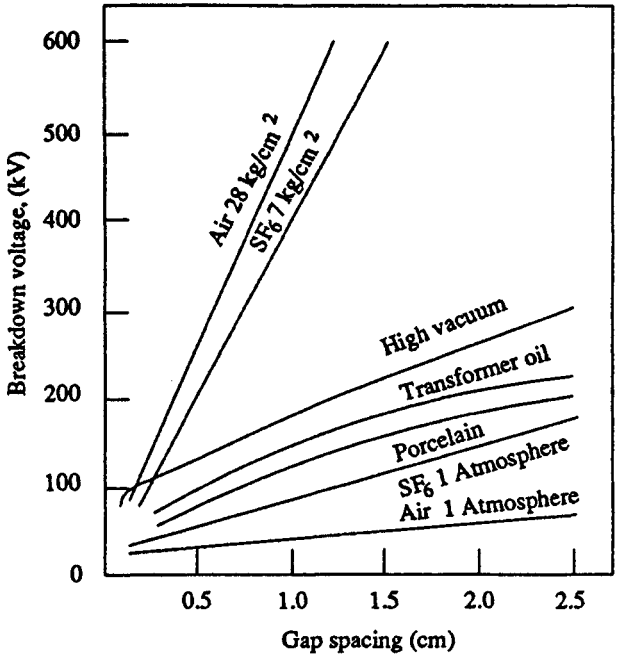


Fig. 2.22 d.c. breakdown strength of typical solid, liquid, gas and vacuum insulations in uniform fields

Table 2.2 Properties of Insulating Gases

Name of the gas	Formula	Molecular weight	Melting point at 760 torr °C	Boiling point at 760 torr °C	Relative dielectric strength ($N_2 = 1$)	Dielectric constant	Specific gravity (Air = 1)	Flammability	Toxicity
Air	—	29	—	−194	1	1.00059	1.00000	No	Physio-inert
Nitrogen	N_2	28	−210	−196	1	1.00058	0.96724	No	-do-
Hydrogen	H_3	2	−259	−253	—	1.00026	0.06952	Yes	-do-
Carbon tetrafluoride	CF_4	88	−183	−128	1.01	1.00050	—	No	-do-
Hexafluoro-ethane	C_2F_6	138	−101	−78	2.02	1.00200	—	No	-do-
Perfluoro-propane	C_3F_8	188	−160	−37	2.2	—	—	No	-do-
Perfluoro-butane	C_4F_{10}	238	−80	−2	2.6	—	—	No	-do-
Perfluoro-n-butane	C_4F_8	200		+2	3.6	1.00340	7.3323	No	-do-
Sulphur hexafluoride	SF_6	146		−63	2.5	1.00191	5.1900	No	-do-
30% SF_6 + 70% Air (Vol.) (Vol.)					2.0			No	-do-
Freon-12	CCl_2F_2	121	−158	−30	2.46	1.00160	—	No	P*

*P: Physio-inert for durations of 2 hr or less with 20% concentration.

Table 2.3

Set 1:									
Gap distance (mm)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
Applied voltage V (volts)	1000	2000	3000	4000	5000	6000	7000	8000	10000
Observed current I (A)	10^{-13}	3×10^{-13}	6×10^{-13}	10^{-12}	4×10^{-12}	10^{-11}	10^{-10}	10^{-9}	5×10^{-9}
Set 2:									
V (volts)	500	.1000	1500	2000	2500	3000	3500	4000	4500
I (A)	5×10^{-14}	1.5×10^{-13}	3×10^{-13}	6×10^{-13}	10^{-12}	5×10^{-12}	5×10^{-11}	3×10^{-10}	10^{-8}

The minimum current observed when 150 V was applied was 5×10^{-14} A.

Table 2.4

Gap (mm)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
I/I_0 for $E_1 = 20$ k V/cm	2	6	12	20	80	200	2×10^3	2×10^4	5×10^7
log I/I_0	0.3010	0.7181	1.0792	1.3010	1.9031	2.3010	3.3010	4.3010	7.6990
I/I_0 for $E_2 = 10$ k V/cm	1	3	6	12	20	100	1000	6000	2×10^5
log I/I_0	0	0.4771	0.7781	1.0792	1.3010	2.0	3.0	3.7781	5.3010

(*e*) good heat transfer, and
(*f*) ready availability at moderate cost.

Sulphur hexafluoride (SF_6) which has received much study in recent years has been found to possess most of the above requirements.

Of the above properties, dielectric strength is the most important property of a gaseous dielectric for practical use. The dielectric strength of gases is comparable with those of solid and liquid dielectrics (see Fig. 2.22). In recent years, the dielectric properties of many complex chlorinated and flourinated molecular compounds have also been studied. These are shown in Fig. 2.23. This feature of high dielectric strength of gases is attributed to the molecular complexity and the high rates of electron attachment (see Sec. 2.7). The relative dielectric strengths and the chemical and physical properties of some of the commercially important gases are shown in Table 2.2.

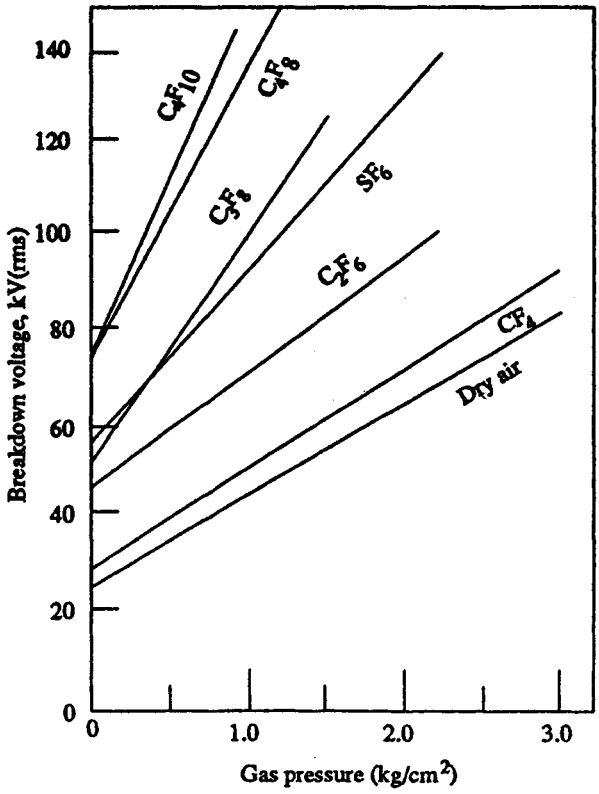


Fig. 2.23 Breakdown strength of insulating gases for 75 cm diameter uniform field electrodes having 12 mm gap

From the figures and the table, it can be seen that SF_6 has high dielectric strength and low liquification temperature, and it can be used over a wide range of operating conditions. SF_6 was also found to have excellent arc-quenching properties. Therefore, it is widely used as an insulating as well as arc-quenching medium in high voltage

QUESTIONS

Q.2.1 Explain the difference between photo-ionisation and photo-electric emission.

Q.2.2 Explain the term "electron attachment". Why are electron attaching gases useful for practical use as insultants when compared to non-attaching gases.

Q.2.3 Describe the current growth phenomenon in a gas subjected to uniform electric fields.

Q.2.4 Explain the experimental set-up for the measurement of pre-breakdown currents in a gas.

Q.2.5 Define Townsend's first and second ionization coefficients. How is the condition for breakdown obtained in a Townsend discharge?

Q.2.6 What are electronegative gases? Why is the breakdown strength higher in these gases compared to that in other gases?

Q.2.7 Derive the criterion for breakdown in electronegative gases.

Q.2.8 Explain the Streamer theory of breakdown in air at atmospheric pressure.

Q.2.9 What are the anode and the cathode streamers? Explain the mechanism of their formation and development leading to breakdown.

Q.2.10 What is Paschen's law? How do you account for the minimum voltage for breakdown under a given '$p \times d$' condition?

Q.2.11 Describe the various factors that influence breakdown in a gas.
Q.2.12 What is vacuum? How is it categorised? What is the usual range of vacuum used in high voltage apparatus?
Q.2.13 Describe how vacuum breakdown is different from normal breakdown of a gas.
Q.2.14 Discuss the various mechanisms of vacuum breakdown.

WORKED EXAMPLES

Example 2.1 : Table 2.3 gives the sets of observations obtained while studying the Townsend phenomenon in a gas. Compute the values of the Townsend's primary and secondary ionization coefficients from the data given.

Solution: The current at minimum applied voltage, I_0, is taken as 5×10^{-14} A, and the graph of d versus log I/I_0 is plotted as shown in Fig. E.2.1. The values of log I/I_0 versus d for two values of electric field, $E_1 = 20$ kV/cm and $E_2 = 10$ kV/cm are given in Table 2.4.

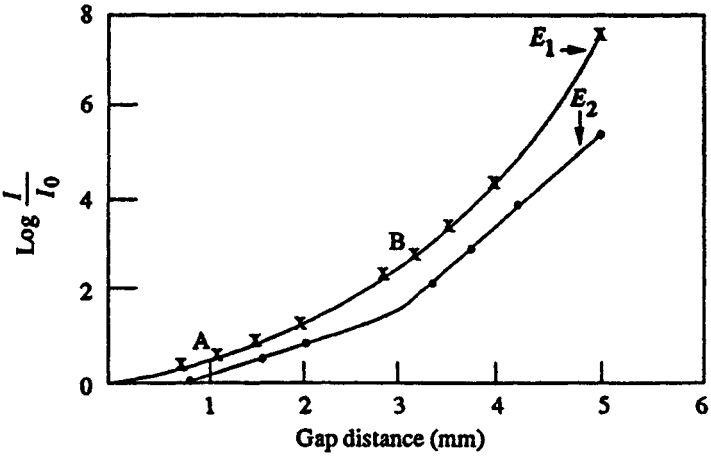


Fig. E.2.1 Log I/I_0 as a function of gap distance

Value of α at E_1 (= 20 kV/cm) i.e. α_2 = slope of curve E_1

$$= \frac{2.9}{2.5 \times 10^{-1}}$$

$$= 11.6 \text{ cm}^{-1} \text{ torr}^{-1}$$

Value of α at E_2 (= 10 kV/cm) i.e. α_1 = slope of curve E_2

$$= \frac{13}{2 \times 10^{-1}}$$

$$= 6.5 \text{ cm}^{-1} \text{ torr}^{-1}$$

As the sparking potential and the critical gap distance are not known, the last observations will be made use in determining the values of γ.

For a gap distance of 5 mm, at $E_1 = 20$ kV/cm,

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

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

Substituting $\alpha_1 = 11.6$, $d = 0.5$ cm, and $I/I_0 = 5 \times 10^7$

$$5 \times 10^7 = \frac{\exp(5.8)}{1 - \gamma[\exp(5.8) - 1]}$$

$$= \frac{330.3}{1 - \gamma(330.3 - 1)}$$

or $\gamma = 3.0367 \quad 10^{-3}$/cm . torr, at $E_1 = 20$ kV/cm

(Check this value with other observations also.)

For $E_2 = 10$ kV/cm

$\alpha_2 = 6.5$/cm . torr

$d = 0.5$ cm

and $I/I_0 = 2 \times 10^5$

Substituting these values in the same equation,

$$2 \times 10^5 = \frac{\exp(3.25}{1\gamma[\exp(3.25) - 1]}$$

$$= \frac{25.79}{1 - \gamma(25.79 - 1)}$$

or, $\gamma = 4.03 \times 10^{-2}$/cm . torr, at $E_2 = 10$ kV/cm

Example 2.2 : A glow discharge tube is to be designed such that the breakdown occurs at the Paschen minimum voltage. Making use of Fig. 2.14 suggest the suitable gap distance and pressure in glow discharge tube when the gas in it is *(a)* hydrogen, *(b)* air.

Solution : In the case of hydrogen, the Paschen minimum voltage occurs at a *pd* (product of pressure and gap spacing) of 7.5 torr-cm, and in the case of air the corresponding value of *pd* is 4.5 torr-cm (see Fig. 2.14).

Since the usual gap distance used for glow discharge tubes of smaller sizes is about 3 mm, the gas pressure used in case of hydrogen will be

$$\frac{7.5}{0.3} = 25 \text{ torr}$$

and in the case of air it will be $\frac{4.5}{0.3} = 15$ torr.

Example 2.3 : What will the breakdown strength of air be for small gaps (1 mm) and large gaps (20 cm) under uniform field conditions and standard atmospheric conditions?

Solution : The breakdown strength of air under uniform field conditions and standard atmospheric conditions is approximately given by

$$E = \frac{V}{d} = \left(24.22 + \frac{6.08}{d^{1/2}}\right) \text{kV/cm}$$

Substituting for 1 mm gap,

$$E = 24.22 + \frac{6.08}{(0.1)^{1/2}} = 43.45 \text{ kV/cm}$$

for 20 cm gap,

$$E = 24.22 + \frac{6.08}{(20.1)^{1/2}} = 25.58 \text{ kV/cm}$$

Example 2.4 : In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8} A at 8 kV at a distance of 0.4 cm between the plane electrodes. Keeping the field constant and reducing the distance to 0.1 cm results in a current of 5.5×10^{-9}A. Calculate Townsend's primary ionization coefficient α.

Solution: The current at the anode I is given by

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

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

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

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

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

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

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

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

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3

Conduction and Breakdown in Liquid Dielectrics

3.1 LIQUIDS AS INSULATORS

Liquid dielectrics, because of their inherent properties, appear as though they would be more useful as insulating materials than either solids or gases. This is because both liquids and solids are usually 10^3 times denser than gases and hence, from Paschen's law it should follow that they possess much higher dielectric strength of the order of 10^7 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 impregnants in high voltage cables and capacitors, and for filling up of transformers, circuit breakers etc. Liquid dielectrics also act as heat transfer agents in transformers and as arc quenching media in circuit breakers. Petroleum oils (Transformer oil) are the most commonly used liquid dielectrics. Synthetic hydrocarbons and halogenated hydrocarbons are also used for certain applications. For very high temperature application, silicone oils and fluorinated hydrocarbons are also employed. In recent times, certain vegetable oils and esters are also being tried. However, it may be mentioned that some of the isomers of poly-chlorinated diphenyls (generally called askerels) have been found to be very toxic and poisonous, and hence, their use has been almost stopped. In recent years, a synthetic ester fluid with the trade name 'Midel' has been developed as a replacement for askerels.

Liquid dielectrics normally are mixtures of hydrocarbons and are weakly polarised. When used for electrical insulation purposes they should be free from moisture, products of oxidation and other contaminants. The most important factor that affects the electrical strength of an insulating oil is the presence of water in the form of fine droplets suspended in the oil. The presence of even 0.01% water in transformer oil reduces its electrical strength to 20% of the dry oil value. The dielectric strength of oil reduces more sharply, if it contains fibrous impurities in addition to water. Table 3.1 shows the properties of some dielectrics commonly used in electrical equipment.

Table 3.1 Dielectric Properties of Some Liquid Dielectrics

Property	Transformer oil	Cable oil	Capacitor oil	Askerels	Silicone oils
Breakdown strength at 20°C on 2.5 mm standard sphere gap	15 kV/mm	30 kV/mm	20 kV/mm	20-25 kV/mm	30-40 kV/mm
Relative permittivity (50 Hz)	2.2-2.3	2.3-2.6	2.1	4.8	2-73
Tan δ (50 Hz)	0.001	0.002	0.25×10^{-3}	0.60×10^{-3}	10^{-3}
(1 kHz)	0.0005	0.0001	0.10×10^{-3}	0.50×10^{-3}	10^{-4}
Resistivity (ohm-cm)	10^{12}-10^{13}	10^{12}-10^{13}	10^{13}-10^{14}	2×10^{12}	3×10^{14}
Specific gravity at 20°C	0.89	0.93	0.88-0.89	1.4	1.0-1.1
Viscosity at 20°C (CS)	30	30	30	100-150	10-1000
Acid value (mg/gm of KOH)	Nil	Nil	Nil	Nil	Nil
Refractive index	1.4820	1.4700	1.4740	1.6000	1.5000-1.6000
Saponification (mg of KOH/gm of oil)	0.01	0.01	0.01	< 0.01	< 0.01
Expansion (20 – 100°C)	7×10^{-4}/°C	7×10^{-4}/°C	7×10^{-4}/°C	7×10^{-1}/°C	5×10^{-4}/°C
Maximum permissible water content (in ppm)	50	50	50	< 30 (negligible)	< 30 (negligible)

Of the insulating liquids shown in table 3.1, transformer oils are the cheapest and the most commonly used. The electrical properties of transformer oil are given in the above table. Oils used in the capacitors are similar to transformer oil but they are subjected to a very high degree of purification. Various kinds of oils are used in cables as impregnants for paper insulation and to improve their heat transfer capability. Table 3.1 gives the dielectric properties of various liquid dielectrics used in cables, capacitors and in other special applications.

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

3.1.1 Transformer Oil

As already mentioned, transformer oil is the most commonly used liquid dielectric in power apparatus. It is an almost colourless liquid consisting a mixture of hydrocarbons which include paraffins, iso-paraffins, naphthalenes and aromatics. When in service, the liquid in a transformer is subjected to prolonged heating at high temperatures of about 95°C, and consequently it undergoes a gradual ageing process. With time the oil becomes darker due to the formation of acids and resins, or sludge in the liquid. Some of the acids are corrosive to the solid insulating materials and metal parts in the transformer. Deposits of sludge on the transformer core, on the coils and inside the oil ducts reduce circulation of oil and thus its heat transfer capability gets considerably reduced. Complete specifications for the testing of transformer oils are given in IS 1866 (1983), IEC 296 (1969) and IEC 474 (1974).

3.1.2 Electrical Properties

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

(*a*) its capacitance per unit volume or its relative permittivity
(*b*) its resistivity
(*c*) its loss tangent (tan δ) or its power factor which is an indication of the power loss under a.c. voltage application
(*d*) its ability to withstand high electric stresses.

Permittivities of most of the petroleum oils vary from 2.0 to 2.6 while those of askerels vary between 4.5 and 5.0 and those of silicone oils from 2.0 to 73 (see Table 3.1). In case of the non-polar liquids, the permittivity is independent of frequency but in the case of polar liquids, such as water, it changes with frequency. For example, the permittivity of water is 78 at 50 Hz and reduces to about 5.0 at 1 MHz.

Resistivities of insulating liquids used for high voltage applications should be more than 10^{16} ohm-metre and most of the liquids in their pure state exhibit this property.

Power Factor of a liquid dielectric under a.c. voltage will determine its performance under load conditions. Power factor is a measure of the power loss and is an important parameter in cable and capacitor systems. However, in the case of transformers, the dielectric loss in the oil is negligible when compared to copper and iron

losses. Pure and dry transformer oil will have a very low power factor varying between 10^{-4} at 20°C and 10^{-3} at 90°C at a frequency of 50 Hz.

Dielectric Strength is the most important parameter in the choice of a given liquid dielectric for a given application. The dielectric strength depends on the atomic and molecular properties of the liquid itself. However, under practical conditions the dielectric strength depends on the material of the electrodes, temperature, type of applied voltage, gas content in the liquid etc., which change the dielectric strength by changing the molecular properties of the liquid. The above factors which control the breakdown strength and lead to electrical breakdown of the liquid dielectrics are discussed in subsequent sections.

3.2 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 10^9, and are structurally simple. Examples of such simple pure liquids are *n*-hexane (C_6H_{14}), *n*-heptane (C_7H_{16}) and other paraffin hydrocarbons. By using simple and pure liquids, it is easier to separate out the various factors that influence conduction and breakdown in them. On the other hand, the commercial 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.

3.2.1 Purification

The main impurities in liquid dielectrics are dust, moisture, dissolved gases and ionic impurities. Various methods employed for purification are filtration (through mechanical filters, spray filters, and electrostatic filters), centrifuging, degassing and distillation, and chemical treatment (adding ion exchange materials such as alumina, fuller's earth, etc. and filtering). Dust particles when present become charged and reduce the breakdown strength of the liquid dielectrics, and they can be removed by careful filtration. Liquid will normally contain moisture and dissolved gases in small quantities. Gases like oxygen and carbon dioxide significantly affect the breakdown strength of the liquids, and hence it is necessary to control the amount of gas present. This is done by distillation and degassing. Ionic impurity in liquids, like water vapour which easily dissociates, leads to very high conductivity and heating of the liquid depending on the applied electric field. Water is removed using drying agents or by vacuum drying. Sometimes, liquids are shaken with concentrated sulphuric acid to remove wax and residue and washed with caustic soda and distilled water. A commonly used closed-cycle liquid purification system to prepare liquids as per the above requirements is shown in Fig. 3.1. This system provides for cycling the liquid. The liquid from the reservoir flows through the distillation column where ionic impurities are removed. Water is removed by drying agents or frozen out in the low-temperature bath. The gases dissolved in the liquid are removed by passing them through the cooling tower and/or pumped out by the vacuum pumps. The liquid then passes through the filter where dust particles are removed. The liquid thus purified is then

used in the test cell. The used liquid then flows back into the reservior. The vacuum system thus helps to remove the moisture and other gaseous impurities.

3.2.2 Breakdown Tests

Breakdown tests are normally conducted using test cells. For testing pure liquids, the test cells used are small so that less quantity of liquid is used during testing. Also, test cells are usually an integral part of the purification system as shown in Fig. 3.1. The electrodes used for breakdown voltage measurements are usually spheres of 0.5 to 1 cm in diameter with gap spacings of about 100-200 μm. The gap is accurately controlled by using a micrometer. Sometimes parallel plane uniform-field electrode systems are also used. Electrode separation is very critical in measurements with liquids, and also the electrode surface smoothness and the presence of oxide films have a marked influence on the breakdown strength. The test voltages required for these tests are usually low, of the order of 50-100 kV, because of small electrode spacings. The breakdown strengths and d.c. conductivities obtained in pure liquids are very high, of the order of 1 MV/cm and 10^{-18} - 10^{-20} mho/cm respectively, the conductivity being measured at electric fields of the order of 1 kV/cm. However, the corresponding values in commercial liquids are relatively low, as can be seen from Table 3.1.

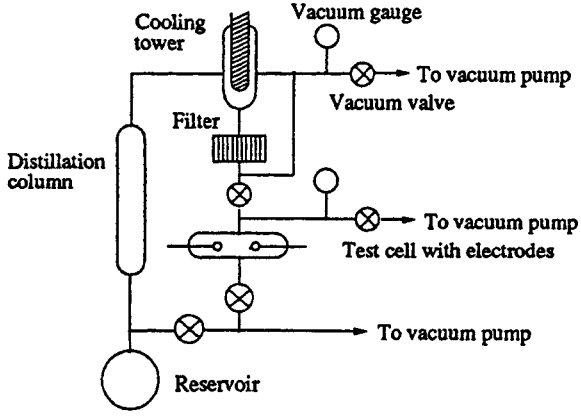


Fig. 3.1 Liquid purification system with test cell

3.3 CONDUCTION AND 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 some time. A typical mean value of the conduction current in hexane is shown in Fig. 3.2.

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. 3.3, can be obtained. This curve will have three distinct regions as shown. At very low fields the current is due to the dissociation of ions. With intermediate fields ithe 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 (see Chapter 2). The current multiplication also occurs from the electrons generated at the interfaces of liquid and impurities. The increase in current by these processes continues till breakdown occurs.

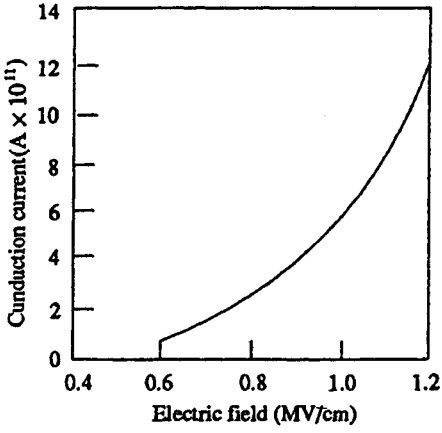


Fig. 3.2 Conduction current-electric field characteristic in hexane at high fields

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 so liberated get multiplied by a process similar to Townsend's primary and secondary ionization in gases (see Chapter 2, Secs. 2.2, 2.3, 2.4). As the breakdown field is approached, the current increases rapidly due to a process similar to the primary ionization process and also the positive ions reaching the cathode generate secondary electrons, leading to breakdown. 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. Typical maximum

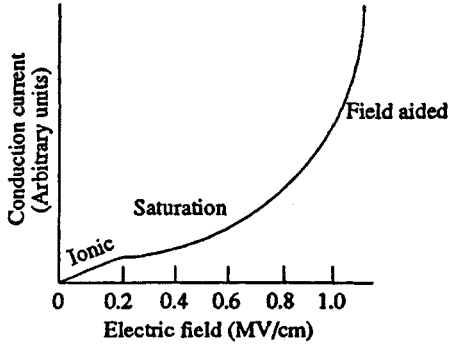


Fig. 3.3 Conduction current-electric field characteristic in a hydrocarbon liquid

breakdown strengths of some highly purified liquids and liquefied gases are given in Table 3.2.

Table 3.2 Maximum Breakdown Strengths of Some Liquids

Liquid	Maximum breakdown strength (MV/cm)
Hexane	1.1-1.3
Benzene	1.1
Transformer oil	1.0
Silicone	1.0-1.2
Liquid Oxygen	2.4
Liquid Nitrogen	1.6-1.9
Liquid Hydrogen	1.0
Liquid Helium	0.7
Liquid Argon	1.10-1.42

It has been observed that the increase in breakdown strength is more, if the dissolved gases are electronegative in character (like oxygen).
Similarly, the increase in the liquid hydrostatic pressure increases the breakdown strength. These properties are shown in Figs. 3.4 and 3.5.

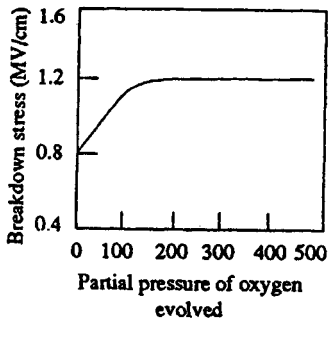


Fig. 3.4 Effect of oxygen gas evolved on the breakdown stress in *n*-hexane.

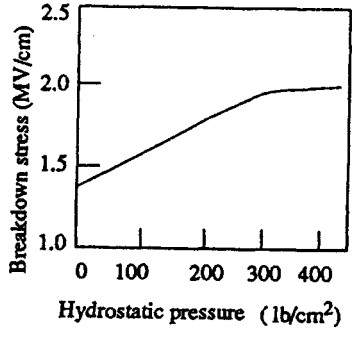


Fig. 3.5 Effect of hydrostatic pressure on breakdown stress in *n*-hexane

To sum up, this type of breakdown process in pure liquids, called the electronic breakdown, involves emission of electrons at fields greater than 100 kV/cm. This emission occurs either at the electrode surface irregularities or at the interfaces of impurities and the liquid. These electrons get further multiplied by Townsend's type of primary and secondary ionisation processes, leading to breakdown.

3.4 CONDUCTION AND BREAKDOWN IN COMMERCIAL LIQUIDS

As already mentioned, commercial insulating liquids are not chemically pure and have impurities like gas bubbles, suspended particles, etc. These impurities reduce the breakdown strength of these liquids considerably. 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.

The breakdown mechanism in commercial liquids is dependent, as seen above, on several factors, such as, the nature and condition of the electrodes, the physical properties of the liquid, and the impurities and gases present in 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.

3.4.1 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 (ε_2) will be different from the permittivity of the liquid (ε_1). If we consider these impurtities to be spherical particles of radius r, and if the applied field is E, then the particles experience a force F, where

$$F = \frac{1}{2r^3} \frac{(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2} \text{ grad } E^2 \tag{3.1}$$

This force is directed towards areas of maximum stress, if $\varepsilon_2 > \varepsilon_1$, 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. $\varepsilon_2 < \varepsilon_1$, 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 are large, they becomes aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

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

The vales of the breakdown strength of liquids containing solid impurities was found to be much less than the vlaues for pure liquids. The impurity particles reduce the breakdown strength, and it was also observed that the larger the size of the particles the lower were the breakdown strengths.

3.4.2 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:

(*a*) Gas pockets at the surfaces of the electrodes;
(*b*) electrostatic repulsive forces between space charges which may be sufficient to overcome the surface tension;
(*c*) gaseous products due to the dissociation of liquid molecules by electron collisions; and
(*d*) vapourization of the liquid by corona type discharge from sharp points and irregularities on the electrode surfaces.

Once a bubble is formed it will elongate in the direction of the electric field under the influence of electrostatic forces. 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 (see Chapter 2, Sec. 2.10) for the gas in the bubble. The breakdown field is given as

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r}\left\{\frac{\pi}{4}\sqrt{\left(\frac{V_b}{2rE_0}\right)} - 1\right\}\right]^{\frac{1}{2}} \tag{3.2}$$

where σ is the surface tension of the liquid, ε_1 is the permittivity of the liquid, ε_2 is the permittivity of the gas bubble, r is the initial radius of the bubble assumed as a sphere and V_b is the voltage drop in the bubble (corresponding to minimum on the Paschen's curve). From this equation, it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid.

This theory does not take into account the production of the initial bubble and hence the results given by this theory do not agree well with the experimental results. This is shown in Fig. 3.6.

Later this theory was modified, and it was suggested that only incompressible bubbles like water globules can elongate at constant volume, according to the simple gas law $pv = RT$. Under the influence of the applied electric field the shape of the globule is assumed to be approximately a prolate spheroid. The incompressible bubbles reach the condition of instability when β, the ratio of the longer to the shorter diameter of the spheriod, is about 1.85, and the critical field producing the instability will be:

$$E_c = 600\sqrt{\frac{\pi\sigma}{\varepsilon_1 R}}\left[\frac{\varepsilon_1}{\varepsilon_1 - \varepsilon_2} - G\right]H \tag{3.3}$$

where σ = surface tension,
R = initial radius of the bubble,
ε_1 = permittivity of the liquid dielectric,

ε_2 = permittivity of the globule,

$$G = \frac{1}{\beta^2 - 1}\left[\frac{\beta \cosh^{-1}\beta}{(\beta^2-1)^{1/2}} - 1\right]$$

and $$H^2 = 2\beta\frac{1}{3}\left(2\beta - 1 - \frac{1}{\beta^2}\right)$$

For a water globule having R = 1 μm with σ = 43 dyne/cm and ε_1 = 2.0 (transformer oil), the above equation gives a critical field E_c = 226 kV/cm which is approximately the maximum strength obtained for commercial oils.

In the case of gas bubbles the equation for the critical field is rewritten as

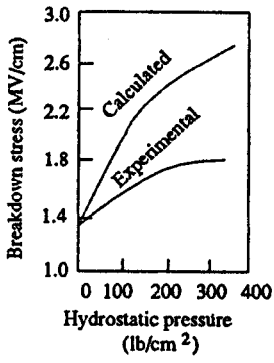


Fig. 3.6 Theoretical and experimental breakdown stresses in *n*-hexane

$$E_c = 600\left[\frac{\pi\sigma}{\varepsilon_1 R}\right]^{1/2}\left[\frac{\varepsilon_1}{\varepsilon_1 - \varepsilon_2} - G\right]\left[\frac{8A^2B}{3\beta(\varepsilon_1 - \varepsilon_2)}\right]^{1/4}(\cosh\theta)^{1/2} \qquad (3.4)$$

where,
$$A = \frac{2}{\beta} - 1 - \frac{1}{\beta^2}$$

$$B = 2\varepsilon_1\beta^3 - \varepsilon_2(1 - \beta^2)$$

G, σ and R are as above for liquid globules, and

$$\theta = \frac{1}{3}\cosh^{-1}\left[\frac{PR}{\sigma}\left\{\frac{27\beta^5(\varepsilon_1 - \varepsilon_2)^3}{2B^3}\right\}^{1/2}\right]$$

where P is the hydrostatic pressure (Equations 3.2-3.4 are in c.g.s. units). The expressions are quite complicated, and the breakdown voltages were obtained using a computer. Results thus obtained showed good agreement with the experimental results in *n*-hexane. This theory suggests that sub-microscopic particles (diameter 100-250 Å) and bubbles greatly influence the maximum electrical strength attainable in commercial liquids.

This theory can also be extended to the study of pure liquids. The critical condition is reached when cavities are formed due to zero pressure conditions given by

$$P_c = P_{vp} = P_{es} + P_s + P_h, \qquad (3.5)$$

where, P_c = coulombic pressure,

P_{vp} = vapour pressure inside the cavity,

P_{es} = electrostatic pressure,

P_s = pressure due to surface tension, and

P_h = hydrostatic pressure

From this condition, an expression has been obtained for the maximum breakdown strength of pure liquids which was found to be in good agreement with the experimental results.

In general, the cavitation and bubble theories try to explain the highest breakdown strengths obtainable, considering the cavities or bubbles formed in the liquid dielectrics.

3.4.3 Thermal Mechanism of Breakdown

Another mechanism proposed to explain breakdown under pulse conditions is thermal breakdown. This mechanism is based on the experimental observations of extremely large currents just before breakdown. This high current pulses are believed to originate from the tips of the microscopic projections on the cathode surface with densities of the order of 1 A/cm^3. These high density current pulses give rise to localised heating of the oil which may lead to the formation of vapour bubbles. The vapour bubbles are formed when the energy exceeds 10^7 W/cm^2. When a bubble is formed, breakdown follows, either because of its elongation to a critical size or when it completely bridges the gap between the electrodes. In either case, it will result in the formation of a spark. According to this mechanism, the breakdown strength depends on the pressure and the molecular structure of the liquid. For example, in *n*-alkanes the breakdown strength was observed to depend on the chain length of the molecule. This theory is only applicable at very small lengths ($\leq 100\ \mu$ m) and does not explain the reduction in breakdown strength with increased gap lengths.

3.4.4 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. 3.7.

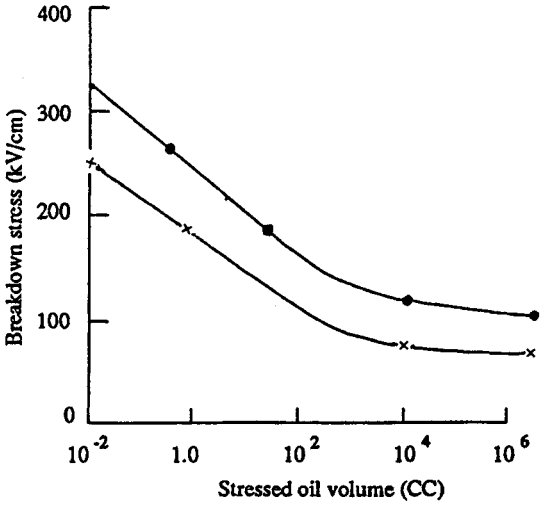


Fig. 3.7 Power frequency (50 Hz) a.c. breakdown stress as a function of the stressed oil volume
- • With steady voltage rise
- × One minute withstand voltage

3.4.5 Conclusions

All the theories discussed above do not consider the dependence of breakdown strength on the gap length. They all try to account for the maximum obtainable breakdown strength only. However, the experimental evidence showed that the breakdown strength of a liquid depends on the gap length, given by the following expression,

$$V_b = Ad^n \tag{3.6}$$

where, d = gap length,

A = constant, and

n = constant, always less than 1.

The breakdown voltage also depends on the nature of the voltage, the mode in which the voltage is applied, and the time of application. The above relationship is of practical importance, and the electrical stress of a given oil used in design is obtained from this. During the last ten years, research work is directed on the measurements of discharge inception levels in oil and the breakdown strengths of large volumes of oil under different conditions.

It may be summarized that the actual mechanism of breakdown in oil is not a simple phenomenon and the breakdown voltages are determined by experimental investigations only. Electrical stresses obtained for small volumes should not be used in the case of large volumes. As a general guideline, the properties of good dielectric oils for electrical purpose are tabulated (see Table 3.1), and the designer should satisfy himself on all the properties before acceptance.

Table 3.3 gives the typical breakdown strengths for highly purified liquids and the design stresses actually used. A factor of safety of about 10 is used as can be seen from the data in the table. The reasons for such an approach can be understood from the various factors considered in the breakdown theories discussed.

Table 3.3 Power Frequency Design Field Strengths and Breakdown Field Strengths for Highly Purified Dielectric Liquids—a Comparison

Dielectric liquid	Used in (equipment)	Design field strength (MV/m)	Breakdown Strength (MV/m)
Transformer oil	Transformers	2-5	100
n-hexane	Cables	13-20	132
Polybutane (Synthetic hydrocarbon)	Capacitors	10-25	109

In the next 20 to 30 years, transformer oils, which are derivatives of petroleum crude, may be in short supply. Therefore, various synthetic insulating oils are being examined as potential insultants in high voltage apparatus. Among the synthetic oils, polybutane liquids have been used for some years in cables and paper capacitors. They are superior to transformer oils in various electrical properties including dielectric strength. Fluorocarbon and silicone liquids are also used in special apparatus. However, their use will require further evaluation of their properties. Further details can be found in refeences 7, 9 and10 cited at the end of this chapter.

QUESTIONS

Q.3.1 Explain the phenomena of electrical conduction in liquids. How does it differ from that in gases?

Q.3.2 What are commercial liquid dielectrics, and how are they different from pure liquid dielectrics?

Q.3.3 What are the factors that influence conduction in pure liquid dielectrics and in commercial liquid dielectrics?

Q.3.4 Explain the various theories that explain breakdown in commercial liquid dielectrics.

Q.3.5 What is "stressed oil volume theory", and how does it explain breakdown in large volumes of commercial liquid dielectrics?

WORKED EXAMPLES

Example 3.1: In an experiment for determining the breakdown strength of transformer oil, the following observations were made. Determine the power law deendence between the gap spacing and the applied voltage of the oil.

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

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

$$V = Kd^n$$

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

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

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

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

$$= 0.947$$

From Fig. E.3.1.,

$$K = 24.5$$

$\therefore$ Relationship between the breakdown voltage and the gap spacing for the transformer oil studied is

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

where V is in kV and d is in mm.

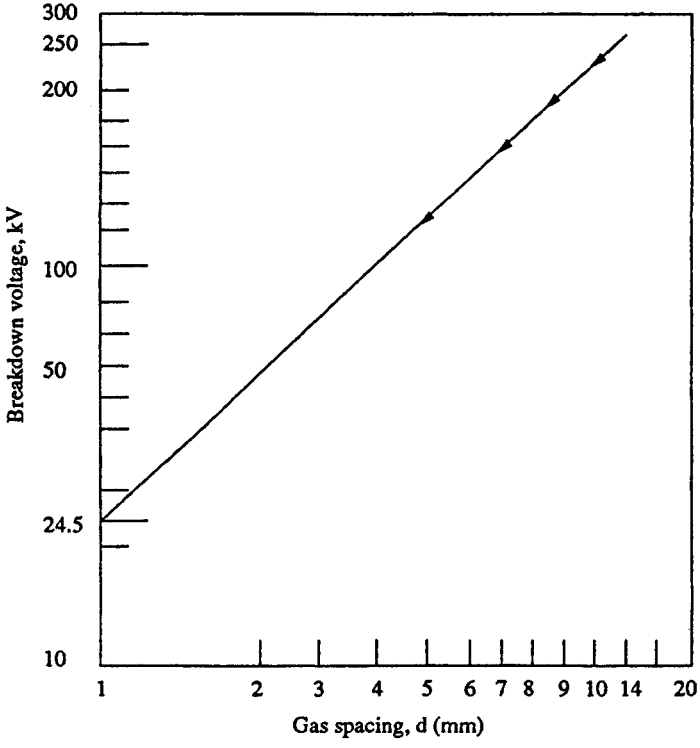


Fig. E.3.1 Breakdown voltage as a function of gap spacing

4

Breakdown in Solid Dielectrics

4.1 INTRODUCTION

Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusions, and moisture, and be resistant to thermal and chemical deterioration. Solid dielectrics have higher breakdown strength compared to liquids and gases.

Studies of the breakdown of solid dielectrics are of extreme importance in insulation studies. When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field is removed.

The mechanism of breakdown is a complex phenomena in the case of solids, and varies depending on the time of application of voltage as shown in Fig. 4.1. 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
(*f*) breakdown due to internal discharges.

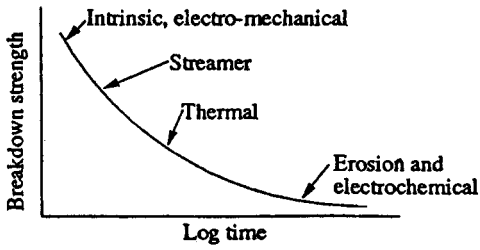


Fig. 4.1 Variation of breakdown strength with time after application of voltage

4.2 INTRINSIC BREAKDOWN

When voltages are applied only for short durations of the order of 10^{-8}s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. Experimentally, this highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature. The maximum electrical strength recorded is 15 MV/cm for polyvinyl-alcohol at – 196°C. The maximum strength usually obtainable ranges from 5 MV/cm to 10 MV/cm.

Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric. Usually, a small number of conduction electrons are present in solid dielectrics, along with some structural imperfections and small amounts of impurities. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have been proposed.

4.2.1 Electronic Breakdown

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

4.2.2 Avalanche or Streamer Breakdown

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

An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions. When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron. This process repeats itself resulting in the formation of an electron avalanche. Breakdown will occur, when the avalanche exceeds a certain critical size.

In practice, breakdown does not occur by the formation of a single avalanche itself, but occurs as a result of many avalanches formed within the dielectric and extending step by step through the entire thickness of the material as shown in Fig. 4.2. This can

be readily demonstrated in a laboratory by applying an impulse voltage between point-plane electrodes with point embedded in a transparent solid dielectric such as perspex.

4.3 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

$$\varepsilon_0 \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \qquad (4.1)$$

where Y is the Young's modulus.

From Eq. (4.1)

$$V^2 = d^2\left[\frac{2Y}{\varepsilon_0 \varepsilon_r}\right] \ln\left[\frac{d_0}{d}\right] \qquad (4.2)$$

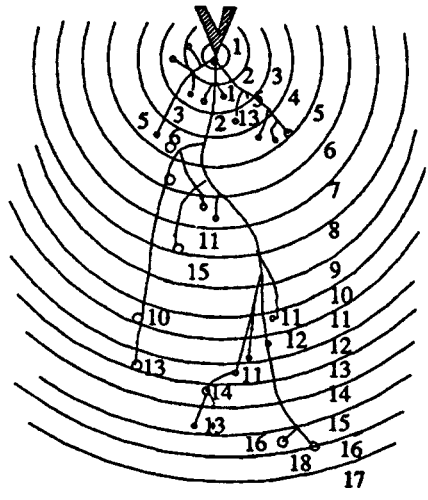


Fig. 4.2 Breakdown channels in perspex between point-plane electrodes. Radius of point 0.01 in, thickness 0.19 in. Total number of impulses 190. Number of channels produced 16; (n) point indicates end of nth channel. Radii of circles increases in units of 10^{-2} in.

Source: R. Cooper, *International Journal of Elec. Engg. Education.* vol. 1 241 (1963)

Usually, mechanical instability occurs when

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

Substituting this in Eq. 4.2, the highest apparent electric stress before breakdown,

$$E_{max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}} \qquad (4.3)$$

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

4.4 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

$$W_{d.c.} = E^2\sigma \qquad \text{W/cm}^3 \tag{4.4}$$

where, σ is the d.c. conductivity of the specimen.
Under a.c. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \qquad \text{W/cm}^3 \tag{4.5}$$

where, f = frequency in Hz,

δ = loss angle of the dielectric material, and

E = rms value.

The heat dissipated (W_T) is given by

$$W_T = C_V \frac{dT}{dt} + \text{div}\,(K \text{ grad } T) \tag{4.6}$$

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 ($W_{d.c.}$ or $W_{a.c.}$) becomes equal to the heat dissipated (W_T). In actual practice there is always some heat that is radiated out.

Breakdown occurs when $W_{d.c.}$ or $W_{a.c.}$ exceeds W_T. The thermal instability condition is shown in Fig. 4.3. 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_2 breakdown 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.

This is of great importance to practising engineers, as most of the insulation failures in high voltage power apparatus occur due to thermal breakdown. Thermal breakdown sets up an upper limit for increasing the breakdown voltage when the thickness of the insulation is increased. For a given loss angle and applied stress, the heat generated is proportional to the frequency and hence thermal breakdown is more serious at high frequencies. Table 4.1 gives the thermal breakdown voltages of various materials under d.c. and a.c. fields.

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

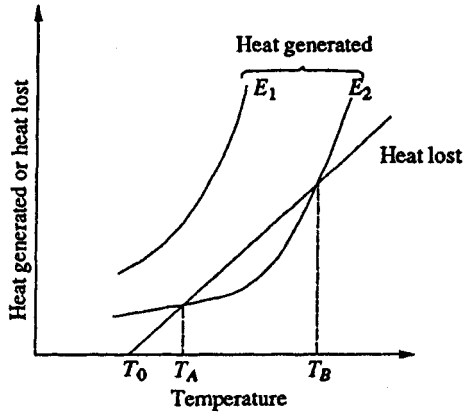


Fig. 4.3 Thermal instability in solid dielectrics

Table 4.1 Thermal Breakdown Stresses in Dielectrics

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

4.5 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. These are, for example, breakdown due to tracking in which dry conducting tracks are formed on the surface of the insulation. These tracks act as conducting paths on the insulator surfaces leading to gradual breakdown along the surface of the insulator. Another type of breakdown in this category is the electrochemical breakdown caused by chemical transformations such as electrolysis, formation of ozone, etc. In addition, failure also occurs due to partial discharges which are brought about in the air pockets

inside the insulation. This type of breakdown is very important in the impregnated paper insulation used in high voltage cables and capacitors.

4.5.1 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.

Chemical Action: Even in the absence of electric fields, progressive chemical degradation of insulating materials can occur due to a variety of processes such as chemical instability at high temperatures, oxidation and cracking in the presence of air and ozone, and hydrolysis due to moisture and heat. Since different insulating materials come into contact with each other in any practical apparatus, chemical reactions occur between these various materials leading to reduction in electrical and mechanical strengths resulting in failure.

The effects of electrochemical and chemical deterioration could be minimized by carefully studying and examining the materials. High soda content glass insulation should be avoided in moist and damp conditions, because sodium, being very mobile, leaches to the surface giving rise to the formation of a strong alkali which will cause deterioration. It was observed that this type of material will lose its mechanical strength within 24 hrs, when it is explosed to atmospheres having 100% relative humidity at 70°C. In paper insulation, even if partial discharges are prevented completely, breakdown can occur due to chemical degradation. The chemical and electrochemical deterioration increases very rapidly with temperature, and hence high temperatures should be avoided.

4.5.2 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*.

Consider a system of a solid dielectric having a conducting film and two electrodes on its surface. In practice, the conducting film very often is formed due to moisture. On application of voltage, the film starts conducting, resulting in generation of heat, and the surface starts becoming dry. The conducting film becomes separate due to drying, and so sparks are drawn damaging the dielectric surface. With organic insulating materials such as paper and bakelite, the dielectric carbonizes at the region

of sparking, and the carbonized regions act as permanent conducting channels resulting in increased stress over the rest of the region. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes. This phenomena, called tracking is common between layers of bakelite, paper and similar dielectrics built of laminates.

On the other hand treeing occurs due to the erosion of material at the tips of the spark. Erosion results in the roughening of the surfaces, and hence becomes a source of dirt and contamination. This causes increased conductivity resulting either in the formation of a conducting path bridging the electrodes or in a mechanical failure of the dielectric.

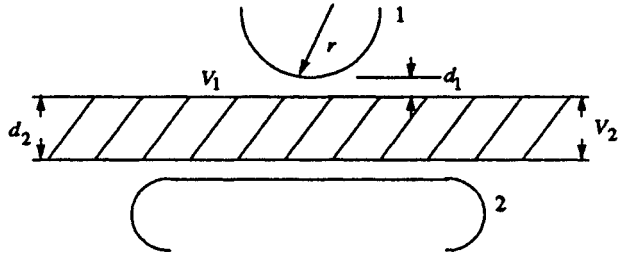


Fig. 4.4 Arrangement for study of treeing phenomena. 1 and 2 are electrodes

When a dielectric material lies between two electrodes as shown in Fig. 4.4, there is a possibility for two different dielectric media, the air and the dielectric, to come in series. The voltages across the two media are as shown (V_1 across the air gap, and V_2 across the dielectric). The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2} \tag{4.7}$$

where V is the applied voltage.

Since $\varepsilon_2 > \varepsilon_1$, most of the voltage appears across d_1, the air gap. Sparking will occur in the air gap and, charge accumulation takes place on the surface of the insulation. Sometimes the spark erodes the surface of the insulation. As time passes, breakdown channels spread through the insulation in an irregular "tree" like fashion leading to the formation of conducting channels. This kind of channelling is called treeing.

Under a.c. voltage conditions treeing can occur in a few minutes or several hours. Hence, care must be taken to see that no series air gaps or other weaker insulation gaps are formed.

Usually, tracking occurs even at very low voltages of the order of about 100 V, whereas treeing requires high voltage. For testing of tracking, low and medium voltage tracking tests are specified. These tests are done at low voltages but for times of about 100 hr or more. The insulation should not fail. Sometimes the tests are done using 5 to 10 kV with shorter durations of 4 to 6 hr. The numerical value of voltage

that initiates or causes the formation of a track is called the "tracking index" and this is used to qualify the surface properties of dielectric materials.

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

Usually, treeing phenomena is observed in capacitors and cables, and extensive work is being done to investigate the real nature and causes of this phenomenon.

4.5.3 Breakdown Due to Internal Discharges

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

Let us consider a dielectric between two conductors as shown in Fig. 4.5a. 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. 4.5b. 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 (4.7)

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

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

$$V_1 = V \varepsilon_r \left(\frac{d_1}{d_2}\right) \tag{4.8}$$

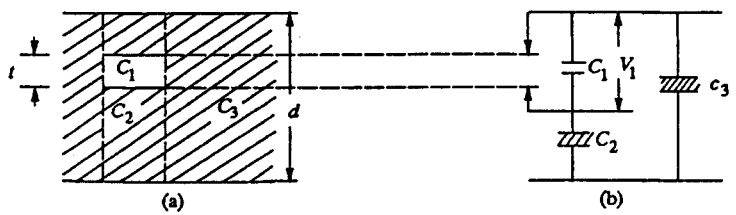


Fig. 4.5 Electrical discharge in a cavity and its equivalent circuit

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. 4.6. 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.

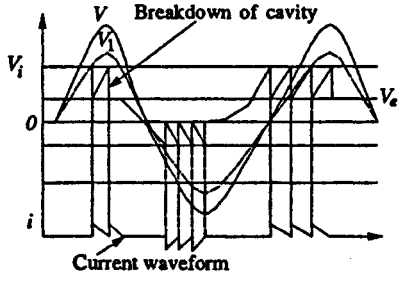


Fig. 4.6 Sequence of cavity breakdown under alternating voltages

These internal discharges (also called partial discharges) will have the same effect as "treeing" on the insulation. When the breakdown occurs in the voids, electrons and positive ions are formed. They will have sufficient energy and when they reach the void surfaces they may break the chemical bonds. Also, in each discharge there will be some heat dissipated in the cavities, and this will carbonize the surface of the voids and will cause erosion of the material. Channels and pits formed on the cavity surfaces increase the conduction. Chemical degradation may also occur as a result of the active discharge products formed during breakdown.

All these effects will result in a gradual erosion of the material and consequent reduction in the thickness of insulation leading to breakdown. 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.

4.6 BREAKDOWN IN COMPOSITE DIELECTRICS

4.6.1 Introduction

It is difficult to imagine a complete insulation system in an 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 SF_6 gas in parallel

with solid insulation or in series with one another. Such insulation systems are called composite dielectrics.

The composite nature of an insulation system arises from the mechanical requirements involved in separating electrical conductors which are at different potentials. Also, parts of a single system that are normally composed of a single material are in fact composite in nature. In actual practice, these single materials will normally have small volumes of another material present in their bulk. For example, a solid will contain gas pockets or voids, while a liquid or gas will contain metallic or dust particles, gas bubbles etc. A commonly encountered composite dielectric is the solid/liquid combination or liquid impregnated flexible solid like thin sheets of paper or plastic. This type of composite dielectric is widely used in a variety of low and high voltage apparatus such as cables, capacitors, transformers, oil-filled switchgear, bushings etc. In recent years solid/SF_6 gas technology has become more acceptable.

All the desirable properties of composite dielectrics cannot be realised to the fullest extent owing to the presence of impurities in them. For example, in a solid-liquid system, the presence of gas bubbles in the liquid phase and cavities in the solid phase will give rise to a number of processes, both physical and chemical, which will reduce the dielectric strength of the system.

In the practical system, in order to reduce the undesirable effects mentioned above, composite insulation is used by combining different dielectrics either in series or in parallel such that it is possible to obtain superior dielectric properties than that possible for a single material of the same thickness.

4.6.2 Properties of Composite Dielectrics

A composite dielectric generally consists of a large number of layers arranged one over the other. This is called "the layered construction" and is widely used in cables, capacitors and transformers. Three properties of composite dielectrics which are important to their performance are given below.

(a) Effect of Multiple Layers

The simplest composite dielectric consists of two layers of the same material. Here, advantage is taken of the fact that two thin sheets have a higher dielectric strength than a single sheet of the same total thickness. The advantage is particularly significant in the case of materials having a wide variation in dielectric strength values measured at different points on its surface.

(b) Effect of Layer Thickness

Increase in layer thickness normally gives increased breakdown voltage. In a layered construction, breakdown channels occur at the interfaces only and not directly through another layer. Also, a discharge having penetrated one layer cannot enter the next layer until a part of the interface also attains the potential which can produce an electric field stress comparable to that of the discharge channel.

The use of layered construction is very important in the case of insulating paper since the paper thickness itself varies from point to point and consequently the dielectric strength across its surface is not homogeneous. The differences in the

thickness impart a rough surface to the paper which can produce an electric field stress comparable to that of the discharge channel. The rough surface of the paper also helps in better impregnation when tightly wound. On the other hand, the existence of areas with lower thickness in the paper can cause breakdown at these points at considerably lower voltages.

Various investigations on composite dielectrics have shown that

(i) the discharge inception voltage depends on the thickness of the solid dielectric, as well as on the dielectric constant of both the liquid and solid dielectric, and

(ii) the difference in the dielectric constants between the liquid and solid dielectrics does not significantly affect the rate of change of electric field at the electrode edge with the change in the dielectric thickness.

(c) Effect of Interfaces

The interface between two dielectric surfaces in a composite dielectric system plays an important role in determining its pre-breakdown and breakdown strengths. Discharges usually occur at the interfaces and the magnitude of the discharge depends on the associated surface resistance and capacitance. When the surface conductivity increases, the discharge magnitude also increases, resulting in damage to the dielectric.

In a composite dielectric, it is essential to maintain low dielectric losses because they normally operate at high electric stresses. However, even in an initially pure dielectric liquid, when used under industrial conditions for impregnating solid dielectrics, impurities arise, resulting in increased dielectric losses. The effect of various impurities in causing the breakdown of composite dielectrics is discussed in the next section.

4.6.3 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. There exists a critical stress in the volume of the dielectric at which discharges of a given magnitude can enter the insulation from the surface and propagate rapidly into its volume to cause breakdown. Experiments with single discharges on an insulating material have shown that breakdown occurs more rapidly when the electric field in the insulation is such that it assists the charged particles in the discharge to penetrate into the insulation, than when the field opposes their entry. Breakdown was observed to occur more readily when the bombarding particles are electrons, rather than positive ions. In addition, there are local field intensifications due to the presence of impurities and variations in the thickness of solid insulation and these local field intensifications play a very important role

QUESTIONS

Q.4.1 What do you understand by "intrinsic strength" of a solid dielectric? How does breakdown occur due to electrons in a solid dielectric?

Q.4.2 What is "thermal breakdown" in solid dielectrics, and how is it practically more significant than other mechanisms?

Q.4.3 Explain the different mechanisms by which breakdown occurs in solid dielectrics in practice.

Q.4.4 How does the "internal discharge" phenomena lead to breakdown in solid dielectrics?

Q.4.5 What is a composite dielectric and what are its properties?

Q.4.6 Describe the mechanism of short-term breakdown of composite insulation.

Q.4.7 How do the temperature and moisture affect the breakdown strength of solid dielectrics?

Q.4.8 What are the advantages of using plastic film insulation over the paper insulation?

Q.4.9 What are the properties that make plastics more suitable as insulating materials?

Q.4.10 What are the special features of epoxy resin insulation?

WORKED EXAMPLES

Example 4.1: A solid specimen of dielectric has a dielectric constant of 4.2, and $\tan \delta = 0.001$ at a frequency of 50 Hz. If it is subjected to an alternating field of 50 kV/cm, calculate the heat generated in the specimen due to the dielectric loss.

Solution: Dielectric heat loss at any electric stress E [Eq. (4.5)]

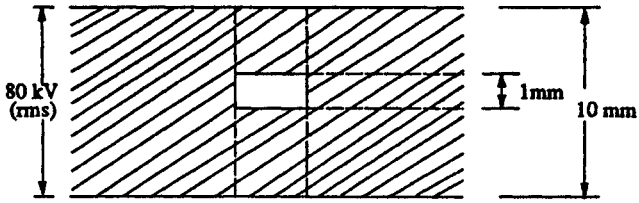
$$= \frac{E^2 f \varepsilon_r \tan \delta}{1.8 \times 10^{12}} \quad \text{W/cm}^3$$

For the specimen under study, the heat loss will be

$$= \frac{50 \times 50 \times 10^6 \times 50 \times 4.2 \times .001}{1.8 \times 10^{12}}$$

$$= 0.291 \text{ mW/cm}^3$$

Example 4.2: A solid dielectric specimen of dielectric constant of 4.0 shown in the figure has an internal void of thickness 1 mm. The specimen is 1 cm thick and is subjected to a voltage of 80 kV (rms). If the void is filled with air and if the breakdown strength of air can be taken as 30 kV (peak)/cm, find the voltage at which an internal discharge can occur.



Solution: Referring to Fig. 4.5(a) and Eqs. (4.7) and (4.8), the voltage that appears across the void is given as

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

where,

$$d_1 = 1 \text{ mm}$$

$$d_2 = 9 \text{ mm}$$

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

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

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

$$= \left(\frac{4V}{13}\right)$$

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

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

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

The internal discharges appear in the sinusoidal voltage 80 sin ωt kV when the voltage reaches a value of 9.75 kV (see Fig. 4.6 for the discharge pattern).

Example 4.3: A coaxial cylindrical capacitor is to be designed with an effective length of 20 cm. The capacitor is expected to have a capacitance of 1000 pF and to operate at 15 kV, 500 kHz. Select a suitable insulating material and give the dimensions of the electrodes.

Solution: The capacitance of the coaxial cylindrical capacitor is

$$\frac{2\pi \varepsilon_0 \varepsilon_r l}{\ln \frac{d_2}{d_1}} \tag{1}$$

where l = length in metres, d_1 and d_2 are the diameters of the inner and outer electrodes, and ε_r = dielectric constant. The dielectric material that can be selected is either polyethylene or P.T.F.E.

Choosing high density polyethylene, its dielectric constant $\varepsilon_r = 2.3$, and its breakdown stress is taken as 500 V/mil or 200 kV/cm. Allowing a factor of safety of 4, the maximum stress $E_{max} = 50$ kV/cm. E_{max} occurs near the inner electrode and is given by

$$E_{max} = \frac{V}{r_1 \ln \frac{r_2}{r_1}} \tag{2}$$

from equation (1),

$$\ln \frac{d_2}{d_1} = \ln \frac{r_2}{r_1} = \frac{2\pi\varepsilon_0\varepsilon_r l}{\text{capacitance}}$$

$$= \frac{2\pi \frac{10^{-9}}{36\pi} \times 2.3 \times 0.2}{100 \times 10^{-12}}$$

$$= 0.02556$$

$$\therefore \frac{r_2}{r_1} = 1.026$$

From equation (2),

$$r_1 = \frac{V}{E_{max}} \ln \frac{1}{\frac{r_2}{r_1}}$$

$$= \frac{15}{50 \times 0.02556}$$

$$= 11.74 \text{ cm}$$

$$\therefore \quad r_2 = 1.026 \times 11.74$$

$$= 12.05 \text{ cm}$$

The thickness of the insulation is 3.1 mm (refer to Tables 4.8 and 4.9 for the properties of the material).

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5

Applications of Insulating Materials

5.1 INTRODUCTION

There is no piece of electrical equipment that does not depend on electrical insulation in one form or other to maintain the flow of electric current in desired paths or circuits. If due to some reasons the current deviates from the desired path, the potential will drop. An example of this is a short circuit and this should always be avoided. This is done by proper choice and application of insulation wherever there is a potential difference between neighbouring conducting bodies that carry current. There are four principal areas where insulation must be applied. They are

(*a*) between coils and earth (phase-to-earth),
(*b*) between coils of different phases (phase-to-phase),
(*e*) between turns in a coil (inter-turn), and
(*d*) between the coils of the same phase (inter-coil).

As we know, there are three broad categories of insulating materials, gases, liquids and solids. The insulating materials are classified mainly based on the thermal endurance. The insulation is primarily meant to resist electrical stresses. In addition, it should also be able to withstand certain other stresses which the insulation encounters during manufacture, storage and operation. The performance of the insulation depends on its operating temperature. The higher the temperature, the higher will be the rate of its chemical deterioration, and hence the lower will be its useful life. If a reasonably long life of an insulation is expected, its operating temperature must be maintained low. Therefore, it is necessary to determine the limits of temperature for the insulation, which will ensure safe operation over its expected life. Thus the insulating materials are grouped into different classes O, A, B, and C with temperature limits of 90°C, 105°C and 130°C for the first three classes and no specific limit fixed for class C. Classes O and A cover the various organic materials without and with impregnation respectively, while classes B and C cover inorganic materials, respectively with and without a binder. With the advent of newer insulating materials, namely, the plastics and silicones, during the middle of this century, a need was felt to reorganize the classification of the insulating materials. This led IEC (International Electrotechnical Commission) to come up with the new categories:

Class Y (formerly O): 90°C: Paper, cotton, silk, natural rubber, polyvinyl chloride, etc. without impregnation.

Class A: 105°C: Same as class Y but impregnated, plus nylon.

Class E: 120°C: Polythylene terephthalate (terylene fibre, melinex film), cellulose triacetate, polyurethanes, polyvinyl acetate enamel.

Class B: 130°C: Mica, fibreglass (alkali free alumino borosilicate), bitumenized asbestos, bakelite, polyester enamel.

Class F: 155°C: As class B but with alkyd and epoxy based resins.

Class H: 180°C: As class B with silicone resin binder, silicone rubber, aromatic polyamide (nomex paper and fibre), polymide film (enamel, varnish and film) and estermide enamel.

Class C: Above 180°C: As class B but with suitable non-organic binders; teflon (polytetraflouroethylene).

The temperatures mentioned above cannot be regarded as the limiting operating temperatures but only as an index to compare the various insulating materials. All the national standards permit the equipment to work up to these temperatures, but in practice, certain differentials are allowed because of the over loads, other manufacturing advantages and economics.

In this chapter we deal with the insulation systems in electrical and electronic equipments. First we deal with insulation in power apparatus under which insulation in rotating electrical machines, transformers and switchgear are discussed followed by the insulation in capacitors and cables. The insulation of electronic equipment is discussed later.

5.2 APPLICATIONS IN POWER TRANSFORMERS

Transformers are the first to encounter lightning and other high voltage surges. The transformer insulation has to withstand very high impulse voltages many times the power frequency operating voltages. The transformer insulation is broadly divided into

(*a*) conductor or turn-to-turn insulation,
(*b*) coil-to-coil insulation,
(*c*) low voltage coil-to-earth insulation,
(*d*) high voltage coil-to-low voltage coil insulation, and
(*e*) high voltage coil-to-ground insulation.

The low voltage coil-to-ground and the high voltage coil-to-low voltage coil insulations normally consist of solid tubes combined with liquid or gas filled spaces. The liquid or gas in the spaces help to remove the heat from the core and coil structure and also help to improve the insulation strengths. The inter-turn insulation is directly applied on the conductor as organic enamel in smaller rating transformers. In the large transformers paper or glass tape is wrapped on the rectangular conductors. In the case of layer to layer, coil-to-coil and coil-to-ground insulations, Kraft paper is used in smaller transformers, whereas thick radial spacers made of pressboard, glass fabric, or porcelain are used in the case of higher rating transformers.

Of all the materials, oil impregnated paper, and pressboard are extensively used in liquid filled transformers. The lack of thermal stability at higher temperatures limits the use of this type of insulation to be used continuously up to 105°C. Paper and its products absorb moisture very rapidly from the atmosphere, and hence this type of insulation should be kept free of moisture during its life in a transformer.

Transformer oil provides the required dielectric strength and insulation and also cools the transformer by circulating itself through the core and the coil structure. The transformer oil, therefore, should be in the liquid state over the complete operating range of temperatures between –40°C and +50°C. The oil gets oxidized when exposed to oxygen at high temperatures, and the oxidation results in the formation of peroxides, water, organic acids and sludge. These products cause chemical deterioration of the paper insulation and the metal parts of the transformer. Sludge being heavy, reduces the heat transfer capabilities of the oil, and also forms as a heat insulating layer on the coil structure, the core and the tank walls. In present-day transformers the effects of oxidation are minimized by designing them such that access to oxygen itself is limited. This is done by the use of (*a*) sealed transformers, (*b*) by filling the air space with nitrogen gas, and (*c*) providing oxygen absorbers like activated clay or alumina.

When an arc discharge occurs inside a transformer, the oil decomposition occurs. The decomposition products consist of hydrogen and gaseous hydrocarbons which may lead to explosion. And hence, oil insulated transformers are seldom used inside buildings or other hazardous locations like mines. Under such conditions dry type and askarel or sulphur hexafluoride (SF_6) gas filled transformers are used. Askarel is a fireproof liquid and is the generic name for a number of synthetic chlorinated aromatic hydrocarbons. These are more stable to oxidation and do not form acids or sludge. Under arcing they are very stable and do not give rise to inflammable gases. However they give out hydrochloric acid which is toxic and which attacks the paper insulation. This is removed by using tin or tetraphenyl. However, if the arc is very heavy, the hydrochloric acid cannot be absorbed completely. For these reasons SF_6 gas insulated transformers are popular. Also, askarel cannot be used in high voltage transformers, because the impulse strength of askarel impregnanted paper is very low compared to that of oil impregnated paper. Moreover, its dielectric strength deteriorates rapidly at high voltages and at high frequencies liberating hydrochloric acid.

Even today there is no perfect all purpose transformer fluid. In recent years, progress has been made with the use of fluorocarbon liquids and SF_6 gas. However, these liquids have not become very popular because of their high cost.

5.3 APPLICATIONS IN ROTATING MACHINES

Rotating machines are normally divided into two categories: those with voltage ratings less than 6,600 V are called low voltage machines, and the others are high voltage machines. Because of the difficulty of insulating high voltages, machines above 22 kV rating are not built except under special conditions. Classes Y and C insulation find no application in rotating machines. Class E which was widely used in low voltage machines for over 20 years is now being replaced by class F which is meant for the high voltage machines. Also, Class F is being increasingly used in place of class B. Thus class F appears to be the insulation of the future. Considerable progress has been made in recent years, in reducing the size of the machines for a given rating by use of class H materials, particularly, for small machines. However, the cost of class H materials (silicones, teflon) is very high, and hence they are used only under special conditions like severe over loads in traction motors and mill motors. The various materials used in modern rotating machines are tabulated in

Table 5.1 Typical Modern Insulating Materials for Rotating Machines

Component		Low voltage machines			High voltage machines	
		Class E	*Class B*	*Class F*	*Class B*	*Class F*
Turn-to-turn insulation		Polyvinyl acetal for both wire and strip conductors	Polyester enamel (wire) or phenolic bonded fibreglass (strip)	Estermide enamel (wire) or alkyd bonded fibreglass (strip)	Phenolic bonded fibre-glass (strip)	Alkyd bonded fibre-glass (strip)
Coil-to-coil and phase-to-phase insulation	Inside the slots	Bakelized fabric strips	Bakelized fabric strips	Epoxy fibreglass strips	Shellac or bitumen bonded mica foil or tape on straight portions of the coils	Epoxy impregnated mica paper foil or tape on straight portions of the coil.
	On over-hangs	Melinex film bonded to press paper	Alkyd bonded mica glass sheet	Nomex sheet	Alkyd varnished glass tape on coil ends and alkyd bonded mica sheet between layers	Epoxy varnished glass tape on coil ends and alkyd bonded mica glass sheet between layers
Phase (or coil) to earth insulation		Melinex film bonded to press paper	Mica alkyd bonded to glass cloth	Nomex sheet	No extra insulation because the phase-to-phase insulation itself is sufficient	
Slot closure (wedge)		Bakelized fabric strip	Bakelized fabric strip	Epoxy fibreglass strip	Bakelized fabric strip	Epoxy fibreglass strip
Insulation for leads		Alyd varnished terylene or glass tape or sleeving			Alkyd varnished glass tape	
Varnish for impregnation treatment		Alkyd phenolic	Alkyd phenolic	Estermide or epoxy	Alkyd-phenolic	Epoxy

Table 5.1. This is only a typical listing and may vary depending on the choice of the design engineer.

Mica has been used in the electrical industry since its inception. Normally, mica is available in the form of very thin splittings. Hence it is bound to a supporting sheet of electrical grade paper or glass cloth with a suitable binding agent. The resulting mica sheets are known as micanite. Since mica splittings of fairly large surface area were not available, methods were evolved to make mica paper using mica of any size. The mica paper so obtained is not sufficiently strong or self-supporting. Hence, it has to be given a backing of glass cloth or other binding material such as epoxy resin. Epoxy resin bounded mica paper is extensively used in both low and high voltage machines. For non-epoxy system a varnish impregnation is essential to fill the voids and also to act as a barrier against moisture and chemicals present in the atmosphere. For this purpose the varnish should have the property of forming an unbroken tightly adhesive and yet reasonably flexible film. The solvent in the varnish must not attack any of the insulating materials used, and the resin should have a long-term compatibility with these materials.

The maintenance of good mechanical properties is also equally important for the reliable operation of machines. The insulation should withstand the expansion and contraction during temperature cycles in large machines. These effects become very severe at the high temperatures observed in power generators of a very large size. Maintenance of good mechanical properties and thermal endurance are very essential in low voltage machines also.

5.4 APPLICATIONS IN CIRCUIT BREAKERS

A circuit breaker is a switch which automatically interrupts the circuit when a critical current or voltage rating is exceeded. a.c. currents are considerably easier to interrupt than d.c. currents. a.c. current interruption generally requires first to substitute an arc for part of the metallic circuit and then its deionization when the current goes through zero, so that the arc will not reestablish again.

Circuit breakers are also divided into two categories, namely, the low voltage and high voltage types. Low voltage breakers use synthetic resin mouldings to carry the metallic parts. For higher temperatures ceramic parts are used. When the arc is likely to come into contact with moulded parts, melanine or some special kind of alkyd resins are used because of their greater arc resistance. The high voltage circuit breakers are further classified into air circuit breakers and oil circuit breakers. Many insulating fluids are suitable for arc extinction and the choice of the fluid depends on the rating and type of the circuit breaker. The insulating fluids commonly used are atmospheric air, compressed air, high vacuum, SF_6 and oil. In some ancillary equipment used with circuit breakers, the fluid serves the purpose of providing only insulation. Many insulants are available for this purpose.

The oils used in circuit breakers normally has the same characteristics as transformer oil. In circuit breakers oil serves an additional purpose of interrupting the arc. Since the gases (mainly hydrogen) help to extinguish the arc, a liquid which generates the maximum amount of the gas for one unit of arc energy is preferred. Transformer oil possesses these characteristics. Many other oils have been tried but with no success. Askarels produce large quantities of toxic and corrosive products.

The circuit breaker bushings of lower voltage ratings may consist of solid cylinders of porcelain and shellac or resin treated paper wrapped on the current carrying electrode. High voltage bushings of voltages of 66 kV and above are filled with oil. The constructional details vary widely. In certain designs, the system of coaxial porcelain or treated paper cylinders are used with space between them filled with oil. In the condenser type bushings, paper is wound on the electrode and metal foils are wrapped on it at intervals throughout the diameter such that the capacitance between successive foils is constant. This ensures uniform voltage distribution, and hence higher dielectric strength.

The different types of insulating materials used in the construction of high voltage switchgear are classified in Table 5.2. This includes some of the modern insulating materials for future applications. Of these, a few are widely used as major insulants. They are, porcelain, insulating oil, synthetic resin bonded paper laminates, epoxy resins, and SF_6 gas.

5.5 APPLICATIONS IN CABLES

In the recent years natural rubber has been completely replaced by synthetic rubbers and plastics as cable insulation. The physical properties required for wire and cable insulation depend on the type of application. It should have good elongation and tensile strength and toughness, so that it will withstand handling during installation and service. It should also have low dielectric constant and power factor but high dielectric strength and insulation resistance. Also, during operation, because of over loading, the insulation may be exposed to high temperatures for long periods of time. This necessitates the insulation to have excellent resistance to ageing at high temperatures. The insulation should also be able to withstand long exposure to sunlight and various chemicals. High voltage cables also give rise to ozone and the insulation will deteriorate in its presence. This is particularly severe for the insulation near the conductors. Cables are also laid in rivers and under the sea. For these applications it should have very low water absorption. When cables have to operate at low temperature the insulation should not become stiff and brittle. The partial discharges in the cable insulation should also be kept as low as possible.

Table 5.2 Insulating in High Voltage Switchgear

Materials	Applications
Epoxy resins	Low pressure castings for bushings, switchgear orifices, bus-bars, instrument transformers. Fluidized bed dip coating for bus-bar insulation and dough moulding for bus-bar barriers and secondary terminals.
Epoxy resin bonded glassfibre	For components such as arc control devices, circuit breaker operating rod and high pressure feed pipes for air blast circuit breakers.

(Contd.)

Materials	Applications
Polyester resins	Insulating lever for circuit breaker and phase barrier plate in switch board.
Porcelain	Insulators and bushings of power transformers, circuit breakers and instrument transformers.
Vulcanized Fibre	Arc chamber segments.
Synthetic resin bonded paper	Bushings, arc chambers, etc.
Nylon	Injunction mouldings for arc control devices in circuit breakers.
Silicone rubber	Filling for moulded joint boxes in air insulated circuit breakers.
Butyl rubber	Presssure moulding of current transformers.
Chloro-sulphonated polyethylene	Cable insulation for use in air or oil.

The main types of insulants used in the cable industries are paper, rubber, plastics and compressed gas. Paper insulated lead sheathed cables are still used because of their reliability, high dielectric strength, low dielectric loss, and long life. The most commonly used insulating materials for low and medium voltage (up to 3.3 kV) cables is polyvinylychloride (P.V.C.) Polyethylene and cross-linked polyethylene are also used. P.V.C. is not suitable for high voltage applications because of its high dielectric constant and high loss. It cannot be operated continuously at higher voltages, although it can be used up to 85°C continuous at low voltages. On the other hand, polyethylene has low dielectric constant and low loss but high dielectric strength. The best material for high voltage and high temperature operation is teflon (P.T.F.E.) which can be used up to 250°C. Silicone rubber has a high degree of heat resistance for continuous operation up to 150°C. It gives rise to very little carbon formation when destroyed by fire, and as such it continues to function even after the fire. Hence it is used for aircraft cables where contamination with aircraft fuel can occur at very high temperatures.

In paper insulated cables the paper is impregnated with oil by the process of mass impregnation using free flowing liquid. Table 5.3 gives the various insulating materials used in cables and the maximum cable operating voltages and temperatures.

Table 5.3 Cable Insulations

Insulation	Maximum cable operating voltage a.c. (kV)	Range of operating temperature (°C)
(a) *Impregnated Paper*		
Solid type	95.0	–10 to 85
Oil-filled	400.0	–20 to 70
Gas-filled	400.0	–20 to 70
Varnished cloth	28.0	–10 to 80

(*Contd.*)

6

Generation of High Voltages and Currents

In the fields of electrical engineering and applied physics, high voltages (d.c., a.c., and impulse) are required for several applications. For example, electron microscopes and x-ray units require high d.c. voltages of the order of 100 kV or more. Electrostatic precipitators, particle accelerators in nuclear physics, etc. require high voltages (d.c.) of several kilovolts and even megavolts. High a.c. voltages of one million volts or even more are required for testing power apparatus rated for extra high transmission voltages (400 kV system and above). High impulse voltages are required for testing purposes to simulate overvoltages that occur in power systems due to lightning or switching surges. For electrical engineers, the main concern of high voltages is for the insulation testing of various components in power systems for different types of voltages, namely, power frequency a.c., high frequency, switching or lightning impulses. Hence, generation of high voltages in laboratories for testing purposes is essential and is discussed in this chapter.

Different forms of high voltages mentioned above are classified as

(*i*) high d.c. voltages
(*ii*) high a.c. voltages of power frequency.
(*iii*) high a.c. voltages of high frequency.
(*iv*) high transient or impulse voltages of very short duration such as lightning overvoltages, and
(*v*) transient voltages of longer duration such as switching surges.

Normally, in high voltage testing, the current under conditions of failure is limited to a small value (less than an ampere in the case of d.c. or a.c. voltages and few amperes in the case of impulse or transient voltages). But in certain cases, like the testing of surge diverters or the short circuit testing of switchgear, high current testing with several hundreds of amperes is of importance. Tests on surge diverters require high surge currents of the order of several kiloamperes. Therefore, test facilities require high voltage and high current generators. High impulse current generation is also required along with voltage generation for testing purposes.

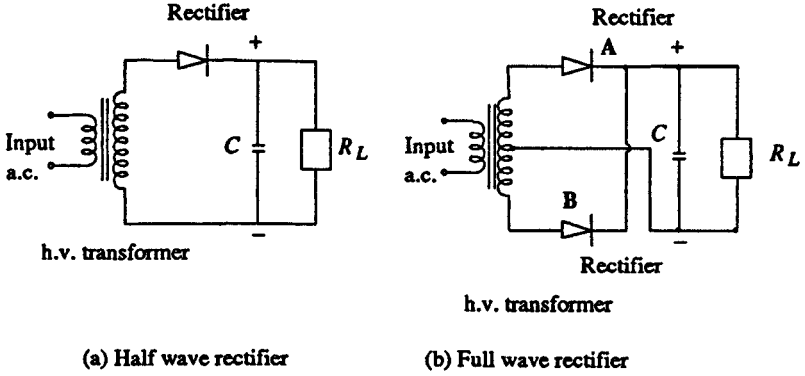
6.1 GENERATION OF HIGH d.c. VOLTAGES

Generation of high d.c. 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 d.c.

voltages of about 100 to 200 kV. Normally, for the generation of d.c. voltages of up to 100 kV, electronic valve rectifiers are used and the output currents are about 100 mA. The rectifier valve require special construction for cathode and filaments since a high electrostatic field of several kV/cm exists between the anode and the cathode in the non-conduction period. The a.c. supply to the rectifier tubes may be of power frequency or may be of audio frequency from an oscillator. The latter is used when a ripple of very small magnitude is required without the use of costly filters to smoothen the ripple.

6.1.1 Half and Full Wave Rectifier Circuits

Rectifier circuits for producing high d.c. voltages from a.c. 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.



(a) Half wave rectifier (b) Full wave rectifier

Fig. 6.1 Full and half wave rectifiers

Commonly used half wave and full wave rectifiers are shown in Fig. 6.1. In the half wave rectifier (Fig. 6.1a) the capacitor is charged to V_{max}, the maximum a.c. 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 a.c. supply. The rectifier valve must have a peak inverse rating of at least $2\,V_{max}$. 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. 6.1b. 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 $2V$.

For applications at high voltages of 50 kV and above, the rectifier valves used are of special construction. Apart from the filament, the cathode and the anode, they contain a protective shield or grid around the filament and the cathode. The anode will be usually a circular plate. Since the electrostatic field gradients are quite large, the heater and the cathode experience large electrostatic forces during the non-conduction periods. To protect the various elements from these forces, the anode is firmly fixed to the valve cover on one side. On the other side, where the cathode and filament are located, a steel mesh structure or a protective grid kept at the cathode potential surrounds them so that the mechanical forces between the anode and the cathode are reflected on the grid structure only.

In modern high voltage laboratories and testing installations, semiconductor rectifier stacks are commonly used for producing d.c. voltages. Semiconductor diodes are not true valves since they have finite but very small conduction in the backward direction. The more commonly preferred diodes for high voltage rectifiers are silicon diodes with peak inverse voltage (P.I.V.) of 1 kV to 2 kV. However, for laboratory applications the current requirement is small (a few milliamperes, and less than one ampere) and as such a selenium element stack with P.I.V. of up to 500 kV may be employed without the use of any voltage grading capacitors.

Both full wave and half wave rectifiers produce d.c. voltages less than the a.c. 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.

Ripple Voltage with Half Wave and Full Wave Rectifiers

When a full wave or a half wave rectifier is used along with the smoothing condenser C, the voltage on no load will be the maximum a.c. voltage. But when on load, the condenser gets charged from the supply voltage and discharges into load resistance R_L whenever the supply voltage waveform varies from peak value to zero value. These waveforms are shown in Fig. 6.2. When loaded, a fluctuation in the output d.c. voltage δV appears, and is called a ripple. The ripple voltage δV is larger for a half wave rectifier than that for a full wave rectifier, since the discharge period in the case of half wave rectifier is larger as shown in Fig. 6.2. The ripple δV depends on (*a*) the supply voltage frequency f, (*b*) the time constant CR_L, and (*c*) the reactance of the supply transformer X_L. For half wave rectifiers, the ripple frequency is equal to the supply frequency and for full wave rectifiers, it is twice that value. The ripple voltage is to be kept as low as possible with the proper choice of the filter condenser and the transformer reactance for a given load R_L.

6.1.2 Voltage Doubler Circuits

Both full wave and half wave rectifier circuits produce a d.c. voltage less than the a.c. maximum voltage. When higher d.c. voltages are needed, a voltage doubler or cascaded rectifier doubler circuits are used. The schematic diagram of voltage doublers are given in Figs. 6.3a and b.

In voltage doubler circuit shown in Fig. 6.3a, 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 $+2V_{max}$.

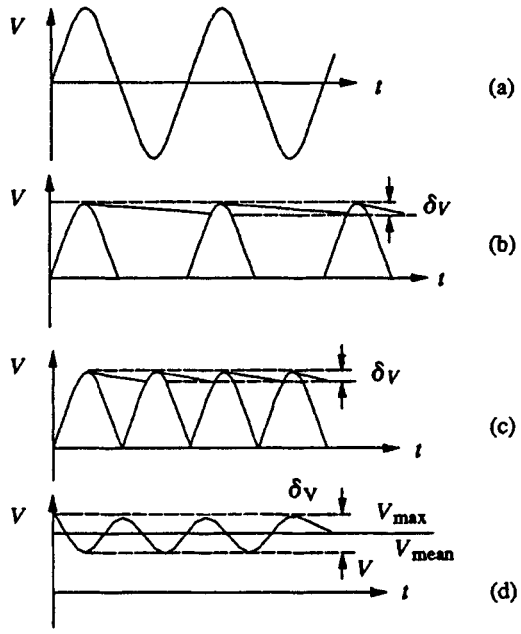


Fig. 6.2 Input and output waveforms of half and full wave rectifiers

(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

Thus, the condenser C_2 in turn is charged through R_2 to $2V_{max}$. Normally the d.c. output voltage on load will be less than $2V_{max}$, depending on the time constant C_2R_L and the forward charging time constants. The ripple voltage of these circuits will be about 2% for $R_L/r \leq 10$ 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. 6.3b and its input and output waveforms are shown in Fig. 6.3(c). The rectifiers R_1 and R_2 with transformer T_1 and condensers C_1 and C_2 produce an output voltage of $2V$ in the same way as described above. This circuit is duplicated and connected in series or cascade to obtain a further voltage doubling to $4V$. T is an isolating transformer to give an insulation for $2V_{max}$ since the transformer T_2 is at a potential of $2V_{max}$ above the ground. The voltage distribution along the rectifier string R_1, R_2, R_3 and R_4 is made uniform by having condensers C_1, C_2, C_3 and C_4 of equal values. The arrangement may be extended to give $6V$, $8V$, and so on by repeating further stages with suitable isolating transformers. 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.

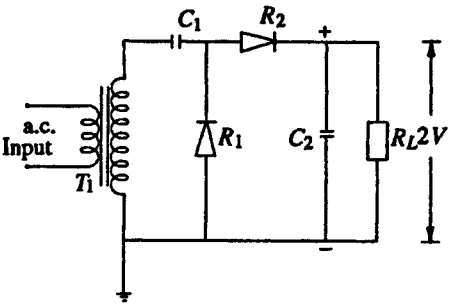


Fig. 6.3a Simple voltage doubler

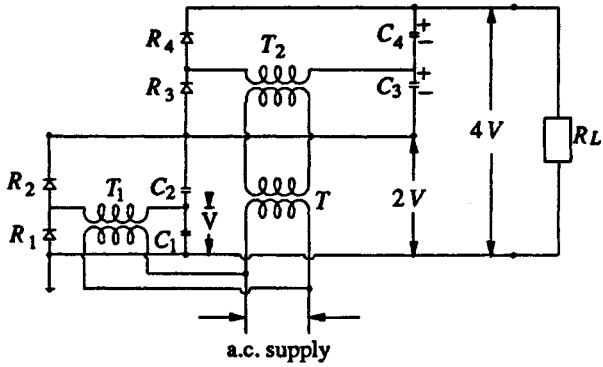


Fig. 6.3b Cascaded voltage doubler

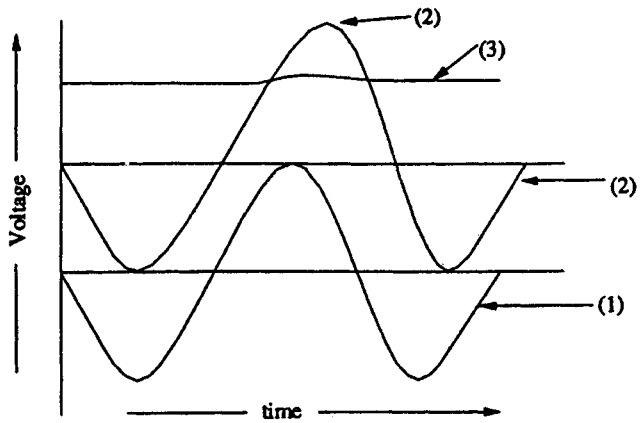


Fig. 6.3 (c) Waveforms of a.c. voltage and the d.c. output voltage on no-load of the voltage doubler shown in Fig. 6.3 (b)

(1) a.c input voltage waveform, (2) a.c. output voltage waveform without condenser filter, (3) a.c. output voltage waveform with condenser filter

Fig. 6.3 Voltage doubler circuits

T_1, T_2 – h.v. transformers; R_1, R_2, R_3, R_4 – rectifiers;
C_1, C_2, C_3 – condensers; R_L – Load resistance; T – isolating transformer

6.1.3 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 d.c. voltages from single supply transformers by extending the simple voltage doubler circuits. This is simple and compact when the load current requirement is less than one milliampere, such as for cathode ray tubes, etc. Valve type pulse generators may be used instead of conventional a.c. supply and the circuit becomes compact. A typical circuit of this form is shown in Fig. 6.4a.

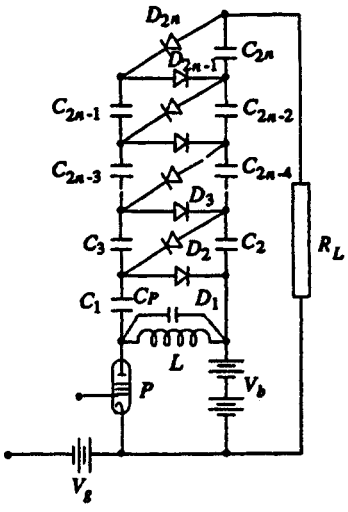


Fig. 6.4a Cascaded rectifier unit with pulse generator

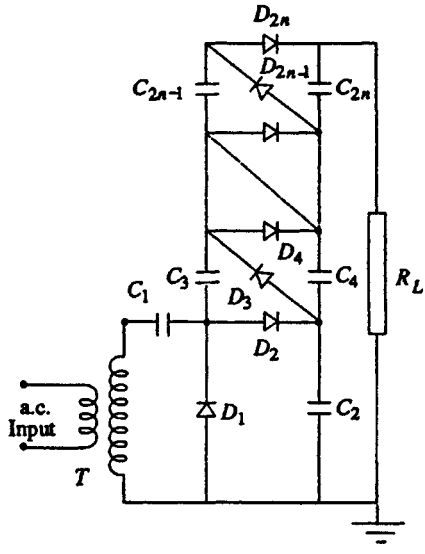


Fig. 6.4b Cockcroft-Walton voltage multiplier circuit

P — Pulse generator

V_b — D.C. supply to pulse generator

V_g — Bias voltage

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 d.c. power supply of about 500 V applied to the pulse generator, is sufficient to generate a high voltage d.c. of 50 to 100 kV with suitable number of stages. The pulse frequency is high (about 500 to 1000 Hz) and the ripple is quite low (<1%). The voltage drop on load is about 5% for load currents of about 150 μ A. The voltage drops rapidly at high load currents.

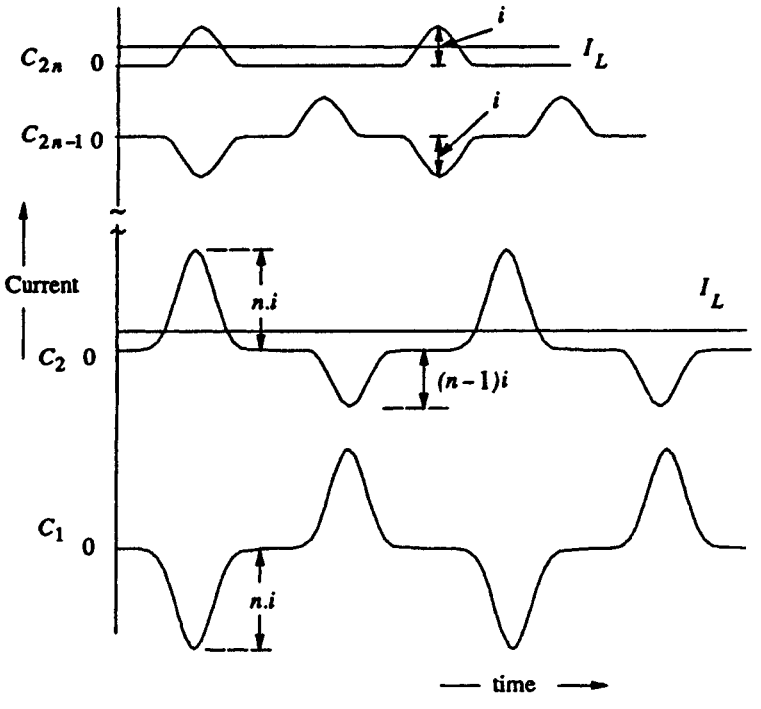


Fig. 6.4c Schematic current waveforms across the first and the last capacitors of the cascaded voltage multiplier circuit shown in Fig. 6.4(b)

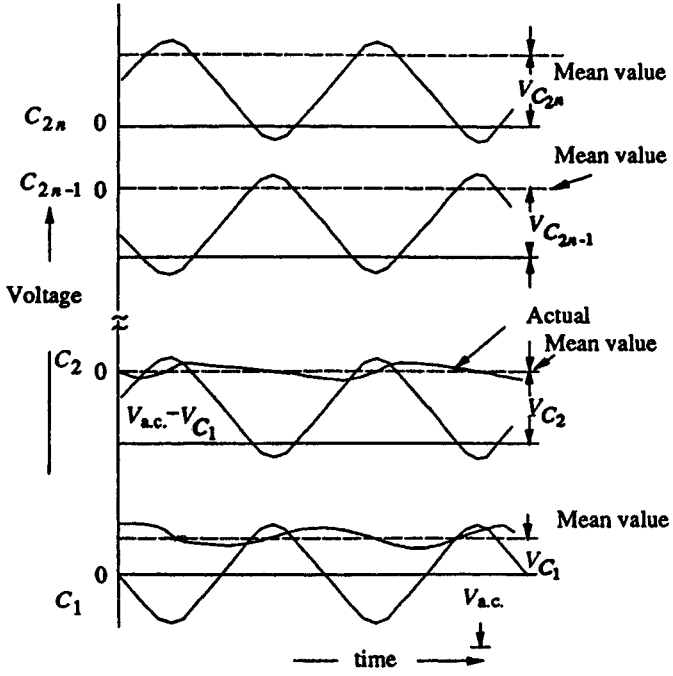


Fig. 6.4d Voltage waveforms across the first and the last capacitors of the cascaded voltage multiplier circuit shown in Fig. 6.4(b)

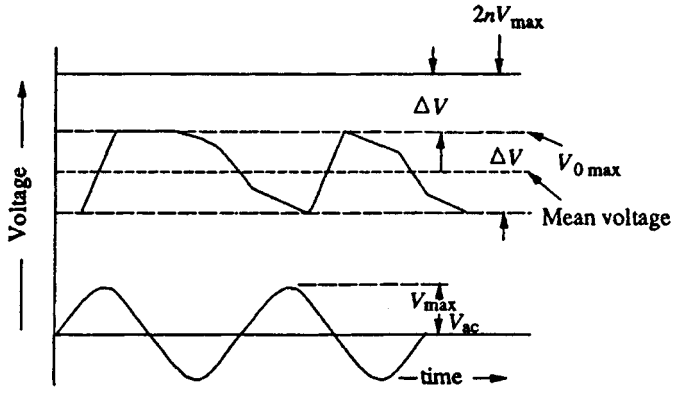


Fig. 6.4e Ripple voltage δV and the voltage drop ΔV in a cascaded voltage multiplier circuit shown in Fig. 6.4(b)

Voltage multiplier circuit using the Cockcroft-Walton principle is shown in Fig. 6.4b. The first stage, i.e. D_1, D_2, C_1, C_2, and the transformer T are identical as in the voltage doubler shown in Fig. 6.3. 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. 6.4b operate and conduct during the positive half cycles while the rectifiers $D_2, D_4 ... D_{2n}$ conduct during the negative half cycles. Typical current and voltage waveforms of such a circuit are shown in Figs. 6.4c and 6.4d respectively. The voltage on C_2 is the sum of the input a.c. voltage. V_{ac} and the voltage across condenser C_1, V_{c_1}) as shown in Fig 6.4. The mean voltage on C_2 is less than the positive peak charging voltage ($V_{ac} + V_{c_1}$). The voltages across other condensers C_2 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. 6.4e.

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 = 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. 6.3a, 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.

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

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

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

Also, $$q = C_2 \delta V$$

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

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 $2V_{max}$

$$= \frac{I_1}{f}\left[\frac{1}{C_1} + \frac{1}{2C_2}\right] \tag{6.1}$$

Therefore, the mean output voltage $= 2V_{max} - \frac{I_1}{f}\left(\frac{1_1}{C_1} + \frac{1}{2C_2}\right)$.

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 Fig. 6.4b, 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 C_{2n} 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

$$\delta V_{\text{total}} = \frac{I_1}{fC}[1+2+3\ldots+n] = \frac{I_1}{fC}\frac{n(n+1)}{2}. \tag{6.2}$$

It can be seen from the above expression that the lowest capacitances (C_2, C_4, etc.) contribute most for the ripple. If these capacitances are increased proportionately, i.e. C_1 and C_2 are made equal to nC, C_3 and C_4 are made equal to $(n-1)C$ and so on, the total ripple will be only $\frac{nI_1}{fC}$.

Regulation or Voltage Drop on Load

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

To find ΔV, the voltage drop under load condition, it is assumed that all the capacitors C_1, C_2 ...C_{2n} have equal value, C. From the analysis of the ripple voltage it may be seen that all the capacitors are not charged to $2V_{\max}$. The condenser C_2 is charged to $[2V_{\max} - 2nI_1/fC]$ volts. Similarly, condenser C_3 is charged to a voltage of $[2V_{\max} - 2nI_1/fC] - (2n-1)I_1/fC]$ volts. This is because, condenser C_3 during the conduction period transfers a charge of $(2n-1)I_1/fC$ to the load and to the next stage.

Thus, the voltage drops at various condenser stages. Taking them in pairs, for a stack of $2n$ stages, the drop will be

$$\begin{aligned}
\Delta V_{2n} &= nI_1/fC \text{ (due to the ripple from } n \text{ stages.)} \\
&= I_1/fC\,(2n-n). \\
\Delta V_{2n-2} &= (n-1)\,I_1/fC + 2n\,I_1/fC \text{ (due to ripple and voltage drop due to charge transfer to the next stage)} \\
&= (I_1/fC)\,[2n+(n-1)] \\
&= I_1/fC\,[2n+2(n-1)-(n-1)] \\
\Delta V_4 &= I_1/fC\,[2n+2(n-1)+\ldots+2] \\
&= I_1/fC\,[2n+2(n-1)+\ldots+2\cdot2-2] \\
\Delta V_2 &= I_1/fC\,[2n+2(n-1)+\ldots+2\cdot2-1] \\
&= I_1/fC\,[2n+2(n-1)+\ldots+2\cdot2+2\cdot1-1].
\end{aligned}$$

So that,

$$\begin{aligned}
\Delta V &= (I_2/fC)\sum_{r=1}^{n}\Delta V_{2r} = (I_1/fC)\left[\sum_{1}^{n}n(2n)-\sum_{1}^{n}n\right] \\
&= (I_1/fC)\sum_{1}^{n}n(2n-1) \\
&= (I_1/fC)\,[2.n.(n+1)\,(2n+1)/6 - n\,(n+1)/2] \\
&= (I_1/fC)\,[(2/3).n^3 + n^2/2 - n/6] \qquad (6.3)
\end{aligned}$$

Here also, it is seen that most of the voltage drop is due to the lowest stage condensers C_1, C_2, etc. Hence, it is advantageous to increase their values proportional to the number of the stage from the top.

For large values of n (≥ 5), $\frac{n^2}{2}$ and $\frac{n}{6}$ terms in Eq. (6.3) will becomes small compared to $\frac{2}{3}n^3$ and may be neglected; then the optimum number of stages for the minimum voltage drop may be expressed as

$$n_{\text{optimum}} = \sqrt{\frac{V_{\max} fC}{I}} \tag{6.4}$$

where I is the load current.

Thus, for a multiplier or a cascaded circuit with $f = 50$ Hz, $C = 0.1\ \mu F$, $V_{\max} = 100$ kV and $I = 5$ mA, the number of stages $n \approx 10$.

The regulation can be improved by increasing f, but an upper limit is set by the high voltage appearing across the inductances and high capacitor currents which are considerable. At present, the Cockcroft-Walton type voltage multipliers are available using selenium rectifiers and a.c. supply frequencies of 500 to 1000 Hz for output voltages of more than one million volts and load currents of 30 mA.

Cascaded Modular Voltage Multipliers or "Deltatron" Circuits for Very High Voltages

A combination of Cockcroft-Walton type voltage multiplier with cascaded transformer d.c. rectifier is developed recently for very high voltages but limited output currents having high stability, small ripple factor and fast regulation. One such unit is recently patented by "ENGE" in U.S.A., called "ENGETRON" or "DELTATRON". The schematic diagram of a typical Deltatron unit is shown in Fig. 6.5.

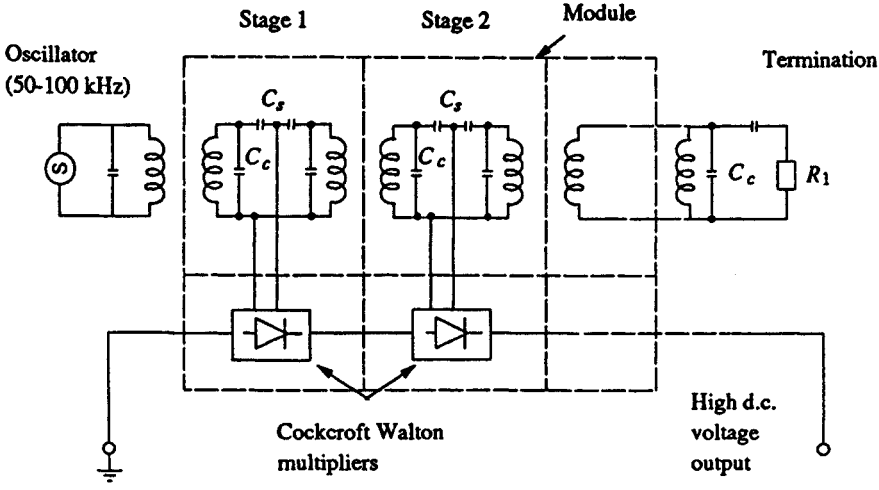


Fig. 6.5 Deltatron unit for generation of very high d.c. voltages

Basically this circuit consists of Cockcroft-Walton multiplier units fed from a supply transformer unit (stage 1). These supply transformers are air-cored to have low inductance and are connected in series through capacitors C. In addition, the windings of the transformers are shunted by a capacitor C to compensate for the magnetising current. The entire unit is terminated by a load resistor R_1. All the Cockcroft-Walton multipliers are connected in series and the entire unit is enclosed in a cylindrical vessel insulated by SF_6 gas. Each stage of the unit is typically rated for 10 to 50 kV, and about 20 to 25 stages are used in a unit. The whole assembly is usually of smaller size and weight than a cascaded rectifier unit. The supply frequency to the transformers is from a high frequency oscillator (50 to 100 kHz) and as such the capacitors used are of smaller value. The voltage regulation system is controlled by a parallel R-C divider which in turn controls the supply oscillator. Regulation due to load variations or power source voltage variations is very fast (response time < 1 ms). The disadvantage of this circuit is that the polarity of the unit cannot be reversed easily. Typical units of this type may have a rating of 1 MV, 2 mA with each module or stage rated for 50 kV with ripple content less than 1%.

6.1.4 Electrostatic Machines: Basic Principle

In electromagnetic machines, current carrying conductors are moved in a magnetic field, so that the mechanical energy is converted into electrical energy. In electrostatic machines charged bodies are moved in an electric field against an electrostatic field in order that mechanical energy is converted into electrical energy. Thus, if an insulated belt with a charge density δ moves in an electric field "$E(x)$" between two electrodes with separation 's' then

(i) the charge on the strip of belt at a distance dx is $dq = \delta\, b.dx$ where b is the width of the belt, and

(ii) the force on the belt, F is

$$F = \int_o^s E(x) \cdot dq = \int_o^s \delta \cdot b \cdot E(x) dx$$

If the belt moves with a velocity, v, then the mechanical power P, required to move the belt is $P = F \cdot v = \delta \cdot b \cdot v \int_o^s E(x)\, dx$

The current, I, in the system is given as

$$I = dq/dt = \delta\, b \cdot dx/dt = \delta \cdot b \cdot v$$

and the potential difference, V, between the electrodes is

$$V = \int_o^s E(x)\, dx$$

Thus, in an electrostatic machine, the mechanical power required to move the belt at a velocity v, i.e. $P = F.v$ is converted into the electrical power, $P = V.I$, assuming that

there are no losses in the system. The Van de Graaff generator is one such electrostatic machine which generates very high voltages, with small output current.

Van de Graaff Generators

The schematic diagram of a Van de Graaff generator is shown in Fig. 6.6. 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 metres per minute. The potential of the high 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 earth. The potential of the high voltage electrode rises at a rate

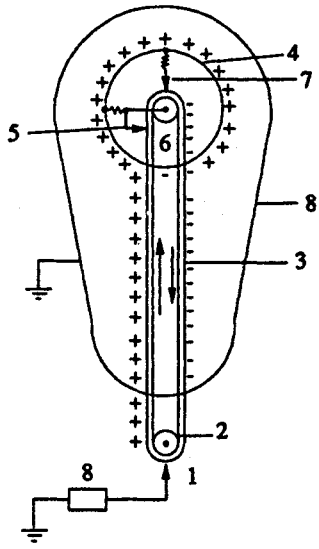


Fig. 6.6 Van de Graaff generator

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

$$\frac{dV}{dt} = \frac{I}{C}\frac{dQ}{dt} = \frac{I}{C}$$ 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 d.c. 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.

The charging current for unit surface area of the belt is given by $I = bv\,\delta$, where b is the breadth of the belt in metres, v is the velocity of the belt in m/sec, and δ is the surface charge density in coulombs/m^2. It is found that $\delta \leq 1.4 \times 10^{-5}$ C/m^2 to have a safe electric field intensity normal to the surface. With $b = 3$ m and $v = 3$ m/sec, the charging current will be approximately 125 μA. The generator is normally worked in a high pressure gaseous medium, the pressure ranging from 5 to 15 atm. The gas may be nitrogen, air, air-freon (CCl_2F_2) mixture, or sulphur hexafluoride (SF_6).

Van de Graaff generators are useful for very high voltage and low current applications. 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.

Electrostatic Generators

Van de Graaff generators are essentially high voltage but low power devices, and their power rating seldom exceeds few tens of kilowatts. As such electrostatic machines which effectively convert mechanical energy into electrical energy using variable capacitor principle were developed. These are essentially duals of electromagnetic machines and are constant voltage variable capacitance machines. An electrostatic generator consists of a stator with interleaved rotor vanes forming a variable capacitor and operates in vacuum.

The current through a variable capacitor is given by $I = \dfrac{dV}{Cdt} + V\dfrac{dC}{dt}$ where C is a capacitor charged to a potential V.

The power input into the circuit at any instant is

$$P = VI = CV\frac{dV}{dt} + V^2\frac{dC}{dt} \tag{6.5}$$

If $\dfrac{dC}{dt}$ is negative, mechanical energy is converted into electrical energy.

With the capacitor charged with a d.c. voltage V, $\dfrac{dC}{dt} = 0$ and the power output will be $P = V^2\dfrac{dC}{dt}$.

A schematic diagram of a synchronous electrostatic generator with interleaved stator and rotor plates is shown in Fig. 6.7. The rotor is insulated from the ground, and is maintained at a potential of $+V$. The rotor to stator capacitance varies from C_0 to C_m, and the stator is connected to a common point between two rectifiers across the d.c. output which is $-E$ volts. When the capacitance of the rotor is maximum (C_m), the rectifier B does not conduct and the stator is at ground potential. The potential E is

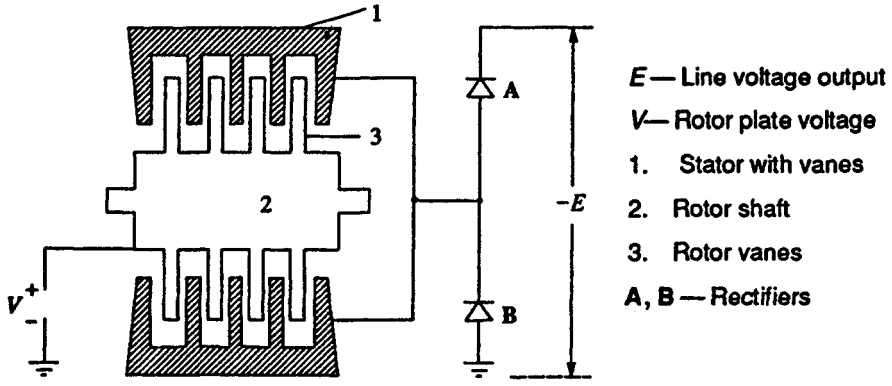


Fig. 6.7 Electrostatic generator

applied across the rectifier A and V is applied across C_m. As the rotor rotates, the capacitance C decreases and the voltage across C increases.

Thus, the stator becomes more negative with respect to ground. When the stator reaches the line potential $-E$ the rectifier A conducts, and further movement of the rotor causes the current to flow from the generator. Rectifier B will now have E across it and the charge left in the generator will be $Q_0 = C_0 (V + E) + E(C_s + C_r)$, where C_s is the stator capacitance to earth, C_r is the capacitance of rectifier B to earth, and C_0 is the minimum capacitance value of C (stator to rotor capacitance).

A generator of this type with an output voltage of one MV and a field gradient of 1 MV/cm in high vacuum and having 16 rotor poles, 50 rotor plates of 4 feet maximum and 2 feet minimum diameter, and a speed of 4000 rpm would develop 7 MW of power.

6.1.5 Regulation of d.c. Voltages

The output voltage of a d.c. source, whether it is a rectifier or any other machine, changes with the load current as well as with the input voltage variations. In order to maintain a constant voltage at the load terminals, it is essential to have a regulator circuit which corrects the variation in voltage. It is essential to keep the change in voltage between ± 0.1% and ± 0.001% depending on the applications.

A d.c. voltage regulator consists of detecting elements which sense the change in voltage from the desired value and controlling elements actuated by the detector in

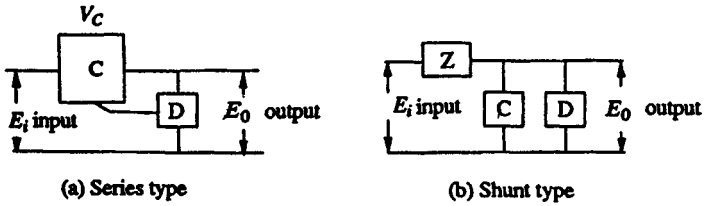


Fig. 6.8 Schematic diagram of voltage stabilizers

such a manner as to correct the changes. The regulators are generally of two types (*a*) series type, and (*b*) shunt or parallel type. Schematic diagrams of these regulators are given in Fig. 6.8.

If ΔE_0 is the change in E_0 as a result of a change of ΔE_i in E_i, then the stabilization ratio S is defined as

$$S = [\Delta E_i / E_i] / [\Delta E_0 / E_0]$$
$$= \frac{\Delta E_i}{\Delta E_0} \frac{E_0}{E_i}. \tag{6.6}$$

A second parameter R_0 is introduced to define completely the functional performance of a regulator. R_0 is the effective internal resistance of the regulator as seen from the output terminals.

$$R_0 = \frac{\Delta E_0}{\Delta I_0}$$

where ΔE_0 is the change in the output voltage caused due to a change in load current of ΔI_0, with the input voltage remaining constant.

The regulation R is defined as,

$$R = [\Delta E_0 / E_0] / [\Delta I_0 / I_0] = \frac{R_0}{R_L} \tag{6.7}$$

where R_L is the load resistance.

Typical series type regulator and degenerative feedback system of voltage regulation are shown in Figs. 6.9a and b respectively.

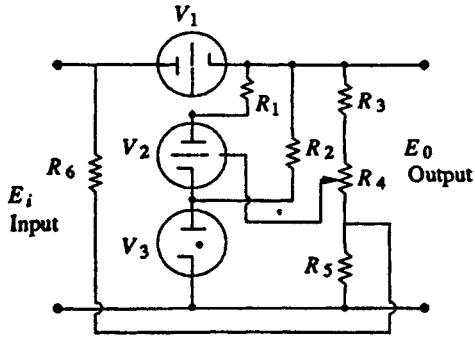


Fig. 6.9a Series d.c. voltage regulator

V_1— Series regulating tube

V_2— Sensing and amplifying tube

V_3— Reference tube

R_1— Grid control resistance for tube 1

R_3, R_4, R_5 — Output potential divider

R_6— Input fluctuation correction resistance

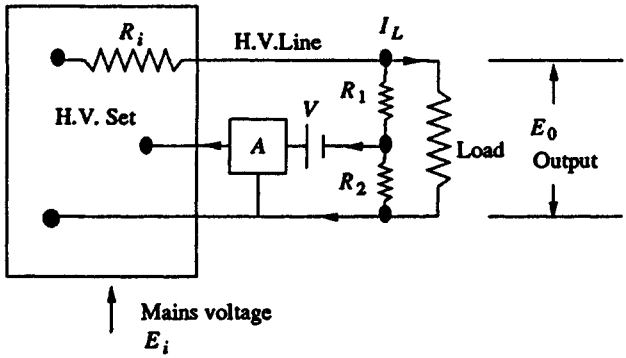


Fig. 6.9b Degenerative feedback system of voltage regulation

R_1, R_2 — Potential divider
A — d.c. amplifier
R_i — Internal resistance of control source, the h.v. set

Figure 6.9a shows the simplified diagram of a series type of voltage regulator. Here the gas tube V_3 provides the reference voltage which keeps the potential of the cathode of the tube V_2 constant. When the output voltage E_0 changes, the current through the divider R_2, R_4 and R_5 changes, and hence the bias voltage of the tube V_2 with respect to its cathode changes in the opposite manner (reduces when the output voltage increases and vice versa). Thus, the grid potential of V_1 is altered in such a manner as to oppose the variation in output voltage E_0; that is, the voltage drop across the tube V_1 reduces, if the output voltage decreases and vice versa. Resistance R_6 together with R_5 provides a voltage input to the d.c. amplifier (the detector) in proportion to fluctuations in the input voltage in such a way as to reduce the effect of these variations in the output voltage.

A convenient method of regulating high d.c. voltages is the degenerative feedback system, shown in Fig. 6.9b. The fluctuations in the output voltage are measured by a detecting device, amplified by a d.c. amplifier and fed back into the high voltage set so as to correct for the original fluctuations. The detecting device in the above circuit is the potential divider of ratio $\beta = R_1/(R_1 + R_2)$. The amplifier is directly coupled and the difference in potential between the tapping on the divider and the amplifier grid voltage is made up by the battery voltage V.

The output voltage E_0 is given as follows:

$$E_0 = NE_i - I_l R_i - Ae \qquad (6.7a)$$

where N = ratio between the output voltage of the h.v. set and the main supply voltage, E_i,

I_l = load current,

R_i = internal resistance of the h.v. set,

A = gain of the feedback amplifier,

e = amplifier input voltage.

Since $e = \beta E_0 - V$, the output voltage becomes

$$E_0 = NE_i - I_l R_i - (\beta E_v - V) A = NE_i - I_l R_i - A\beta E_0 + AV$$

or, $$E_0(1 + A\beta) = NE_i + AV - I_l R_i$$

or, $$E_0 = \frac{NE_i}{(1+A\beta)} + \frac{AV}{(1+A\beta)} - \frac{I_l R_i}{(1+A\beta)}.$$

For large values of A

$$E_0 = \frac{AV}{(1+A\beta)} \simeq \frac{V}{\beta}.$$

The stabilization ratio = $[\Delta E_i/E_i]/[\Delta E_0/E_0] = 1 + A\beta$.

In practice, values of $A\beta$ of the order of 1000 are common. It can be seen that for given value of A, stabilization ratio can be increased by making β as large as possible.

Stabilities to about 2 parts in 10^4 in high voltage are easily obtained by this method if load changes are kept small.

6.2 GENERATION OF HIGH ALTERNATING VOLTAGES

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

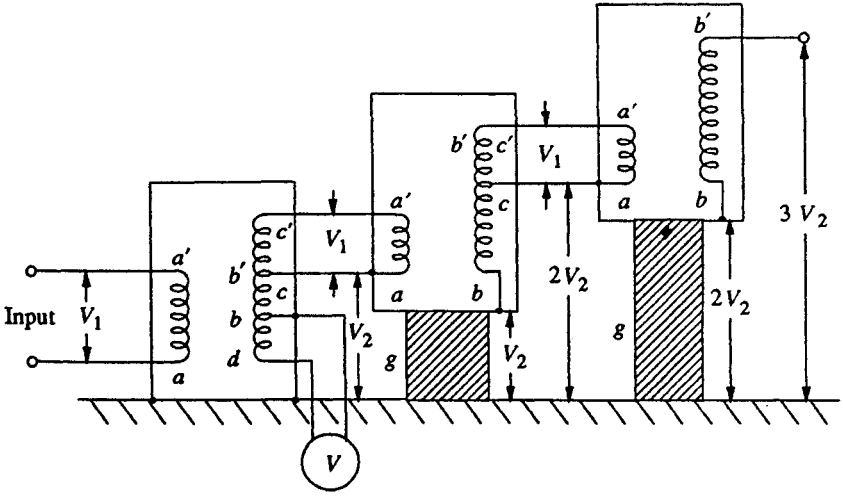


Fig. 6.10 Cascade transformer connection (schematic)

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)

voltage windings, 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 Figs. 6.10 and 6.11.

6.2.1 Cascade Transformers

Figure 6.10 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

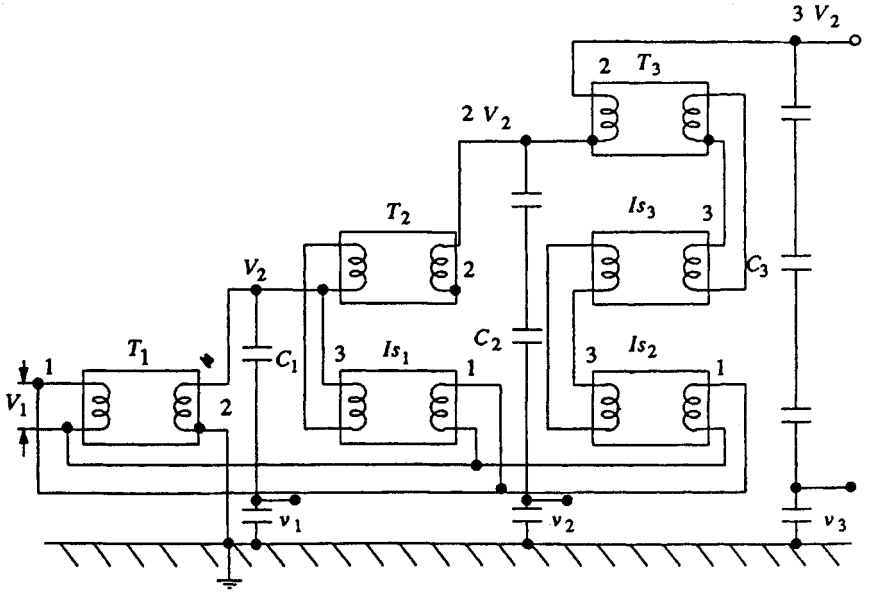


Fig. 6.11 Cascade transformer unit with isolating transformers for excitation

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.

connection from the first transformer winding and the excitation winding terminal are taken through a bushing to the second transformer. 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 $\sqrt{3}V_2$ can be obtained between the lines.

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

In Fig. 6.11, a second scheme for providing the excitation to the second and the third stages is shown. 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 a.c. 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. Three phase connection in delta or star is possible for three units. Testing transformers of ratings up to 10 MVA in cascade connection to give high voltages up to 2.25 MV are available for both indoor and outdoor applications.

Testing of an H.V. apparatus or insulation always involves supplying of capacitive loads with very low power dissipation. Thus if C is the capacitance of the test object, V is the rms value of the nominal output voltage of the transformer at an angular frequency ω, then the nominal rating of the transformer in kVA will be $P = K \cdot V^2 \omega C$, where K (> 1.0) is a factor to account for any extra capacitance in the test circuit like that of the measuring capacitance divider etc. K may have values of the order of 2 or more for very high voltages (> 1MV). Typical capacitance values for high capacitance test objects like power transformers, cables etc. are as follows:

Power transformers (rating < 1MVA)	1000 pF
Power transformers (rating > 1MVA)	1000-10,000 pF
High Voltage power cables (with solid insulation)	250-300 pF/m
High Voltage power cables (with gas insulation)	50-80 pF/m
Metal Clad sub-station with gas insulation (G.I.S.)	100-10,000 pF

The charging currents for the test apparatus may range from 10 mA at 100 kV to a few milliamperes in the megavolt range. As such the transformers should have only a short time rating (10 to 15 min) for high power ratings, as compared to those with nominal power ratings.

Large testing transformers rated for more than 1 MVA at 1 MV are now-a-days designed for outdoor use only. The design is of the type mentioned in the second scheme and ensures that the units are enclosed by large-size metal rings to prevent corona, and are terminated with near spherical polycone electrodes. Modern test transformers are built to withstand transients during the flashover of the test object. However, particular care need to be taken to see that steady state voltage distribution

within the cascade units is uniform. Sometimes reactor compensation may have to be provided for excessive load currents of capacitive nature. Cascade transformers are very expensive apparatus and are difficult to repair. Therefore it is necessary to limit the high short-circuit currents by using limiting reactors in the input stage.

Power Supply for a.c. Test Circuits

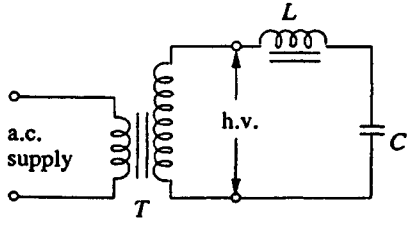
Large cascade transformers units are supplied power through a separate motor-generator set or by means of voltage regulators. Supply through a voltage regulator will be cheaper, and will be more flexible in the sense that the units in the cascade set can be operated in cascade, or in parallel,or as three-phase units. It is also necessary that the impedance of the voltage regulating transformer is low in all voltage positions, from the minimum to the rate value.

6.2.2 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. 6.12 (a) with its equivalent circuit in Fig. 6.12(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

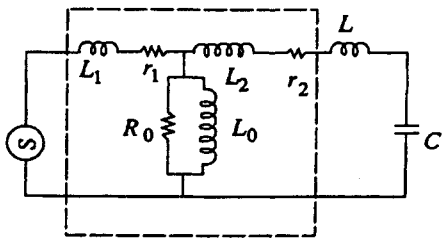
$$V_C = \left| \frac{-jVX_C}{R+j\,(X_L - X_C)} \right| = \frac{V}{R} X_C = \frac{V}{\omega CR} \qquad (6.8)$$

where R is the total series resistance of the circuit.



(a)

Fig. 6.12a Transformer



(b)

Fig. 6.12b Equivalent circuit

T — Testing transformer
L — Choke
C — Capacitance of h.v. terminal and test object
L_0 — Magnetizing inductance
L_1, L_2 — Leakage inductances of the transformer
r_1, r_2 — Resistances of the windings
R_0 — Resistance due to core loss

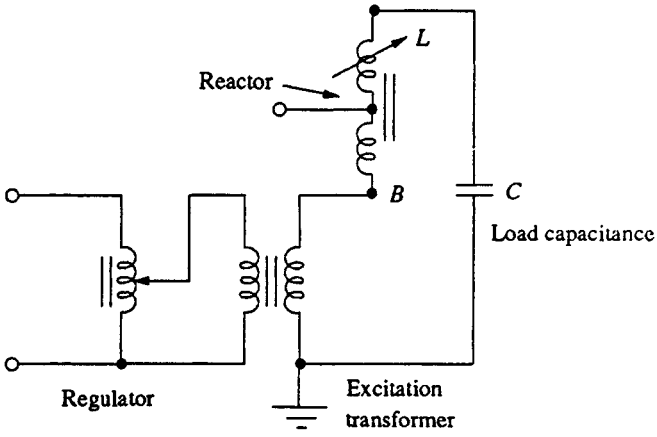


Fig. 6.12c Series resonant a.c. test system

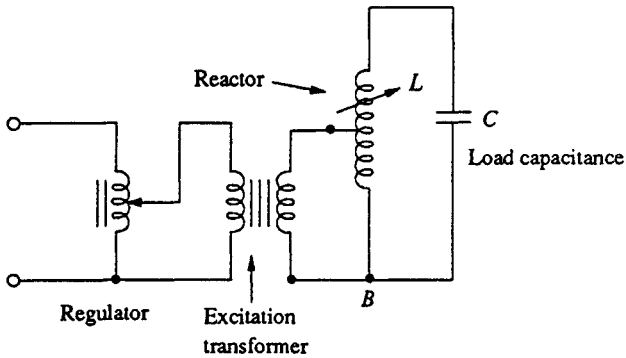


Fig. 6.12d Parallel resonant a.c. test system

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

Fig. 6.12 Resonant transformer and equivalent circuit

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 test condition is set such that $\omega(L_e + L) = 1/\omega C$ where L_e is the total equivalent leakage inductance of the transformer including its regulating transformer. 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.

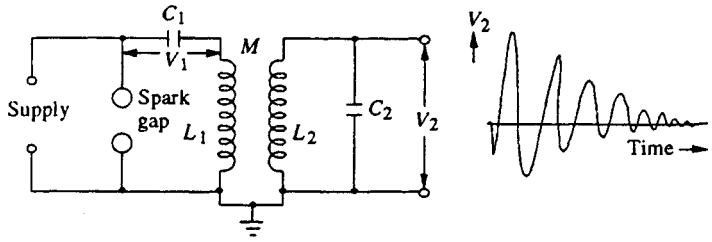
A simplified diagram of the series resonance test system is given in Fig. 6.12c and that of the parallel resonant test system in 6.12d. A voltage regulator of either the auto-transformer type or the induction regulator type is connected to the supply mains and the secondary winding of the exciter transformer 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. Single unit resonant test systems are built for output voltages up to 500 kV, while cascaded units for outputs up to 3000 kV, 50/60 Hz are available.

6.2.3 Generation of High Frequency a.c. High Voltages

High frequency high voltages are required for rectifier d.c. power supplies as discussed in Sec. 6.1. Also, for testing electrical apparatus for switching surges, high frequency high voltage damped oscillations are needed which need high voltage high frequency transformers. The advantages of these high frequency transformers are:

(*i*) the absence of iron core in transformers and hence saving in cost and size,
(*ii*) pure sine wave output,
(*iii*) slow build-up of voltage over a few cycles and hence no damage due to switching surges, and
(*iv*) uniform distribution of voltage across the winding coils due to subdivision of coil stack into a number of units.

The commonly used high frequency resonant transformer is the Tesla coil, which is a doubly tuned resonant circuit shown schematically in Fig. 6.13a. The primary voltage rating is 10 kV and the secondary may be rated to as high as 500 to 1000 kV. The primary is fed from a d.c. or a.c. supply through the condenser C_1. A spark gap G connected across the primary is triggered at the desired voltage V_1 which induces



(a) Equivalent circuit (b) Output waveform

Fig. 6.13 Tesla coil equivalent circuit and its output waveform

a high self-excitation in the secondary. The primary and the secondary windings (L_1 and L_2) are wound on an insulated former with no core (air-cored) and are immersed in oil. The windings are tuned to a frequency of 10 to 100 kHz by means of the condensers C_1 and C_2.

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

The analysis of the output waveform can be done in a simple manner neglecting the winding resistances. Let the condenser C_1 be charged to a voltage V_1 when the spark gap is triggered. Let a current i_1 flow through the primary winding L_1 and produce a current i_2 through L_2 and C_2.

Then,

$$V_1 = \frac{1}{C_1}\int_0^t i_1\,dt + L_1\frac{di_1}{dt} + M\frac{di_2}{dt} \tag{6.9}$$

and,

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

The Laplace transformed equations for the above are,

$$\frac{V_1}{s} = \left[L_1 s + \frac{1}{C_1 s}\right] I_1 + MsI_2 \tag{6.10}$$

and,

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

where I_1 and I_2 are the Laplace transformed values, of i_1 and i_2.

The output voltage V_2 across the condenser C_2 is

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

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$$V_2(s) = \frac{I_2}{C_2 s} \tag{6.11}$$

where $V_2(s)$ is the Laplace transform of V_2.
The solution for V_2 from the above equations will be

$$V_2 = \frac{MV_1}{\sigma L_1 L_2 C_1} \frac{1}{\gamma_2^2 - \gamma_1^2} [\cos \gamma_1 t - \cos \gamma_2 t] \tag{6.12}$$

where,

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

K = coefficient of coupling between the windings L_1 and L_2

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

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

The output waveform is shown in Fig. 6.13b.

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

$$V_{2max} = V_1 e \sqrt{\frac{L_2}{L_1}} \tag{6.13}$$

where,

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

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

A more simplified analysis for the Tesla coil may be presented by considering that the energy stored in the primary circuit in the capacitance C_1 is transferred to C_2 via the magnetic coupling. If W_1 is the energy stored in C_1 and W_2 is the energy transferred to C_2 and if the efficiency of the transformer is η, then

$$W_1 = \frac{1}{2} \eta C_1 V_1^2 = (\tfrac{1}{2} C_2 V_2^2) \tag{6.14}$$

from which

$$V_2 = V_1 \sqrt{\eta \frac{C_1}{C_2}} \tag{6.14a}$$

It can be shown that if the coefficient of coupling K is large the oscillation frequency is less, and for large values of the winding resistances and K, the waveform may become a unidirectional impulse. This is shown in the next sections while dealing with the generation of switching surges.

6.3 GENERATION OF IMPULSE VOLTAGES

6.3.1 Standard Impulse Waveshapes

Transient overvoltages 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 μ s and decay time to 50% of the peak value of the order of 30 to 200 μ s. The waveshapes are arbitrary, but mostly unidirectional. It is shown that lightning overvoltage wave can be represented as double exponential waves defined by the equation

$$V = V_0 [\exp(-\alpha t) - \exp(-\beta t)] \qquad (6.15)$$

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 waveshape is given in Fig. 6.14. 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 peak value of 1000 kV. When impulse waveshapes 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 waveshape in Fig. 6.14, the peak value A is fixed and referred to as 100% value. The points corresponding to 10% and 90% of the peak values are located in the front portion (points C and D). The line joining these points is extended to cut the time axis at 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)

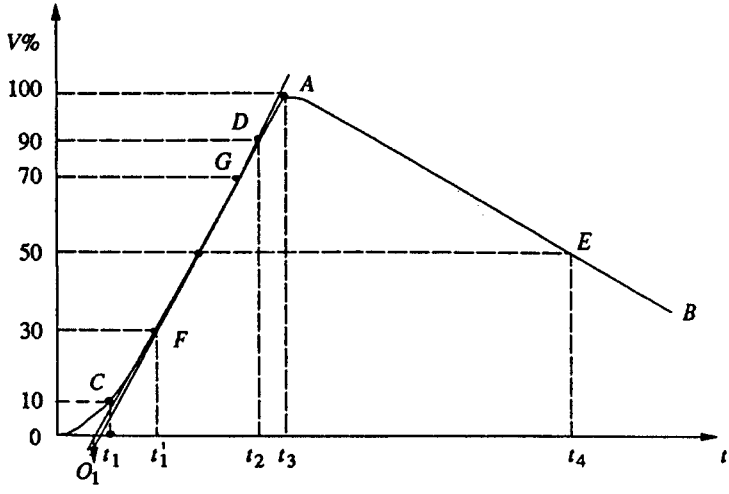


Fig. 6.14 Impulse waveform and its definitions

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 waveshape record, the point corresponding to 30% peak value F is taken and its projection t'_1 is located on time axis. The wavefront time in that case will be defined as 1.67 ($O_1t_3 - O_1t'_1$), 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%.

6.3.2 Theoretical Representation of Impulse Waves

The impulse waves are generally represented by the Eq. (6.15) given earlier. V_0 in the equation represents a factor that depends on the peak value. For impulse wave of 1.2/50 μs, $\alpha = -0.0146$, $\beta = -2.467$, and $V_0 = 1.04$ when time t is expressed in microseconds, α and β control the front and tail times of the wave respectively.

6.3.3 Circuits for Producing Impulse Waves

A double exponential waveform of the type mentioned in Eq. (6.15) 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 Figs. 6.15a to d. Out of these circuits, the ones shown in Figs. 6.15a to d are commonly used. Circuit shown in Fig. 6.15a is limited tomodel generators only, and commercial generators employ circuits shown in Figs. 6.15b to 6.15d.

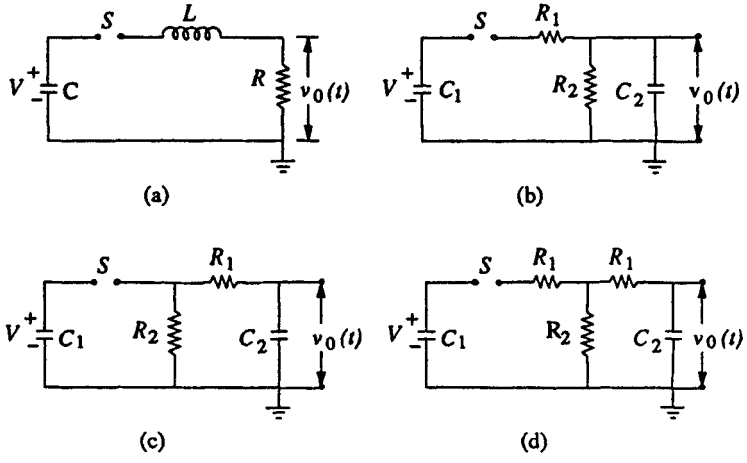


Fig. 6.15 Circuits for producing impulse waves

A capacitor (C_1 or C) previously charged to a particular d.c. voltage is suddenly discharged into the waveshaping network (LR, $R_1R_2C_2$ or other combination) by closing the switch S. The discharge voltage V_0 (t) shown in Fig. 6.15 gives rise to the desired double exponential waveshape.

Analysis of Impulse Generator Circuit of Series R-L-C Type

Referring to Fig. 6.15 the current through the load resistance R is given by

$$V = \frac{1}{C}\int_0^t i\,dt + Ri + L\frac{di}{dt} \tag{6.16}$$

with initial condition at $t = 0$ being $i(0) = 0$ and the net charge in the circuit $i = dq/dt = 0$. Writing the above equation as a Laplace transform equation,

$$V/s = \left(\frac{1}{Cs} + R + Ls\right) I(s)$$

or,
$$I(s) = \frac{V}{L}\left[\frac{1}{s^2 + \frac{Rs}{L} + \frac{1}{LC}}\right]$$

The voltage across the resistor R (which is the output voltage) is, $v_0(s) = I(s)\,R$; hence,

$$v_0(s) = V\frac{R}{L}\frac{1}{s^2 + \frac{Rs}{L} + \frac{1}{LC}}$$

For an overdamped condition, $R/2L \geq 1/\sqrt{LC}$

Hence, the roots of the equation $s^2 + \frac{Rs}{L} + \frac{1}{LC}$ are

$$\alpha = s_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$\beta = s_2 = -\frac{R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

The solution of the equation for $v_0(t)$ is

$$v_0(t) = \frac{V\left(\frac{R}{2L}\right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC}\right]^{\frac{1}{2}}}\left[\exp(-\alpha t) - \exp(-\beta t)\right] \tag{6.17}$$

$$= V_0\left[\exp(-\alpha t) - \exp(-\beta t)\right] \tag{6.17a}$$

where,
$$V_0 = \frac{V\left(\frac{R}{2L}\right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC}\right]^{\frac{1}{2}}} = \frac{V}{\left[1 - \frac{4L}{CR^2}\right]^{\frac{1}{2}}} \tag{6.17b}$$

The sum of the roots $(\alpha + \beta) = -\frac{R}{2L}$

and, the product of the roots $\alpha\beta = \frac{1}{LC}$ (6.17c)

The wave front and the wave tail times are controlled by changing the values of R and L simultaneously with a given generator capacitance C; choosing a suitable value for L. β or the wave front time is determined and α or the wave tail time is controlled by the value of R in the circuit. The advantage of this circuit is its simplicity. But the waveshape control is not flexible and independent. Another disadvantage is that the basic circuit is altered when a test object which will be mainly capacitive in nature, is connected across the output. Hence, the waveshape gets changed with the change of test object.

Analysis of the Other Impulse Generator Circuits

The most commonly used configurations for impulse generators are the circuits shown in Figs. 6.15b and c. The advantages of these circuits are that the wave front and wave tail times are independently controlled by changing either R_1 or R_2 separately. Secondly, the test objects which are mainly capacitive in nature form part of C_2.

For the configuration shown in Fig. 6.15b, the output voltage across C_2 is given by, $v_0(t) = \frac{1}{C_2}\int_0^t i_2\, dt$.

Performing Laplace transformation, $\frac{1}{C_2 s} I_2(s) = v_0(s)$

where i_2 is the current through C_2.

Taking the current through C_1 as i_1 and its transformed value as $I_1(s)$,

$$I_2(s) = \left[\frac{R_2}{R_2 + \frac{1}{C_2 s}}\right] I_1(s)$$

$$I_1(s) = \frac{V}{s} \frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}}$$

where, $\frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}$ represents the impedance of the parallel combination of R_2 and C_2.

Substitution of $I_1(s)$ gives

$$v_0(s) = \frac{1}{C_2 s} \frac{R_2}{R_2 + \frac{1}{C_2 s}} \frac{V}{s} \frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2(1/C_2 s)}{R_2 + (1/C_2 s)}}$$

After simplification and rearrangement,

$$v_0(s) = \frac{V}{R_1C_2}\left[\frac{1}{s^2 + \left(\frac{1}{C_1R_1} + \frac{1}{C_2R_2} + \frac{1}{C_2R_1}\right)s + \frac{1}{C_1C_2R_1R_2}}\right] \tag{6.18}$$

Hence, the roots of the equation

$$s^2 + \left[\frac{1}{C_1R_1} + \frac{1}{C_2R_2} + \frac{1}{C_2R_1}\right]s + \frac{1}{C_1C_2R_1R_2}$$

are found from the relations,

$$\alpha + \beta = -\left[\frac{1}{C_1R_1} + \frac{1}{C_2R_2} + \frac{1}{C_2R_1}\right] \tag{6.19}$$

$$\alpha\beta = \frac{1}{C_1C_2R_1R_2}$$

Taking inverse transform of $v_0(s)$ gives

$$v_0(t) = \frac{V}{R_1C_2(\alpha - \beta)}[\exp(-\alpha t) - \exp(-\beta t)] \tag{6.20}$$

Usually, $\frac{1}{C_1R_1}$ and $\frac{1}{C_2R_2}$ will be much smaller compared to $\frac{1}{R_1C_2}$.

Hence, the roots may be approximated as

$$\alpha \approx \frac{1}{R_1C_2} \text{ and, } \beta = \frac{1}{R_2C_1} \tag{6.21}$$

Following a similar analysis, it may be shown that the output waveform for the circuit configuration of Fig. 6.15c will be

$$v_0(t) = \frac{VC_1R_2\alpha\beta}{(\beta - \alpha)}[\exp(-\alpha t) - \exp(-\beta t)]$$

where α and β are the roots of the Eq. (6.19). The approximate values of α and β given by Eq. (6.21) are valid for this circuit also.

The equivalent circuit given in Fig. 6.15d is a combination of the configurations of Fig. 6.15b and Fig. 6.15c. The resistance R_1 is made into two parts and kept on either side of R_2 to give greater flexibility for the circuits.

Restrictions on the Ratio of the Generator and Load Capacitances, C_1/C_2 on the Circuit Performance

For a given waveshape, the choice of R_1 and R_2 to control the wave front and wave tail times is not entirely independent but depends on the ratio of C_1/C_2. It can be shown mathematically that

$$R_2 = P(y)/C_1 \text{ and } R_1 = Q(y)/C_1$$

where $y = C_1/C_2$ and P and Q are functions of y. In order to get real values for R_1 and R_2 for a given waveshape, a maximum and minimum value of y exists in practice. This is true whether the configuration of Fig. 6.15b or 6.15c is used. For example, with the

circuit of Fig. 6.15b, the ratio of C_1/C_2 cannot exceed 3.35 for a 1/5 μ s waveshape. Similarly, for a 1/50 μ s waveshape the ratio C_1/C_2 lies between 6 and 106.5. If the configuration chosen is 6.15c, the minimum value of C_1/C_2 for 1/5 μ s waveshape is about 0.3 and that for the 1/50 μ s waveshape is about 0.01. The reader is referred to *High Voltage Laboratory Techniques* by Craggs and Meek for further discussion on the restrictions imposed on the ratio C_1/C_2.

Effect of Circuit Inductances and Series Resistance on the Impulse Generator Circuits

The equivalent circuits shown in Figs. 6.15a to d, in practice comprise several stray series inductances. Further, the circuits occupy considerable space and will be spread over several metres in a testing laboratory. Each component has some residual inductance and the circuit loop itself contributes for further inductance. The actual value of the inductance may vary from 10 μ H to several hundreds of microhenries. The effect of the inductance is to cause oscillations in the wave front and in the wave tail portions. Inductances of several components and the loop inductance are shown in Fig. 6.16a. Figure 6.16b gives a simplified circuit for considering the effect of inductance. The effect of the variation of inductance on the waveshape is shown in Fig. 6.16c. If the series resistance R_1 is increased, the wave front oscillations are damped, but the peak value of the voltage is also reduced. Sometimes, in order to control the front time a small inductance is added.

Impulse Generators for Testing Objects having Large Capacitance

When test objects with large capacitances are to be tested ($C > 5$ nF), it is difficult to generate standard impulses with front time within the specified tolerance of ± 30% and the specified less than 5% tolerance in the overshoot. This is mainly because of the effect of the inductance of the impulse generator and the front resistors. Normally the inductance of the impulse generator will be about 3 to 5 μH per stage and that of the leads about 1 μH/m. Also the front resistor which is usually of bifilar type, has inductance of about 2 μH/unit. An overshoot in the voltage wave of more than 5% will occur if $R/(\sqrt{L}/c) \leq 1.38$, where R is the front resistance, L is the generator inductance and C is the equivalent capacitance of the generator given by $C = C_1 \cdot C_2/(C_1 + C_2)$.

Impulse Generators for Test Objects with Inductance

Often impulse generators are required to test equipment with large inductance, such as power transformers and reactors. Usually, generating the impulse voltage wave of proper time-to-front and obtaining a good voltage efficiency are easy, but obtaining the required time-to-tail as per the standards will be very difficult. The equivalent circuit for medium and low inductive loads will be as shown in Fig. 6.16(d). For the calculation of time-to-tail the circuit can still be approximated as a series C-R-L circuit. As the value $R/(\sqrt{L/C})$ decreases, the overshoot and the swing of the wave to the opposite polarity increases thereby deviating from the standard wave shape. Therefore, it is necessary to keep the value of the effective resistance R in the circuit large. One method of doing this is to connect a large resistance, R_2 in parallel with the

test object or to connect the untested winding of the transformer (load) with a suitable resistance. Another method that can be used is to increase the generator capacitance with which the time-to-tail also increases, but without alterating the time-to-front and the overshoot. Figure 6.16(d) gives the circuit arrangement for inductive loads and 6.16(e) gives the requirement of energy and capacitance of the impulse voltage generator. Figure B of 6.16(e) gives the generator capacitance required to give the time-to-tail values in the range of 40 to 60 μ s at different inductive loads.

Waveshape Control

Generally, for a given impulse generator of Fig. 6.15b or c the generator capacitance C_1 and load capacitance C_2 will be fixed depending on the design of the generator and the test object. Hence, the desired waveshape is obtained by controlling R_1 and R_2. The following approximate analysis is used to calculate the wave front and wave tail times.

The resistance R_2 will be large. Hence, the simplified circuit shown in Fig. 6.16b is used for wave front time calculation. Taking the circuit inductance to be negligible during charging, C_1 charges the load capacitance C_2 through R_1. Then the time taken for charging is approximately three times the time constant of the circuit and is given by

$$t_1 = 3.0 R_1 \frac{C_1 C_2}{C_1 + C_2} = 3 R_1 C_e \qquad (6.22)$$

where $C_e = \dfrac{C_1 C_2}{C_1 + C_2}$. If R_1 is given in ohms and C_e in microfarads, t_1 is obtained in microseconds.

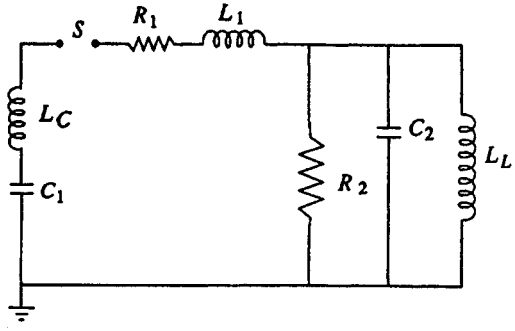


Fig. 6.16 (a) Series inductances in impulse generator circuit

L_C — Inductance of the generator capacitance C_1 and lead capacitances
L_1 — Inductance of the series resistance and the circuit loop inductance
L_L — Test object inductance

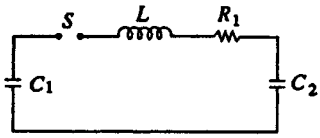


Fig. 6.16 (b) Simplified circuit for calculation of wave front time
$L = L_C + L_1$ + any other added inductance

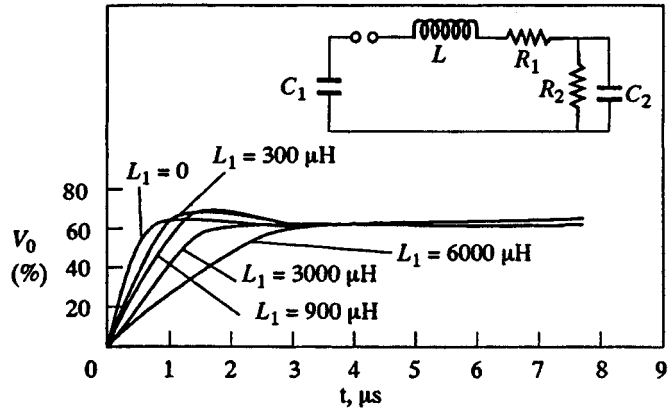
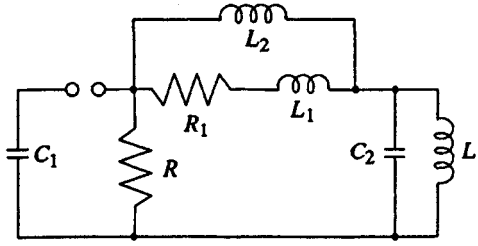
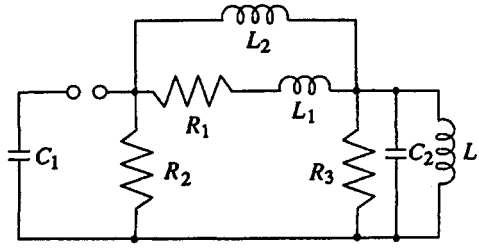


Fig. 6.16 (c) Effect of series inductance on wave front time. v_0 is the percentage of charging voltage V, to which C_1 is charged

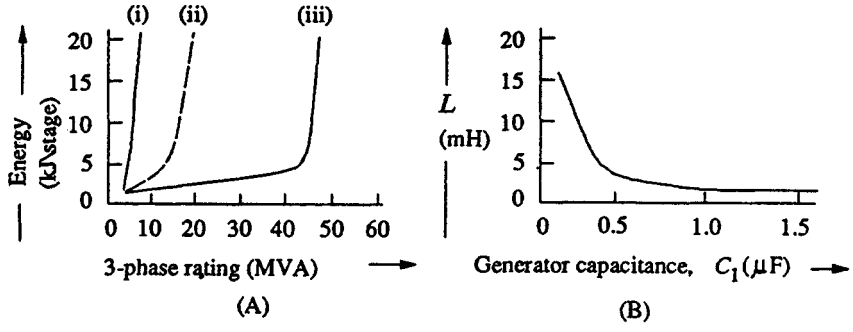


Medium inductance load (L = 0.4 to 15 mH)



Low inductance load (L = 0.4 to 4mH)

Fig. 6.16 (d) Effect of inductive loads on impulse voltage generator circuits



Energy requirement per 200 kV stage of an impulse voltage generator as a function of the MVA rating of 3-phase reactor transformer. Curves (i) for 11 kV, (ii) for 22 kV and (iii) for 33 kV winding ratings.

Generator capacitance (C_1) required for different inductive loads (L) to give the standard tail time of an impulse voltage wave.

Fig. 6.16 (e) Requirements of an impulse voltage generator energy and capacitance for the testing of the transformer (reactor) winding using standard impulse voltages

Fig. 6.16 Series inductance in impulse generator circuits and its effect on waveshape

For discharging or tail time, the capacitances C_1 and C_2 may be considered to be in parallel and discharging occurs through R_1 and R_2. Hence, the time for 50% discharge is approximately given by

$$t_2 = 0.7\,(R_1 + R_2)\,(C_1 + C_2) \qquad (6.23)$$

These formulae for t_1 and t_2 hold good for the equivalent circuits shown in Fig. 6.15b and c. For the circuit given in Fig. 6.15d, R is to be taken as $2R_1$. With the approximate formulae, the wave front and wave tail times can be estimated to within ± 20% for the standard impulse waves.

6.3.4 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 the 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.

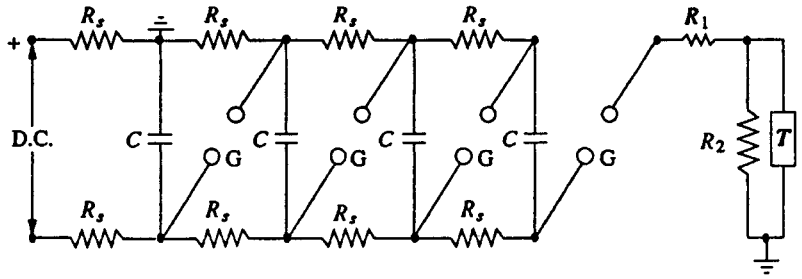


Fig. 6.17a Schematic diagram of Marx circuit arrangement for multistage impulse generator

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

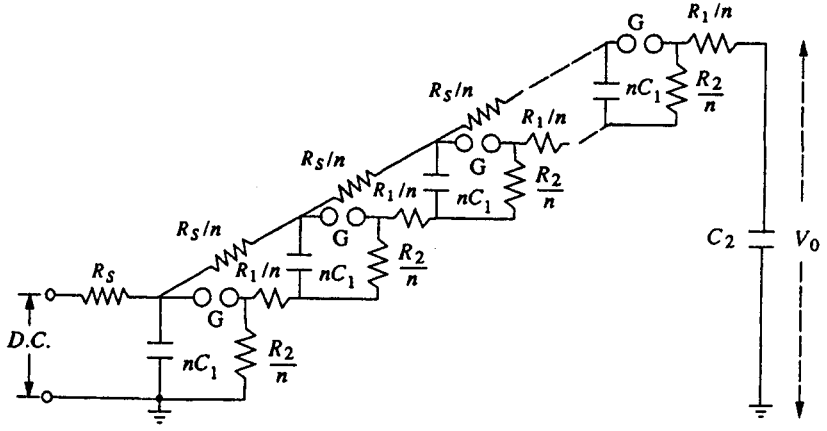


Fig. 6.17b Multistage impulse generator incorporating the series and wave tail resistances within the generator

The schematic diagram of Marx circuit and its modification are shown in Figs. 6.17a and 6.17b, respectively. Usually the charging resistance R_s is chosen to limit the charging current to about 50 to 100 mA, and the generator capacitance C is chosen such that the product CR_s is about 10 s to 1 min. The gap spacing is chosen such that the breakdown voltage of the gap G is greater than the charging voltage V. Thus, all the capacitances are charged to the voltage V in about 1 minute. When the impulse generator is to be discharged, the gaps G are made to spark over simultaneously by some external means. Thus, all the capacitors C get connected in series and discharge

into the load capacitance or the test object. The discharge time constant CR_1/n (for n stages) will be very very small (microseconds), compared to the charging time constant CR_s which will be few seconds. Hence, no discharge takes place through the charging resistors R_s. In the Marx circuit is of Fig. 6.17a the impulse wave shaping circuit is connected externally to the capacitor unit. In Fig. 6.17b, the modified Marx circuit is shown, wherein the resistances R_1 and R_2 are incorporated inside the unit. R_1 is divided into n parts equal to R_1/n and put in series with the gap G. R_2 is also divided into n parts and arranged across each capacitor unit after the gap G. This arrangement saves space, and also the cost is reduced. But, in case the waveshape is to be varied widely, the variation becomes difficult. The additional advantages gained by distributing R_1 and R_2 inside the unit are that the control resistors are smaller in size and the efficiency (V_0/nV) is high.

Impulse generators are nominally rated by the total voltage (nominal), the number of stages, and the gross energy stored. The nominal output voltage is the number of stages multiplied by the charging voltage. The nominal energy stored is given by $\frac{1}{2} C_1 V^2$ where $C_1 = C/n$ (the discharge capacitance) and V is the nominal maximum voltage (n times charging voltage). A 16-stage impulse generator having a stage capacitance of 0.280 μ F and a maximum charging voltage of 300 kV will have an energy rating of 192 kW sec. The height of the generator will be about 15 m and will occupy a floor area of about 3.25 × 3.00 m. The waveform of either polarity can be obtained by suitably changing the charging unit polarity.

6.3.5 Components of a Multistage Impulse Generator

A multistage impulse generator requires several components parts for flexibility and for the production of the required waveshape. These may be grouped as follows:

(i) d.c. Charging Set

The charging unit should be capable of giving a variable d.c. voltage of either polarity to charge the generator capacitors to the required value.

(ii) Charging Resistors

These will be non-inductive high value resistors of about 10 to 100 kilo-ohms. Each resistor will be designed to have a maximum voltage between 50 and 100 kV.

(iii) Generator Capacitors and Spark Gaps

These are arranged vertically one over the other with all the spark gaps aligned. The capacitors are designed for several charging and discharging operations. On dead short circuit, the capacitors will be capable of giving 10 kA of current. The spark gaps will be usually spheres or hemispheres of 10 to 25 cm diameter. Sometimes spherical ended cylinders with a central support may also be used.

(iv) Wave-shaping Resistors and Capacitors

Resistors will be non-inductive wound type and should be capable of discharging impulse currents of 1000 A or more. Each resistor will be designed for a maximum voltage of 50 to 100 kV. The resistances are bifilar wound or non-inductive thin flat insulating sheets. In some cases, they are wound on thin cylindrical formers and are completely enclosed. The load capacitor may be of compressed gas or oil filled with a capacitance of 1 to 10 μF.

Modern impulse generators have their wave-shaping resistors included internally with a flexibility to add additional resistors outside, when the generator capacitance is changed (with series parallel connection to get the desired energy rating at a given test voltage). Such generators optimize the set of resistors. A commercial impulse voltage generator uses six sets of resistors ranging from 1.0 ohm to about 160 ohms with different combinations (with a maximum of two resistors at a time) such that a resistance value varying from 0.7 ohm to 235 ohms per stage is obtained, covering a very large range of energy and test voltages. The resistors used are usually resin cast with voltage and energy ratings of 200 to 250 kV and 2.0 to 5.0 kWsec. The entire range of lightning and switching impulse voltages can be covered using these resistors either in series or in parallel combination.

(v) Triggering System

This consists of trigger spark gaps to cause spark breakdown of the gaps (see Sec. 6.5).

(vi) Voltage Dividers

Voltage dividers of either damped capacitor or resistor type and an oscilloscope with recording arrangement are provided for measurement of the voltages across the test object. Sometimes a sphere gap is also provided for calibration purposes (see Chapter 7 for details).

6.3.6 Generation of Switching Surges

Now-a-days in extra high voltage transmission lines and power systems, switching surge is an important factor that affects the design of insulation. All transmission lines rated for 220 kV and above, incorporate switching surge sparkover voltage for their insulation levels. A switching surge is a short duration transient voltage produced in the system due to a sudden opening or closing of a switch or circuit breaker or due to an arcing at a fault in the system. The waveform is not unique. The transient voltage may be an oscillatory wave or a damped oscillatory wave of frequency ranging from few hundred hertz to few kilo hertz. It may also be considered as a slow rising impulse having a wave front time of 0.1 to 10 ms, and a tail time of one to several ms. Thus, switching surges contain larger energy than the lightning impulse voltages.

Several circuits have been adopted for producing switching surges. They are grouped as (*i*) impulse generator circuit modified to give longer duration waveshapes, (*ii*) power transformers or testing transformers excited by d.c. voltages giving oscillatory waves and these include Tesla coils.

Standard switching impulse voltage is defined, both by the Indian Standards and the IEC, as 250/2500 μs wave, with the same tolerances for time-to-front and

time-to-tail as those for the lightning impulse voltage wave i.e. time-to-front of (250 ± 50) μs and time-to-half value of (2500 ± 500) μs. Other switching impulse voltage waves commonly used for testing the lightning arresters are 250/1500 μs with a tolerance of ± 500 μs in time-to-half value.

Figure 6.18 shows the impulse generator circuits modified to give switching surges. The arrangement is the same as that of an impulse generator. The values of R_1 and R_2 for producing waveshapes of long duration, such as 100/1000 μs or 400/4000 μs, will range from 1 to 5 kilo-ohms and 5 to 20 kilo-ohms respectively. Thus, R_1 is about 20 to 30% of R_2. The efficiency of the generator gets considerably reduced to about 50% or even less. Moreover, the values of the charging resistors R_1 are to be increased to very high values as these will come in parallel with R_2 in the discharge circuit.

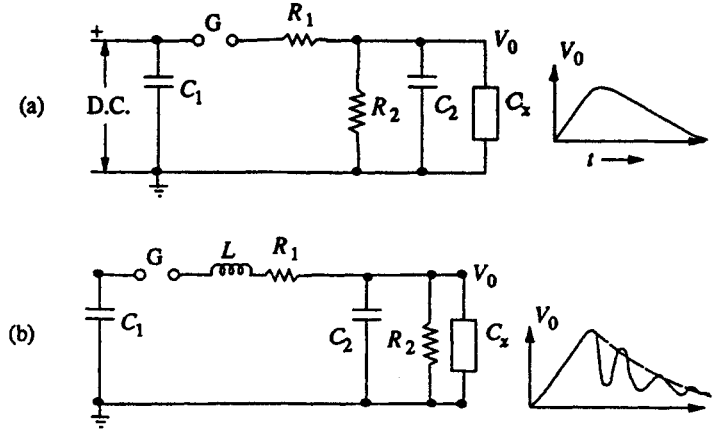


Fig. 6.18 Circuits for producing switching surge voltages. Also shown are the output waveshapes across the load C_x

The circuit given in Fig. 6.18b produces unidirectional damped oscillations. With the use of an inductor L, the value of R_1 is considerably reduced, and the efficiency of the generator increases. The damped oscillations may have a frequency of 1 to 10 kHz depending on the circuit parameters. Usually, the maximum value of the switching surge obtained is 250 to 300 kV with an impulse generator having a nominal rating of 1000 kV and 25 kW sec. Bellaschi *et al.*[12] used only an inductor L of low resistance to produce switching impulse up to 500 kV. A sphere gap was included in parallel with the test object for voltage measurement and also for producing chopped waves.

Switching surges of very high peaks and long duration can be obtained by using the circuit shown in Fig. 6.19. An impulse generator condenser C_1 charged to a low voltage d.c. (20 to 25 kV) is discharged into the low voltage winding of a power or testing transformer. The high voltage winding is connected in parallel to a load capacitance C_2, a potential divider R_2, a sphere gap S, and the test object. Through an autotransformer action, switching surge of proper waveshape can be generated across

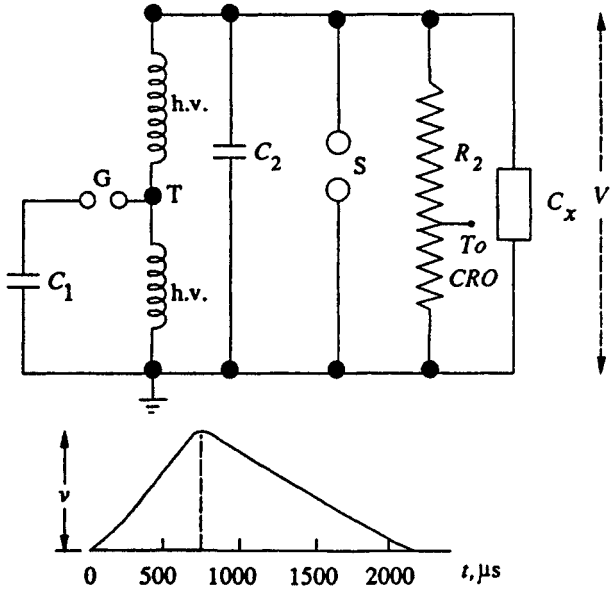


Fig. 6.19 Circuit for producing switching surges using a transformer

C_1	— Surge generator	G	— Triggering spark gap
T	— Power transformer	S	— Sphere gap
C_2	— Load capacitance	R_2	— Potential divider
C_x	— Test object	h.v.,l.v.	— Transformer high and low voltage windings

the test object. The efficiency obtained by this method is high but the transformer should be capable of withstanding very high voltages.

Multi Test Sets for High Voltage Testing

In many small laboratories like in the teaching institutions, small industries and utility organizations, the requirements of high voltages may be less than about 200 kV, 50 Hz, a.c., 400 kV d.c. and 400 kV standard lightning and switching impulse voltages. The power requirements will be around 5 kW or kVA and the energy requirement will be less than 1.5 kJ. For such applications, flexible and universally interchangeable modular systems of the above voltage and energy ratings are available under different trade names. These systems mainly consist of

(i) a.c. Testing Transformers :
With continuous power ratings of 3 to 5 kVA with a short time rating about 150%. The unit can be one single transformer of up to 100 kV(rms), or 2 or 3 units connected in cascade with voltage ratings up to 300 kV(rms).

(ii) d.c Units :

A.C. transformer with the addition of a rectifier unit and a filter capacitor, with ripple factor at rated current less than 5% and a voltage drop or regulation less than 10%, for a single stage output of about 100 kV (half-wave rectifier) constitute a d.c. set. D.C. sets are available as multi-stage voltage doubler units with one pulse output, or as a quadampler unit of up to 400 kV rating with the same specifications. In either case, the power ratings will be about 3 to 5 kW continuous. The rectifier stacks used are the selenium diode type.

(iii) Impulse Voltage Units :

Marx circuit of 2 to 4 stages can be assumed using the transformer and d.c. rectifier unit described earlier for an output voltage of about 400 kV(peak) using a one stage rectifier unit. The necessary wave front and wave tail resistors and load capacitances are normally provided. The units are assembled with modular components mounted on suitable insulating columns. The units normally have voltage efficiency of about 90%.

All the basic units are clearly and compactly arranged. By having increased number of units the system can be expanded to obtain higher and desired type of voltage. Control cubicles/boxes are provided for the control and measurement of voltages. The units can be mounted on wheels or located permanently in a test hall of size 4m × 3m × 3m.

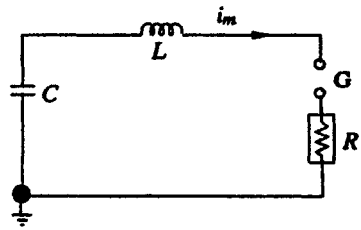
Multi-test sets are currently being manufactured and assembled in India by some leading manufacturers of high voltage test equipments.

6.4 GENERATION OF IMPULSE CURRENTS

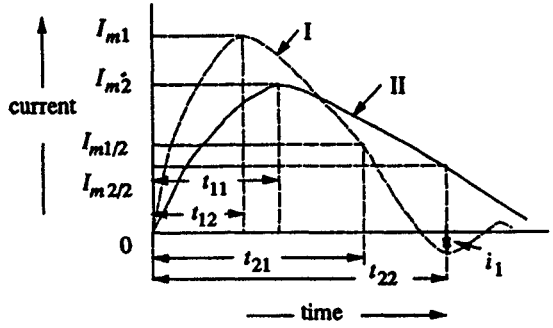
Lightening discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gear like surge diverters have to discharge the lightning currents without damage. Therefore, generation of impulse current waveforms of high magnitude (≈ 100 kA peak) find application 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.

6.4.1 Definition of Impulse Current Waveforms

The waveshapes used in testing surge diverters are 4/10 and 8/20 μ s, the figures respectively representing the nominal wave front and wave tail times (see Fig. 6.14). 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 waveshape 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.



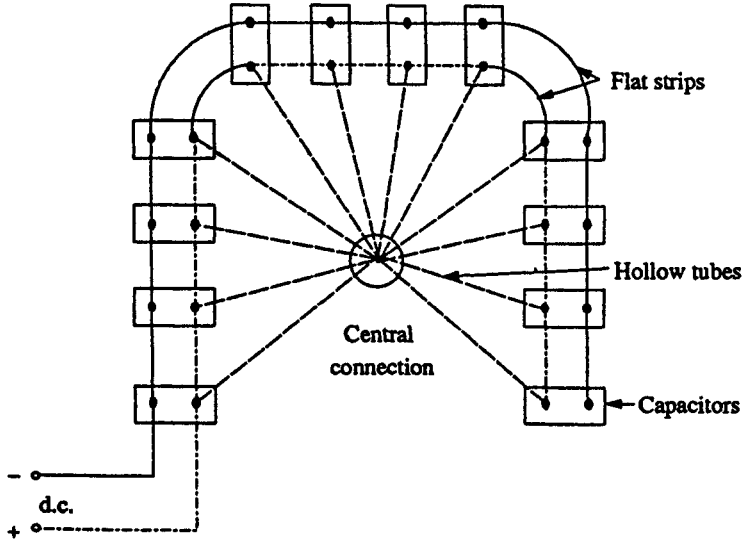
(a) Basic circuit of an impulse current generator



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

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

(b) Types of impulse current waveforms



(c) Arrangement of capacitors for high impulse current generation

Fig. 6.20 Impulse current generator circuit and its waveform

6.4.2 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. 6.20. C represents a bank of capacitors connected in parallel which are charged from a d.c. 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

$$V = R\,i_m + L\frac{di_m}{dt} + \frac{1}{C}\int_0^t i_m\,dt \tag{6.24}$$

The circuit is usually underdamped, so that

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

Hence, i_m is given by

$$i_m = \frac{V}{\omega L}[\exp(-\alpha t)]\sin(\omega t) \tag{6.25}$$

where

$$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{6.25a}$$

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

$$t_1 = t_f = \frac{1}{\omega}\sin^{-1}\frac{\omega}{\sqrt{LC}} = \frac{1}{\omega}\tan^{-1}\frac{\omega}{\alpha} \tag{6.26}$$

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

$$t_2 = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \tag{6.27}$$

It can be shown that the maximum value of i_m 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. (6.25) 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 $\alpha = 0.0535 \times 10^6$ and $\omega = 0.113 \times 10^6$, 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.

6.4.3 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. 6.20c. 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

$$L = L_0 + \frac{L_1}{n} + \frac{L_2}{n_1 n_2}$$

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.

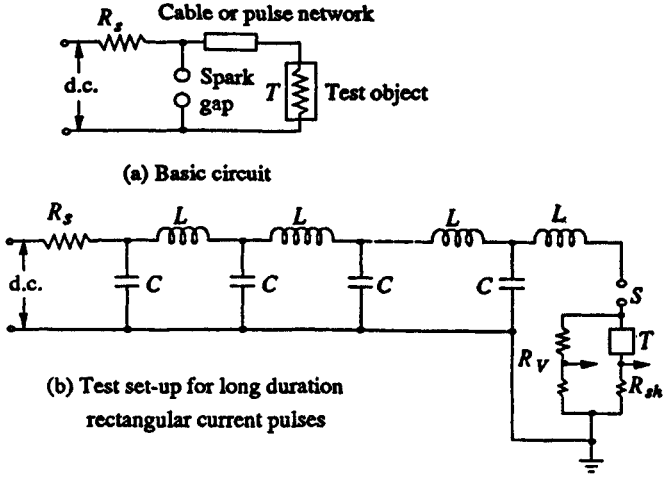


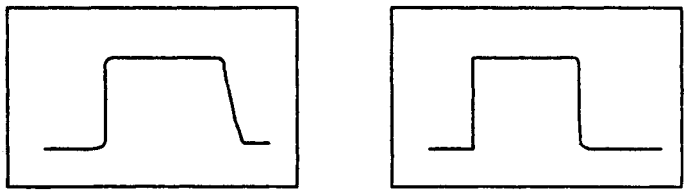
Fig. 6.21 Basic circuit and schematic set-up for producing rectangular current pulses

R_s — Charging resistor
S — Trigger spark gap
T — Test object
L-C — Pulse forming network
R_v — Potential divider for voltage measurement
R_{sh} — Current shunt for current measurement

6.4.4 Generation of Rectangular Current Pulses

Generation of rectangular current pulses of high magnitudes (few hundred amperes and duration up to 5 ms) can be done by discharging a pulse network or cable previously charged. The basic circuit for producing rectangular pulses is given in Fig. 6.21. The length of a cable or an equivalent pulse forming network is charged to a specified d.c. voltage. When the spark gap is short-circuited, the cable or pulse network discharges through the test object.

To produce a rectangular pulse, a coaxial cable of surge impedance $Z_0 = \sqrt{L_0/C_0}$ (where L_0 is the inductance and C_0 is the capacitance per unit length) is used. If the cable is charged to a voltage V and discharged through the test object of resistance R, the current pulse I is given by $I = V/(Z_0 + R)$. A pulse voltage $RV/(R + Z_0)$ is developed across the test object R, and the pulse current is sustained by a voltage wave $(V\text{-}IR)$. For $R = Z_0$, the reflected wave from the open end of the cable terminates the pulse current into the test object, and the pulse voltage becomes equal to $V/2$.



(a) Pulse waveform using pulse forming network (3.5 μ s)
(b) Pulse waveform using a coaxial cable (3.6 μ s)

Fig. 6.22 Current waveforms produced by rectangular current generators

In practice, it is difficult to get a coaxial cable of sufficient capacitance and length. Often artificial transmission lines with lumped L and C as shown in Fig. 6.21b are used. Usually, 6 to 9 L-C sections will be sufficient to give good rectangular waves. The duration of the pulse time is seconds (t) is given by $t = 2\,(n-1)\,\sqrt{LC}$, where n is the number of sections used, C is the capacitance per stage or section, and L is the inductance per stage or section.

The current waveforms produced by an artificial line or pulse network and a coaxial cable are shown in Figs. 6.22a and b.

6.5 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.

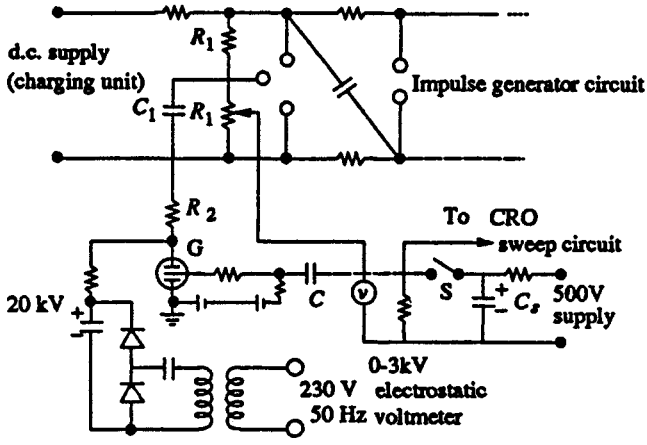


Fig. 6.23 Tripping of an impulse generator with a three electrode gap

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 6.23 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

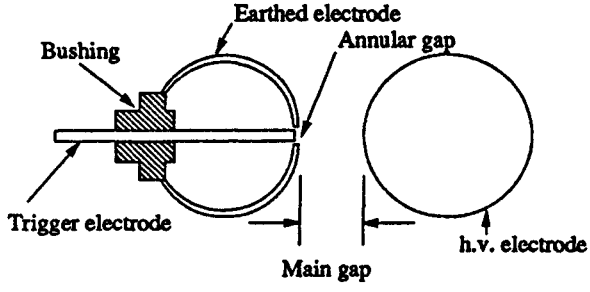
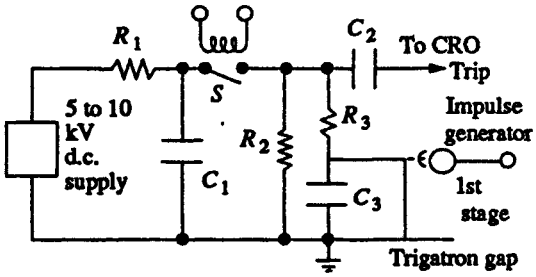


Fig. 6.24 (a) Trigatron gap



(b) Tripping circuit using a trigatron

Fig. 6.24 Trigatron gap and tripping circuit

begins before the start of the impulse generator voltage. The resistance R_2 ensures decoupling of voltage oscillations produced at the spark gap entering the oscilloscope through the common trip circuit.

The three electrode gap requires larger space and an elaborate construction. Now-a-days a trigatron gap shown in Fig. 6.24 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. 6.24b. Tripping of the impulse generator is effected by a trip pulse which produces a spark between the trigger electrode and the earthed sphere. Due to space charge effects and distortion of the field in the main gap, sparkover of the main gap

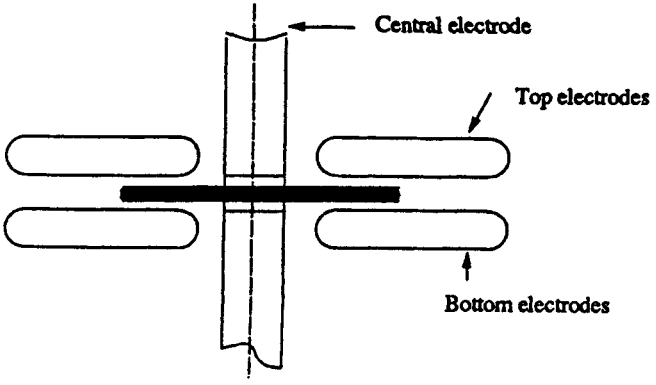


Fig. 6.25 Three electrode gap for high current switching

occurs. The trigatron gap is polarity sensitive and a proper polarity pulse should be applied for correct operation.

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.

For high current capacitor banks, a number of spark gap switches connected in parallel as shown in Fig. 6.25 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.

QUESTIONS

Q.6.1 Explain with diagrams, different types of rectifier circuits for producing high d.c. voltages.

Q.6.2 What are the special features of high voltages rectifier valves? How is proper voltage division between the valves ensured, if a number of tubes are used in series ?

Q.6.3 Why is a Cockcroft-Walton circuit preferred for voltage multiplier circuits ? Explain its working with a schematic diagram.

Q.6.4 Give the expression for ripple and regulation in voltage multiplier circuits. How are the ripple and regulation minimized ?

Q.6.5 Describe, with a neat sketch, the working of a Van de Graaff generator. What are the factors that limit the maximum voltage obtained ?

Q.6.6 Explain the different schemes for cascade connection of transformers for producing very high a.c. voltages.

Q.6.7 Why is it preferable to use isolating transformers for excitation with cascade transformer units, if the power requirement is large ?

Q.6.8 What is the principle of operation of a resonant transformer ? How is it advantageous over the cascade connected transformers ?

Q.6.9 What is a Tesla coil ? How are damped high frequency oscillations obtained from a Tesla coil ?

Q.6.10 Define the front and tail times of an impulse wave. What are the tolerances allowed as per the specifications ?

Q.6.11 Give different circuits that produce impulse waves explaining clearly their relative merits and demerits.

Q.6.12 Give the Marx circuit arrangement for multistage impulse generators. How is the basic arrangement modified to accommodate the wave time control resistances ?

Q.6.13 How are the wave front and wave tail times controlled in impulse generator circuits ?

Q.6.14 Explain the different methods of producing switching impulses in test laboratories.

Q.6.15 Explain the effect of series inductance on switching impulse waveshapes produced.

Q.6.16 Describe the circuit arrangement for producing lightning current waveforms in laboratories.

Q.6.17 How is the circuit inductance controlled and minimized in impulse current generators ?

Q.6.18 How are rectangular current pulses generated for testing purposes ? How is their time duration controlled ?

Q.6.19 Explain one method of controlled tripping of impulse generators. Why is controlled tripping necessary ?

Q.6.20 What is a trigatron gap ? Explain its functions and operation.

Q.6.21 An impulse generator has 12 capacitors of 0.12 μF, and 200 kV rating. The wave front and wave tail resistances are 1.25 kΩ and 4 kΩ respectively. If the load capacitance including that of the test object is 10 000 pF, find the wave front and wave tail times and the peak voltage of impulse wave produced.

Q.6.22 A 8-stage impulse generator has 0.12 μF capacitors rated for 167 kV. What is its maximum discharge energy ? If it has to produce a 1/50 μs waveform across a load capacitor of 15,000 pF, find the values of the wave front and wave tail resistances.

Q.6.23 Calculate the peak current and waveshape of the output current of the following generator. Total capacitance of the generator is 53 μF. The charging voltage is 200 kV. The circuit inductance is 1.47 mH, and the dynamic resistance of the test object is 0.051 ohms.

Q.6.24 A single phase testing transformer rated for 2 kV/350 kV, 3500 kVA, 50 Hz on testing yields the following data: (i) No-load voltage on H.V. side = 2% higher than the rated value when the input voltage is 2 kV on the L.V. side. (ii) Short circuit test with H.V. side shorted, rated current was obtained with 10% rated voltage on the input side. Calculate the self-capacitance on the H.V. side and the leakage reactance referred to the H.V. side. Neglect resistance.

Q.6.25 Determine the ripple voltage and regulation of a 10 stage Cockcroft-Walton type d.c. voltage multiplier circuit having a stage capacitance = 0.01 μF, supply voltage = 100 kV at a frequency of 400 Hz and a load current = 10mA.

Q.6.26 A voltage doubler circuit has $C_1 = C_2 = 0.01$ μF and is supplied from a voltage source of $V = 100 \sin 314t$ kV. If the d.c. output current is to be 4 mA, calculate the output voltage and the ripple.

Q.6.27 The primary and secondary winding inductances of a Tesla coil are 0.093 H and 0.011 H respectively with a mutual inductance between the windings equal to 0.026 H. The capacitance included in the primary and secondary circuits are respectively 1.5 μF and 18 ηF. If the Tesla coil is charged through a 10 kV DC supply, determine the output voltage and its waveform. Neglect the winding resistances.

Q.6.28 An impulse current generator is rated for 60 kW sec. The parameters of the circuit are $C = 53$ μF, $L = 1.47$ μH and the dynamic resistance = 0.0156 ohm. Determine the peak value of the current and the time-to-front and the time-to-tail of the current waveform.

WORKED EXAMPLES

Example 6.1: A Cockcroft-Walton type voltage multiplier has eight stages with capacitances, all equal to 0.05 μF. The supply transformer secondary voltage is 125 kV at a frequency of 150 Hz. If the load current to be supplied is 5 mA, find (*a*) the percentage ripple, (*b*) the regulation, and (*c*) the optimum number of stages for minimum regulation or voltage drop.

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

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

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

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

$$= 24 \text{ kV}$$

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

$$= 1.2\%$$

(b) Calculation of Regulation

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

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

$$= 248 \text{ kV}$$

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

$$= 12.4\%$$

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

Since $n > 5$,

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

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

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

$$= 13.69$$

$$= 14 \text{ stages}$$

Example 6.2: A 100 kVA, 400 V/250 kV testing transformer has 8% leakage reactance and 2% resistance on 100 kVA base. A cable has to be tested at 500 kV using the above transformer as a resonant transformer at 50 Hz. If the charging current of the cable at 500 kV is 0.4 A, find the series inductance required. Assume 2% resistance for the inductor to be used and the connecting leads. Neglect dielectric loss of the cable. What will be the input voltage to the transformer ?

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

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

$X_C =$ Reactance of the cable is

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

$X_L =$ Leakage reactance of the transformer is

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

At resonance, $X_C = X_L$.
Hence, additional reactance needed

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

Inductance of additional reactance (at 50 Hz frequency)

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

R = Total resistance in the circuit on 100 kVA base is 2% + 2% = 4%.
Hence, the ohmic value of the resistance

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

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

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

The primary voltage or the supply voltage, E_1

$$= \frac{10 \times 10^3 \times 400}{250 \times 10^3}$$
$$= 16\ \text{V}$$

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

(The magnetizing current and the core losses of the transformer are neglected.)

Example 6.3: An impulse generator has eight stages with each condenser rated for 0.16 μF and 125 kV. The load capacitor available is 1000 pF. Find the series resistance and the damping resistance needed to produce 1.2/50 μs impulse wave. What is the maximum output voltage of the generator, if the charging voltage is 120 kV ?

Solution : Assume the equivalent circuit of the impulse generator to be as shown in Fig. 6.15b.

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

C_2, the load capacitance $= 0.001\ \mu\text{F}$

t_1, the time to front $= 1.2\ \mu\text{s}$

$$= 3.0 R_1 \frac{C_1 C_2}{C_1 + C_2}$$

$$\therefore \quad R_1 = 1.2 \times 10^{-6} \frac{C_1 + C_2}{C_1 C_2} \times \frac{1}{3}$$

$$= 1.2 \times 10^{-6} \frac{0.021 \times 10^{-6}}{0.02 \times 0.001 \times 10^{-12}} \times \frac{1}{3}$$

$$= 420\ \Omega$$

$$t_2, \text{ time to tail} = 0.7(R_1 + R_2)(C_1 + C_2)$$
$$= 50 \times 10^{-6} \text{ s}$$

or, $0.7(420 + R_2)(0.021 \times 10^{-6}) = 50 \times 10^{-6}$

or, $R_2 = 2981\ \Omega$

The d.c. charging voltage for eight stages is

$$V = 8 \times 120 = 960 \text{ kV}$$

The maximum output voltage is

$$\frac{V}{R_1 C_2 (\alpha - \beta)} (e^{-\alpha t_1} - e^{-\beta t_1})$$

where $\alpha \approx \frac{1}{R_1 C_2}$, $\beta = \frac{1}{R_2 C_1}$ and V is the d.c. charging voltage.

Substituting for R_1, C_1 and R_2, C_2,

$$\alpha = 0.7936 \times 10^{+6}$$
$$\beta = 0.02335 \times 10^{+6}$$

$\therefore$ maximum output voltage = 932.6 kV.

Example 6.4: An impulse current generator has a total capacitance of 8 μF. The charging voltage is 25 kV. If the generator has to give an output current of 10kA with 8/20 μs waveform, calculate (*a*) the circuit inductance and (*b*) the dynamic resistance in the circuit.

Solution: For an 8/20 μs impulse wave,

$$\alpha = R/2L = 0.0535 \times 10^{+6}$$

and, the product to $LC = 65$. Given $C = 8$ μF (L in μH, C in μF, and R in ohms) Therefore, the circuit inductance is

$$\frac{65}{C} = 8.125 \text{ μH}$$

The dynamic resistance $2L\alpha = 2 \times \frac{65 \times 10^{-6}}{8} \times 0.0535 \times 10^{+6}$

$$= 0.8694 \text{ ohms}$$

Peak current is given by $\frac{VC}{14} = 10$ kA

(V in kV, C in μF, and I in kA),

$\therefore$ charging voltage needed is,

$$V = \frac{14 \times 10}{8} = 15.5 \text{ kV}$$

Example 6.5 (*Alternative Solution*) : Assuming the wave to have a time-to-half value of 20 μs and a time-to-front of 8 μs, the time-to-first half cycle of the damped oscillatory wave will be 20 μs. Then

$$t_1 = t_f = 1/\omega \text{ [arc tan } (\omega/\alpha)] = 8 \text{ μs}$$

and

$$t_2 = \pi/\omega = 20 \text{ μs}$$

Therefore, $\omega = \pi/t_2 = \pi \times 10^6/20 = 0.1571 \times 10^6$

$\text{arc tan } (\omega/\alpha) = \omega \cdot t_1 = 1.2566.$

i.e. $\omega/\alpha = 0.8986$ radians

and $\alpha = 0.1748 \times 10^6.$

Then, $\sqrt{1/(L\,C) - \alpha^2} = 0.1571 \times 10^6.$

Substituting the value of α and simplifying,

$LC = 32.47 \times 10^{12}$, hence $L = 4.06\ \mu H$

and $R = 2L.\alpha = 1.419$ ohm

$i_m = V/\omega L\ .\ \text{Exp}\ (-\alpha t) = 10$ kA

$V = \omega L \times 10 \times \text{Exp}\ (-\alpha t) = 25.8$ kV.

Example 6.6: A 12-stage impulse generator has 0.126 μF condensers. The wave front and the wave tail resistances connected are 800 ohms and 5000 ohms respectively. If the load condenser is 1000 pF, find the front and tail times of the impulse wave produced.

Solution: The generator capacitance $C_1 = \dfrac{0.126}{12} = 0.0105\ \mu F$

The load capacitance $C_2 = 0.001\ \mu F$

Resistances, $R_1 = 800$ ohms and $R_2 = 5000$ ohms

$$\therefore \quad \text{time to front, } t_1 = 3(R_1)\left(\frac{C_1 C_2}{C_1 + C_2}\right)$$

$$= 3 \times 800 \times \frac{(0.0105 \times 10^{-6} \times 0.001 \times 10^{-6})}{(0.0105 + 0.001) \times 10^{-6}}$$

$$= 2.19\ \mu s$$

$$\text{time to tail, } t_2 = 0.7(R_1 + R_2)\,(C_1 + C_2)$$

$$= 0.7(800 + 5000) \times (0.0105 + 0.001) \times 10^{-6}$$

$$= 46.7\ \mu s$$

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7

Measurement of High Voltages and Currents

In industrial testing and research laboratories, it is essential to measure the voltages and currents accurately, ensuring perfect safety to the personnel and equipment. Hence a person handling the equipment as well as the metering devices must be protected against overvoltages and also against any induced voltages due to stray coupling. Therefore, the location and layout of the devices are important. Secondly, linear extrapolation of the devices beyond their ranges are not valid for high voltage meters and measuring instruments, and they have to be calibrated for the full range. Electromagnetic interference is a serious problem in impulse voltage and current measurements, and it has to be avoided or minimized. Therefore, even though the principles of measurements may be same, the devices and instruments for measurement of high voltages and currents differ vastly from the low voltage and low current devices. Different devices used for high voltage measurements may be classified as in Tables 7.1 and 7.2.

7.1 MEASUREMENT OF HIGH DIRECT CURRENT VOLTAGES

Measurement of high d.c. voltages as in low voltage measurements, is generally accomplished by extension of meter range with a large series resistance. The net current in the meter is usually limited to one to ten microamperes for full-scale deflection. For very high voltages (1000 kV or more) problems arise due to large power dissipation, leakage currents and limitation of voltage stress per unit length, change in resistance due to temperature variations, etc. Hence, a resistance potential divider with an electrostatic voltmeter is sometimes better when high precision is needed. But potential dividers also suffer from the disadvantages stated above. Both series resistance meters and potential dividers cause current drain from the source. Generating voltmeters are high impedance devices and do not load the source. They provide complete isolation from the source voltage (high voltage) as they are not directly connected to the high voltage terminal and hence are safer. Spark gaps such as sphere gaps are gas discharge devices and give an accurate measure of the peak voltage. These are quite simple and do not require any specialized construction. But the measurement is affected by the atmospheric conditions like temperature, humidity, etc. and by the vicinity of earthed objects, as the electric field in the gap is affected by the presence of earthed objects. But sphere gap measurement of voltages is independent of the waveform and frequency.

Table 7.1 High voltage Measurement Techniques

Type of voltage	Method or technique
(a) d.c. voltages	*(i)* Series resistance microammeter
	(ii) Resistance potential divider
	(iii) Generating voltmeters
	(iv) Sphere and other spark gaps
(b) a.c. voltages	*(i)* Series impedance ammeters
(power frequency)	*(ii)* Potential dividers (resistance or capacitance type)
	(iii) Potential transformers (electromagnetic or CVT)
	(iv) Electrostatic voltmeters
	(v) Sphere gaps
(c) a.c. high frequency voltages, impulse voltages, and other rapidly changing voltages	*(i)* Potential dividers with a cathode ray oscillograph (resistive or capacitive dividers)
	(ii) Peak voltmeters
	(iii) Sphere gaps

Table 7.2 High Current Measurement Techniques

Type of current	Device or technique
(a) Direct currents	*(i)* Resistive shunts with milliammeter
	(ii) Hall effect generators
	(iii) Magnetic links
(b) Alternating currents	*(i)* Resistive shunts
(Power frequency)	*(ii)* Electromagnetic current transformers
(c) High frequency a.c.,	*(i)* Resistive shunts
impulse and rapidly	*(ii)* Magnetic potentiometers or Rogowski coils
changing currents	*(iii)* Magnetic links
	(iv) Hall effect generators

7.1.1 High Ohmic Series Resistance with Microammeter

High d.c. voltages are usually measured by connecting a very high resistance (few hundreds of megaohms) in series with a microammeter as shown in Fig. 7.1. Only the current I flowing through the large calibrated resistance R is measured by the moving coil microammeter. The voltage of the source is given by

$$V = I R$$

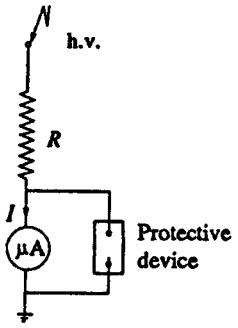


Fig. 7.1 Series resistance micrometer

The voltage drop in the meter is negligible, as the impedance of the meter is only few ohms compared to few hundred mega-ohms of the series resistance R. A protective device like a paper gap, a neon glow tube, or a zener diode with a suitable series resistance is connected across the meter as a protection against high voltages in case the series resistance R fails or flashes over. The ohmic value of the series resistance R is chosen such that a current of one to ten microamperes is allowed for full-scale deflection. The resistance is constructed from a large number of wire wound resistors in series. The voltage drop in each resistor element is chosen to avoid surface flashovers and discharges. A value of less than 5 kV/cm in air or less than 20 kV/cm in good oil is permissible. The resistor chain is provided with corona free terminations. The material for resistive elements is usually a carbon-alloy with temperature coefficient less than 10^{-4}/°C. Carbon and other metallic film resistors are also used. A resistance chain built with ±1% carbon resistors located in an airtight transformer oil filled P.V.C. tube, for 100 kV operation had very good temperature stability. The limitations in the series resistance design are:

(*i*) power dissipation and source loading,
(*ii*) temperature effects and long time stability,
(*iii*) voltage dependence of resistive elements, and
(*iv*) sensitivity to mechanical stresses.

Series resistance meters are built for 500 kV d.c. with an accuracy better than 0.2%.

7.1.2 Resistance Potential Dividers for d.c. Voltages

A resistance potential divider with an electrostatic or high impedance voltmeter is shown in Fig. 7.2. The influence of temperature and voltage on the elements is eliminated in the voltage divider arrangement. The high voltage magnitude is given by $[(R_1 + R_2)/R_2]v_2$, where v_2 is the d.c. voltage across the low voltage arm R_2. With sudden changes in voltage, such as switching operations, flashover of the test objects, or source short circuits, flashover or damage may occur to the divider elements due to the stray capacitance across the elements and due to ground capacitances. To avoid these transient voltages, voltage controlling capacitors are connected across the elements. A corona free termination is also necessary to avoid unnecessary discharges at high voltage ends. A series resistor with a parallel capacitor connection for linearization of transient potential distribution is shown in Fig. 7.3. Potential dividers are made with 0.05% accuracy up to 100 kV, with 0.1% accuracy up to 300 kV, and with better than 0.5% accuracy for 500 kV.

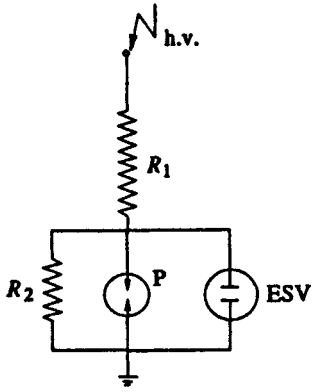


Fig. 7.2 Resistance potential divider with an electrostatic voltmeter

P — Protective device
ESV — Electrostatic volt-meter

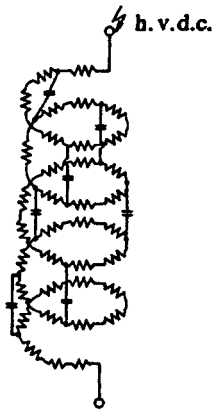


Fig. 7.3 Series resistor with parallel capacitors for potential linearization for transient voltages

7.1.3 Generating Voltmeters

High voltage measuring devices employ generating principle when source loading is prohibited (as with Van de Graaff generators, etc.) or when direct connection to the high voltage source is to be avoided. A generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the applied external voltage. The device is driven by an external synchronous or constant speed motor and does not absorb power or energy from the voltage measuring source.

Principle of Operation

The charge stored in a capacitor of capacitance C is given by $q = CV$. If the capacitance of the capacitor varies with time when connected to the source of voltage V, the current through the capacitor,

$$i = \frac{dq}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt} \tag{7.1}$$

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

$$i = \frac{dq}{dt} = V\frac{dC}{dt} \tag{7.2}$$

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

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

the current i is

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

where

$$i_m = V C_m \omega$$

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

$$i_{r\,ms} = \frac{VC_m\omega}{\sqrt{2}} \tag{7.3}$$

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

A generating voltmeter with a rotating cylinder consists of two excitating field electrodes and a rotating two pole armature driven by a synchronous motor at a constant speed n. The a.c. current flowing between the two halves of the armature is rectified by a commutator whose arithmetic mean may be calculated from:

$$i = \frac{n}{30}\Delta C\, V, \qquad \text{where } \Delta C = C_{max} - C_{min}$$

For a symmetric voltage $C_{min} = 0$. When the voltage is not symmetrical, one of the electrodes is grounded and C_{min} has a finite value. The factor of proportionality $\frac{n}{30} \cdot \Delta C$ is determined by calibration.

This device can be used for measuring a.c. voltages provided the speed of the drive-motor is half the frequency of the voltage to be measured. Thus a four-pole synchronous motor with 1500 rpm is suitable for 50 Hz. For peak value measurements, the phase angle of the motor must also be so adjusted that C_{max} and the crest value occur at the same instant.

Generating voltmeters employ rotating sectors or vanes for variation of capacitance. Figure 7.4 gives a schematic diagram of a generating voltmeter. The high voltage source is connected to a disc electrode S_3 which is kept at a fixed distance on the axis of the other low voltage electrodes S_0, S_1, and S_2. The rotor S_0 is driven at a constant speed by a synchronous motor at a suitable speed (1500, 1800, 3000, or 3600 rpm). The rotor vanes of S_0 cause periodic change in capacitance between the insulated disc S_2 and the h.v. electrode S_3. The shape and number of the vanes of S_0 and S_1 are so designed that they produce sinusoidal variation in the capacitance. The generated a.c. current through the resistance R is rectified and read by a moving coil instrument. An amplifier is needed, if the shunt capacitance is large or longer leads are used for connection to rectifier and meter. The instrument is calibrated using a potential divider or sphere gap. The meter scale is linear and its range can be extended

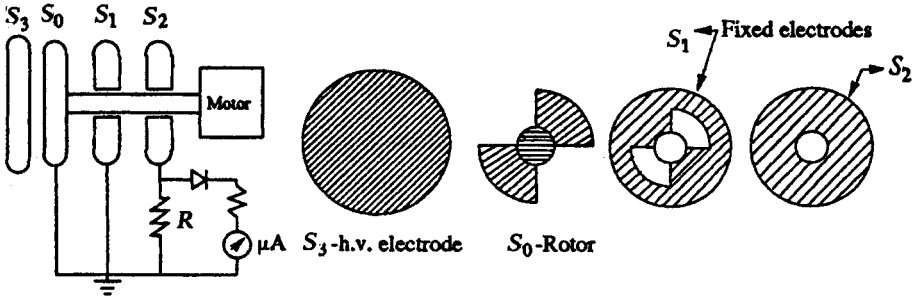
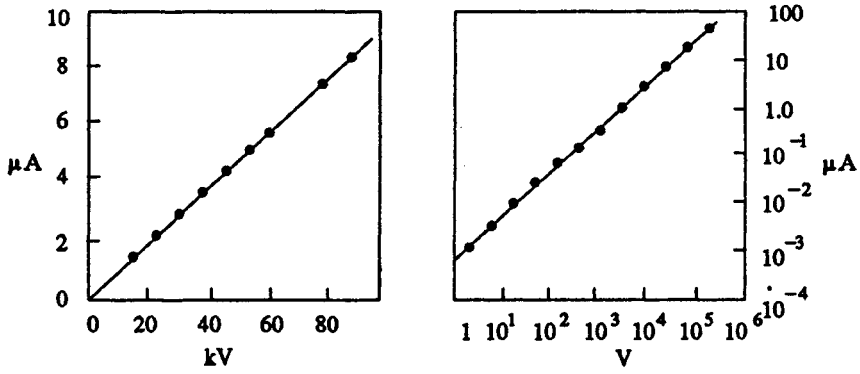


Fig. 7.4 Schematic diagram of a generating voltmeter (rotating vane type)



(a) Rotating cylinder type (b) Rotating vane type

Fig. 7.5 Calibration curves for a generating voltmeter

by extrapolation. Typical calibration curves of a generating voltmeter are given in Figs. 7.5a and b.

Advantages of Generating Voltmeters

(*i*) No source loading by the meter,
(*ii*) no direct connection to high voltage electrode,
(*iii*) scale is linear and extension of range is easy, and
(*iv*) a very convenient instrument for electrostatic devices such as Van de Graaff generator and particle accelerators.

Limitations of Generating Voltmeters

(*i*) They require calibration,
(*ii*) careful construction is needed and is a cumbersome instrument requiring an auxiliary drive, and
(*iii*) disturbance in position and mounting of the electrodes make the calibration invalid.

7.1.4 Other Methods—Oscillating Spheroid

The period of oscillation of an oscillating spheroid in a uniform electric field is proportional to the applied electric field. This principle is made use of in measuring high d.c. voltages. The period of oscillation of a suspended spheroid between two electrodes with and without an electric field present is measured. If the frequency of the oscillation for small amplitudes is f and f_0 respectively, then the electric field

$$E \propto [f^2 - f_0^2]^{1/2}$$

and hence the applied voltage

$$V \propto [f^2 - f_0^2]^{1/2} \tag{7.4}$$

since $E = V/d$ (d being the gap separation between the electrodes). The proportionality constant can be determined from the dimensions of the spheroid or experimentally.

The uniform electric field is produced by employing two electrodes with a Bruce profile for a spacing of about 50 cm. One of the electrodes is earthed and the other is connected to a high voltage d.c. source. The spheroid is suspended at the centre of the electrodes in the axis of the electric field. The period of oscillation is measured using a telescope and stop watch. Instruments of this type are constructed for voltages up to 200 kV, and the accuracy is estimated to be ±0.1%. In Bruce's design, electrodes of 145 cm diameter with 45 cm spacing were used. An overall accuracy of ±0.03% was claimed up to a maximum voltage of 250 kV. Since this is a very complicated and time consuming method, it is not widely used. The useful range of the spheroidal voltmeter is limited by local discharges.

7.1.5 Measurement of Ripple Voltage in d.c. Systems

It has been discussed in the previous chapter that d.c. rectifier circuits contain ripple, which should be kept low (<< 3%). Ripple voltages are a.c. voltages of non-sinusoidal nature, and as such oscillographic measurement of these voltages is desirable. However, if a resistance potential divider is used along with an oscilloscope, the measurement of small values of the ripple δV will be inaccurate.

A simple method of measuring the ripple voltage is to use a capacitance-resistance (C-R) circuit and measure the varying component of the a.c. voltage by blocking the d.c. component. If V_1 is the d.c. source voltage with ripple (Fig. 7.6a) and V_2 is the voltage across the measuring resistance R, with C acting as the blocking capacitor, then

$$V_2(t) = V_1(t) - V_{d.c.} = \text{ripple voltage}$$

The condition to be satisfied here is $\omega CR >> 1$.

Measurement of Ripple with CRO

The detailed circuit arrangement used for this purpose is shown in Fig. 7.6b. Here, the capacitance 'C' is rated for the peak voltage. It is important that the switch 'S' be closed when the *CRO* is connected to the source so that the *CRO* input terminal does not receive any high voltage signal while 'C' is being charged. Further, C should be

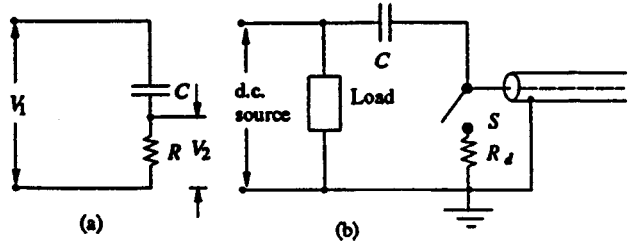


Fig. 7.6 Circuit arrangement for the measurement of ripple voltage

larger than the capacitance of the cable and the input capacitance of the *CRO*, taken together.

7.2 MEASUREMENT OF HIGH a.c. AND IMPULSE VOLTAGES: INTRODUCTION

Measurement of high a.c. voltages employ conventional methods like series impedance voltmeters, potential dividers, potential transformers, or electrostatic voltmeters. But their designs are different from those of low voltage meters, as the insulation design and source loading are the important criteria. When only peak value measurement is needed, peak voltmeters and sphere gaps can be used. Often, sphere gaps are used for calibration purposes. Impulse and high frequency a.c. measurements invariably use potential dividers with a cathode ray oscillograph for recording voltage waveforms. Sphere gaps are used when peak values of the voltage are only needed and also for calibration purposes.

7.2.1 Series Impedance Voltmeters

For power frequency a.c. measurements the series impedance may be a pure resistance or a reactance. Since resistances involve power losses, often a capacitor is preferred as a series reactance. Moreover, for high resistances, the variation of resistance with temperature is a problem, and the residual inductance of the resistance gives rise to an impedance different from its ohmic resistance. High resistance units for high voltages have stray capacitances and hence a unit resistance will have an equivalent circuit as shown in Fig. 7.7. At any frequency ω of the a.c. voltage, the impedance of the resistance R is

$$Z = \frac{R + j\omega L}{(1 - \omega^2 LC) + j\omega CR} \tag{7.5}$$

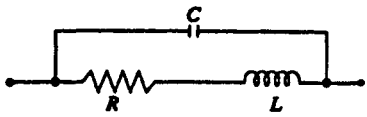


Fig. 7.7 Simplified lumped parameter equivalent circuit of a high ohmic resistance R

L — Residual inductance

C — Residual capacitance

If ωL and ωC are small compared to R,

$$Z \approx R\left[1 + j\left(\frac{\omega L}{R} - \omega CR\right)\right] \tag{7.6}$$

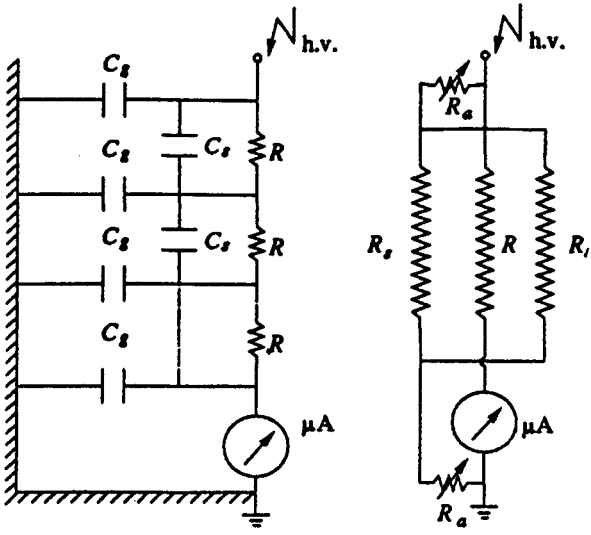
and the total phase angle is

$$\varphi \approx \left(\frac{\omega L}{R} - \omega CR\right) \tag{7.7}$$

This can be made zero and independent of frequency, if

$$L/C = R^2 \tag{7.8}$$

For extended and large dimensioned resistors, this equivalent circuit is not valid and each elemental resistor has to be approximated with this equivalent circuit. The entire resistor unit then has to be taken as a transmission line equivalent, for calculating the effective resistance. Also, the ground or stray capacitance of each element influences the current flowing in the unit, and the indication of the meter results in an error. The equivalent circuit of a high voltage resistor neglecting inductance and the circuit of compensated series resistor using guard and tuning resistors is shown in Figs. 7.8a and b respectively. Stray ground capacitance effects (refer Fig. 7.8b) can be removed by shielding the resistor R by a second surrounding spiral R_s, which shunts the actual resistor but does not contribute to the current through the instrument. By tuning the resistors R_a, the shielding resistor end potentials may be adjusted with respect to the actual measuring resistor so that the resulting compensation currents between the shield and the measuring resistors provide a minimum phase angle.



(a) Extended series resistance with inductance neglected

C_g — Stray capacitance to ground
C_s — Winding capacitance

(b) Series resistance with guard and tuning resistances

R — Series resistor
R_s — Guard resistor
R_a — Tuning resistor

Fig. 7.8 Extended series resistance for high a.c. voltage measurements

Series Capacitance Voltmeter

To avoid the drawbacks pointed out earlier, a series capacitor is used instead of a resistor for a.c. high voltage measurements. The schematic diagram is shown in Fig. 7.9. The current I_c through the meter is:

$$I_c = j\,\omega\,CV \tag{7.9}$$

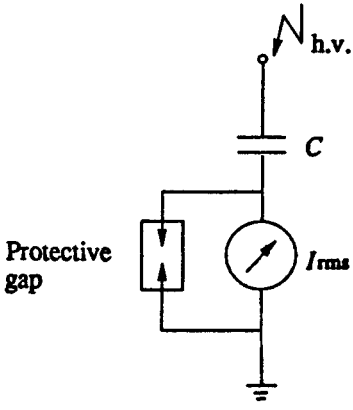


Fig. 7.9 Series capacitance with a milliammeter for measurement of high a.c. voltages

where, C = capacitance of the series capacitor,

ω = angular frequency, and

V = applied a.c. voltage.

If the a.c. voltage contains harmonics, error due to changes in series impedance occurs. The rms value of the voltage V with harmonics is given by

$$V = \sqrt{V_1^2 + V_2^2 + \ldots V_n^2} \tag{7.10}$$

where V_1, V_2, ... V_n represent the rms value of the fundamental, second ... and nth harmonics.

The currents due to these harmonics are

$$\begin{aligned} I_1 &= \omega\,CV_1 \\ I_2 &= 2\,\omega\,CV_2, \ldots, \text{and} \\ I_n &= n\,\omega\,CV_n \end{aligned} \tag{7.11}$$

Hence, the resultant rms current is:

$$I = \omega\,C\,(V_1^2 + 4V_2^2 + \ldots + n^2V_n^2)^{1/2} \tag{7.12}$$

With a 10% fifth harmonic only, the current is 11.2% higher, and hence the error is 11.2% in the voltage measurement.

This method is not recommended when a.c. voltages are not pure sinusoidal waves but contain considerable harmonics.

Series capacitance voltmeters were used with cascade transformers for measuring rms values up to 1000 kV. The series capacitance was formed as a parallel plate capacitor between the high voltage terminal of the transformer and a ground plate suspended above it. A rectifier ammeter was used as an indicating instrument and was directly calibrated in high voltage rms value. The meter was usually a 0-100 μA moving coil meter and the over all error was about 2%.

7.2.2 Capacitance Potential Dividers and Capacitance Voltage Transformers

The errors due to harmonic voltages can be eliminated by the use of capacitive voltage dividers with an electrostatic voltmeter or a high impedance meter such as a V.T.V.M. If the meter is connected through a long cable, its capacitance has to be

taken into account in calibration. Usually, a standard compressed air or gas condenser is used as C_1 (Fig. 7.10), and C_2 may be any large capacitor (mica, paper, or any low loss condenser). C_1 is a three terminal capacitor and is connected to C_2 through a shielded cable, and C_2 is completely shielded in a box to avoid stray capacitances. The applied voltage V_1 is given by

$$V_1 = V_2\left(\frac{C_1 + C_2 + C_m}{C_1}\right) \quad (7.13)$$

where C_m is the capacitance of the meter and the connecting cable and the leads and V_2 is the meter reading.

Capacitance Voltage Transformer—CVT

Capacitance divider with a suitable matching or isolating potential transformer tuned for resonance condition is often used in power systems for voltage measurements. This is often referred to as CVT. In contrast to simple capacitance divider which requires a high impedance meter like a V.T.V.M. or an electrostatic voltmeter, a CVT can be connected to a low impedance device like a wattmeter pressure coil or a relay coil. CVT can supply a load of a few VA. The schematic diagram of a CVT with its equivalent circuit is given in Fig. 7.11. C_1 is made of a few units of high voltage condensers, and the total capacitance will be around a few thousand picofarads as against a gas filled standard condenser of about 100 pF. A matching transformer is connected between the load or meter M and C_2. The transformer ratio is chosen on economic grounds, and the h.v. winding rating may be 10 to 30 kV with the l.v. winding rated from 100 to 500 V. The value of the tuning choke L is chosen to make the equivalent circuit of the CVT purely resistive or to bring resonance condition. This condition is satisfied when

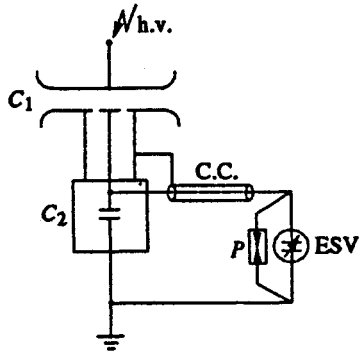


Fig. 7.10 Capacitance potential divider

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

$$\omega(L + L_T) = \frac{1}{\omega(C_1 + C_2)} \quad (7.14)$$

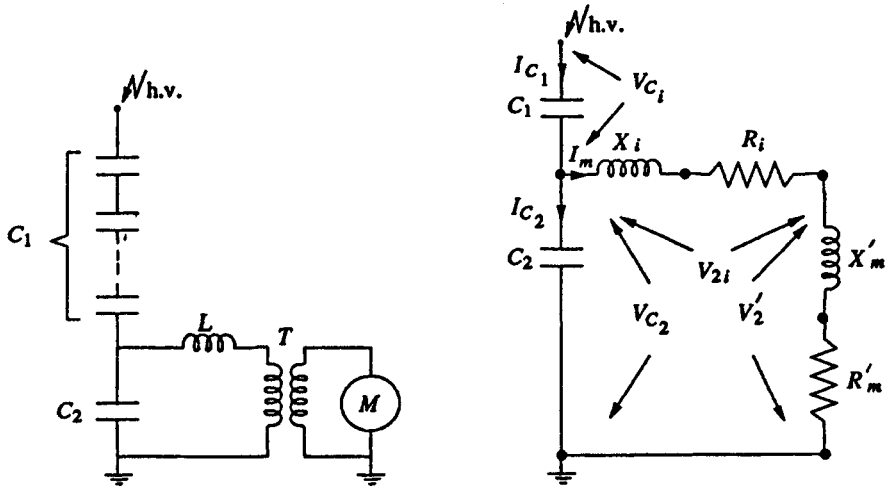
where,

L = inductance of the choke, and

L_T = equivalent inductance of the transformer referred to h.v. side.

The voltage V_2 (meter voltage) will be in phase with the input voltage V_1.

The phasor diagram of CVT under resonant conditions is shown in Fig. 7.11. The meter is taken as a resistive load, and X'_m is neglected. The voltage across the load referred to the divider side will be $V'_2 = (I'_m R'_m)$ and $V_{C_2} = V'_2 + I_m(R_e + X_e)$. It is clear from the phasor diagram that V_1 (input voltage) = $(V_{C_1} + V_{C_2})$ and is in phase



(a) Schematic representation (b) Equivalent circuit

Fig. 7.11 Capacitive voltage transformer (CVT)

with V_2', the voltage across the meter. R_e and X_e include the potential transformer resistance and leakage reactance. Under this condition, the voltage ratio becomes

$$a = (V_1/V_2) \simeq (V_{C_1} + V_{Ri} + V_2')/V_2' \qquad (7.15)$$

(neglecting the voltage drop $I_m \cdot X_e$ which is very small compared to the voltage V_{C_1}) where V_{Ri} is the voltage drop in the transformer and choke windings.

The advanges of a CVT are:

(*i*) simple design and easy installation,

(*ii*) can be used both as a voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.

(*iii*) frequency independent voltage distribution along elements as against conventional magnetic potential transformers which require additional insulation design against surges, and

(*iv*) provides isolation between the high voltage terminal and low voltage metering.

The disadvantages of a CVT are:

(*i*) the voltage ratio is susceptible to temperature variations, and

(*ii*) the problem of inducing ferro-resonance in power systems.

Resistance Potential Dividers

Resistance potential dividers suffer from the same disadvantages as series resistance voltmeters for a.c. applications. Moreover, stray capacitances and inductances (Figs 7.7 and 7.8) associated with the resistances make them inaccurate, and compensation has to be provided. Hence, they are not generally used.

7.2.3 Potential Transformers (Magnetic Type)

Magnetic potential transformers are the oldest devices for a.c. measurements. They are simple in construction and can be designed for any voltage. For very high voltages, cascading of the transformers is possible. The voltage ratio is:

$$\frac{V_1}{V_2} = a = \frac{N_1}{N_2} \qquad (7.16)$$

where V_1 and V_2 are the primary and secondary voltages, and N_1 and N_2 are the respective turns in the windings.

These devices suffer from the ratio and phase angle errors caused by the magnetizing and leakage impedances of the transformer windings. The errors are compensated by adjusting the turns ratio with the tappings on the high voltage side under load conditions. Potential transformers (PT) do not permit fast rising transient or high frequency voltages along with the normal supply frequency, but harmonic voltages are usually measured with sufficient accuracy. With high voltage testing transformers, no separate potential transformer is used, but a PT winding is incorporated with the high voltage windings of the testing transformer.

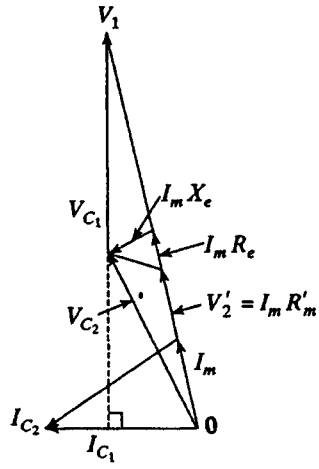


Fig. 7.12 Phasor diagram of a CVT under resonance or tuned condition, Z_m is taken to be equal to resistance R_m

With test objects like insulators, cables, etc. which are capacitive in nature, a voltage rise occurs on load with the testing transformer, and the potential transformer winding gives voltage values less than the actual voltages applied to the test object. If the percentage impedance of the testing transformer is known, the following correction can be applied to the voltage measured by the PT winding of the transformer.

$$V_2 = V_{20}(1 + 0.01\, v_x C/C_N) \qquad (7.17)$$

where,

V_{20} = open circuit voltage of the PT winding,

C_N = load capacitance used for testing,

C = test object capacitance ($C << C_N$), and

v_x = % reactance drop in the transformer.

7.2.4 Electrostatic Voltmeters

Principle

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

$$F = \left|\frac{-\delta W_s}{dS}\right| = \left|\frac{\delta}{\delta S}\left(\tfrac{1}{2}CV^2\right)\right| = \left|\tfrac{1}{2}V^2\frac{\delta C}{\delta S}\right|$$

$$= \tfrac{1}{2}\varepsilon_0 V^2 \frac{A}{S^2} = \tfrac{1}{2}\varepsilon_0 A\left(\frac{V}{s}\right)^2 \qquad (7.18)$$

where,

V = applied voltage between plates,

C = capacitance between the plates,

A = area of cross-section of the plates,

s = separation between the plates,

ε_0 = permittivity of the medium (air or free space), and

W_s = work done in displacing a plate

When one of the electrodes is free to move, the force on the plate can be measured by controlling it by a spring or balancing it with a counter weight. For high voltage measurements, a small displacement of one of the electrodes by a fraction of a millimetre to a few millimetres is usually sufficient for voltage measurements. As the force is proportional to the square of the applied voltage, the measurement can be made for a.c. or d.c. voltages.

Construction

Electrostatic voltmeters are made with parallel plate configuration using guard rings to avoid corona and field fringing at the edges. An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight. Usually the electrostatic voltmeters have a small capacitance (5 to 50 pF) and high insulation resistance ($R \geq 10^{13}\ \Omega$). Hence they are considered as devices with high input impedance. The upper frequency limit for a.c. applications is determined from the following considerations:

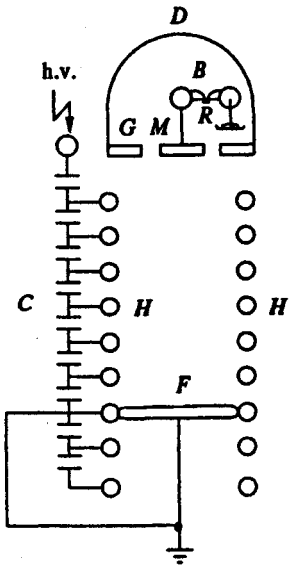
(*i*) natural frequency of the moving system,

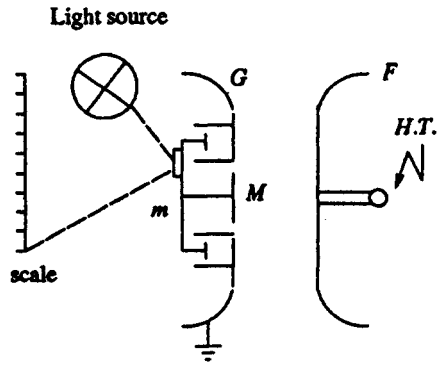
(*ii*) resonant frequency of the lead and stray inductances with meter capacitance, and

(*iii*) the *R-C* behaviour of the retaining or control spring (due to the frictional resistance and elastance).

An upper frequency limit of about one MHz is achieved in careful designs. The accuracy for a.c. voltage measurements is better than ±0.25%, and for d.c. voltage measurements it may be ±0.1% or less.

The schematic diagram of an absolute electrostatic voltmeter or electrometer is given in Fig. 7.13. It consists of parallel plane disc type electrodes separated by a small distance. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region. In order to measure the given voltage with precision, the disc diameter is to be increased, and the gap distance is to be made less. The limitation on the gap distance is the safe working stress (V/s) allowed in air which is normally 5 kV/cm or less. The main difference between several forms of voltmeters lies in the manner in which the restoring force is obtained. For conventional versions of meters, a simple spring control is used, which actuates a pointer to move on the scale of the instruments. In more versatile instruments, only small movements of the moving electrodes is allowed, and the movement is amplified through optical means (lamp and scale arrangement as used with moving coil galvanometers). Two air vane dampers are used to reduce vibrational tendencies in the moving system, and the





(a) Absolute electrostatic voltmeter

(b) Light beam arrangement

M — Mounting plate
G — Guard plate
F — Fixed plate
H — Guard hoops or rings

m — mirror
B — Balance
C — Capacitance divider
D — Dome
R — Balancing weight

Fig. 7.13 Electrostatic voltmeter

elongation of the spring is kept minimum to avoid field disturbances. The range of the instrument is easily changed by changing the gap separation so that *V/s* or electric stress is the same for the maximum value in any range. Multi-range instruments are constructed for 600 kV rms and above.

The constructional details of an absolute electrostatic voltmeter is given in Fig. 7.13a. The control torque is provided by a balancing weight. The moving disc M forms the central core of the guard ring G which is of the same diameter as the fixed plate F. The cap D encloses a sensitive balance B, one arm of which carries the suspension of the moving disc. The balance beam carries a mirror which reflects a beam of light. The movement of the disc is thereby magnified. As the spacing between the two electrodes is large, the uniformity of the electric field is maintained by the guard rings H which surround the space between the discs F and M. The guard rings H are maintained at a constant potential in space by a capacitance divider ensuring a uniform special potential distribution.

Some instruments are constructed in an enclosed structure containing compressed air, carbon dioxide, or nitrogen. The gas pressure may be of the order of 15 atm. Working stresses as high as 100 kV/cm may be used in an electrostatic meter in

vacuum. With compressed gas or vacuum as medium, the meter is compact and much smaller in size.

7.2.5 Peak Reading a.c. Voltmeters

In some occasions, the peak value of an a.c. waveform is more important. This is necessary to obtain the maximum dielectric strength of insulating solids, etc. When the waveform is not sinusoidal, rms value of the voltage multiplied by $\sqrt{2}$ is not correct. Hence a separate peak value instrument is desirable in high voltage applications.

Series Capacitor Peak Voltmeter

When a capacitor is connected to a sinusoidal voltage source, the charging current $i_0 = C \int_0 v dt = j \omega CV$ where V is the rms value of the voltage and ω is the angular frequency. If a half wave rectifier is used, the arithmetic mean of the rectifier current is proportional to the peak value of the a.c. voltage. The schematic diagram of the circuit arrangement is shown in Fig. 7.14. The d.c. meter reading is proportional to the peak value of the value V_m or

$$V_m = \frac{I}{2\pi fC}$$

where I is the d.c. current read by the meter and C is the capacitance of the capacitor. This method is known as the Chubb-Frotscue method for peak voltage measurement.

The diode D_1 is used to rectify the a.c. current in one half cycle while D_2 by-passes in the other half cycle. This arrangement is suitable only for positive or negative half

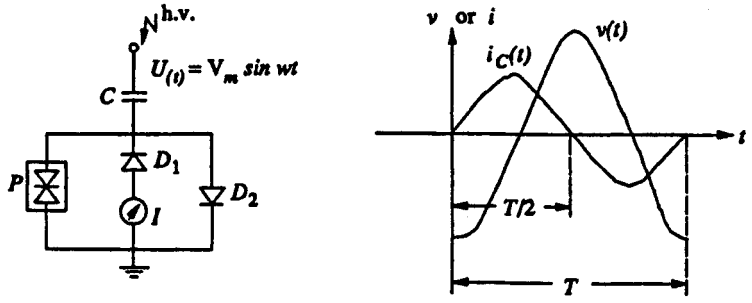


Fig. 7.14 Peak voltmeter with a series capacitor

C — Capacitor
D_1, D_2 — Diodes
P — Protective device
I — Indicating meter (rectified current indicated)
$v(t)$ — Voltage waveform
$I_c(t)$ — Capacitor current waveform
T — Period

cycles and hence is valid only when both half cycles are symmetrical and equal. This method is not suitable when the voltage waveform is not sinusoidal but contains more than one peak or maximum as shown in Fig. 7.14. The charging current through the capacitor changes its polarity within one half cycle itself. The shaded areas in Fig. 7.15 give the reverse current in any one of the half cycles and the current within that period subtracts from the net current. Hence the reading of the meter will be less and is not proportional to V_m as the current flowing during the intervals $(t_1 - t_2)$ etc. will not be included in the mean value. The 'second' or the false maxima is easily spotted out by observing the waveform of the charging current on an oscilloscope. Under normal conditions with a.c. testing, such waveforms do not occur and as such do not give rise to errors. But pre-discharge currents within the test circuits cause very short duration voltage drops which may introduce errors. This problem can also be overcome by using a resistance R in series with capacitor C such that $CR << 1/\omega$ for 50 Hz application. The error due to the resistance is

$$\frac{\Delta V}{V} = \frac{V - V_m}{V} = \left(1 - \frac{1}{1 + \omega^2 C^2 R^2}\right) \tag{7.19}$$

where, V = actual value, and

V_m = measured value

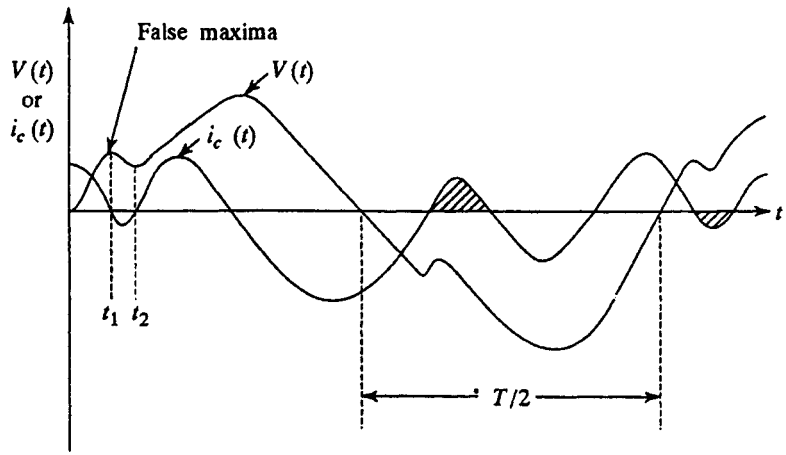


Fig. 7.15 Voltage waveform with harmonic content showing false maxima

In determining the error, the actual value of the angular frequency ω has to be determined.

The different sources that contribute to the error are

(*i*) the effective value of the capacitance being different from the measured value of C

(*ii*) imperfect rectifiers which allow small reverse currents

(*iii*) non-sinusoidal voltage waveforms with more than one peak or maxima per half cycle

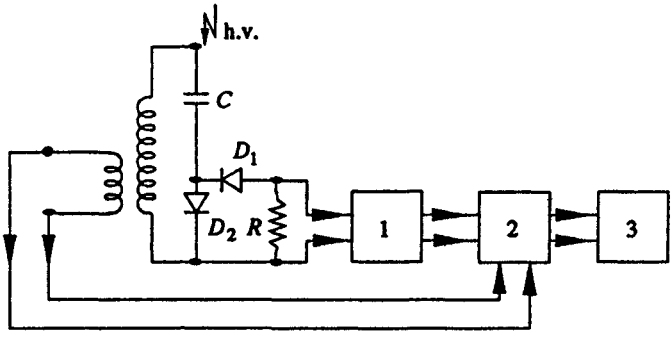
(*iv*) deviation of the frequency from that of the value used for calibration

As such, this method in its basic form is not suitable for waveforms with more than one peak in each half cycle.

A digital peak reading meter for voltage measurements is shown in Fig. 7.16. Instead of directly measuring the rectified charging current, a proportional analog voltage signal is derived which is then converted into a proportional medium frequency, f_m. The frequency ratio f_m/f is measured with a gate circuit controlled by the a.c. power frequency (f) and a counter that opens for an adjustable number of periods $\Delta t = p/f$. During this interval, the number of impulses counted, n, is

$$n = f_m \cdot \Delta t = p \cdot \frac{f_m}{f} = 2pCV_m AR \tag{7.20}$$

where p is a constant of the instrument and A represents the conversion factor of the a.c. to d.c. converter. $A = f_m/(R\, i_m)$; i_m is the rectified current through resistance R. An immediate reading of the voltage in kV can be obtained by suitable choice of the parameters R and the number of periods p. The total estimated error in this instrument was less than 0.35%. Conventional instruments of this type are available with less than 2% error.



C — Series capacitor
D_1, D_2 — Diodes
R — Input resistor
1 — Voltage to frequency converter
2 — Gate circuit
3 — Read out counter (indicator)

Fig. 7.16 Digital peak voltmeter

Peak Voltmeters with Potential Dividers

Peak voltmeters using capacitance dividers designed by Bowlder *et al.*, are shown in Fig. 7.17a. The voltage across C_2 is made use of in charging the storage capacitor C_s. R_d is a discharge resistor employed to permit variation of V_m whenever V_2 is reduced. C_s is charged to a voltage proportional to the peak value to be measured. The indicating meter is either an electrostatic voltmeter or a high impedance V.T.V.M. The discharge time constant C_sR_d is designed to be about 1 to 10 s. This gives rise to a discharge error which depends on the frequency of the supply voltage. To compensate for the charging and discharging errors due to the resistances, the circuit is modified as shown in Fig. 7.17b. Measurement of the average peak is done by a microameter. Rabus' modification to compensate the charging errors is given in Fig. 7.17c.

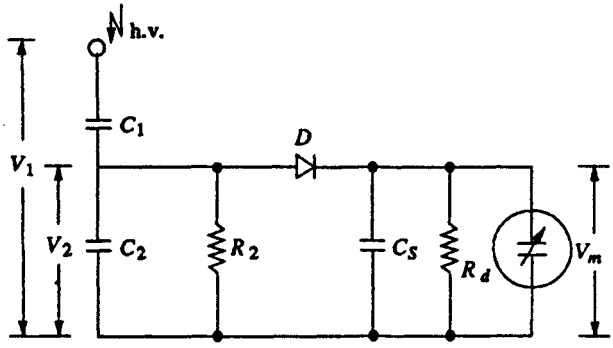


Fig. 7.17a Peak voltmeter with a capacitor potential divider and electrostatic voltmeter

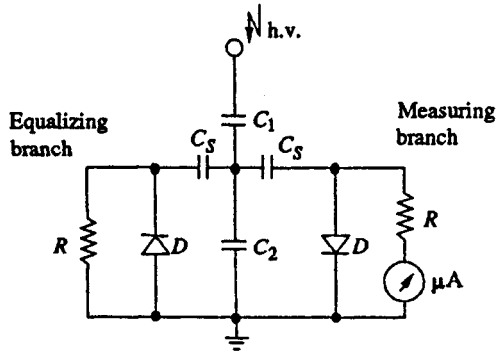
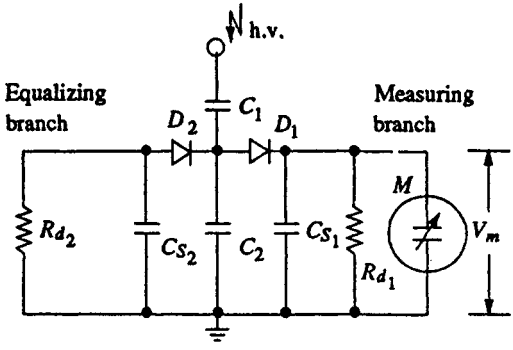


Fig. 7.17b Peak voltmeter as modified by Haefeely (ref. 19)



Rabus (ref. 20)

M — Electrostatic voltmeter or V.T.V.M. of high impedance

C_{S_2} — C_{S_1} + *C* meter

R_{d_2} — R_{d_1}

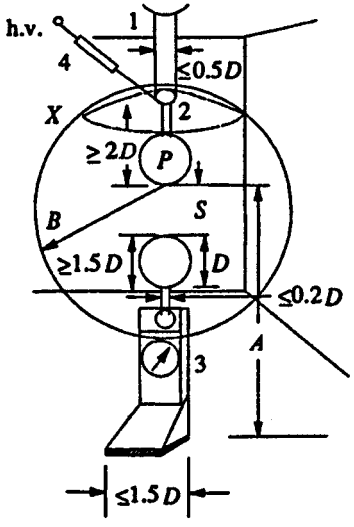
Fig. 7.17c Peak voltmeter with equalizing branch as designed by Rabus

7.2.6 Spark Gaps for Measurement of High d.c., a.c. and Impulse Voltages (Peak Values)

A uniform field spark gap will always have a sparkover voltage within a known tolerance under constant atmospheric conditions. Hence a spark gap can be used for measurement of the peak value of the voltage, if the gap distance is known. A sparkover voltage of 30 kV (peak) at 1 cm spacing in air at 20°C and 760 torr pressure occurs for a sphere gap or any uniform field gap. But experience has shown that these measurements are reliable only for certain gap configurations. Normally, only sphere gaps are used for voltage measurements. In certain cases uniform field gaps and rod gaps are also used, but their accuracy is less. The spark gap breakdown, especially the sphere gap breakdown, is independent of the voltage waveform and hence is highly suitable for all types of waveforms from d.c. to impulse voltages of short rise times (rise time $\geq 0.5\ \mu$ s). As such, sphere gaps can be used for radio frequency a.c. voltage peak measurements also (up to 1 MHz).

Sphere Gap Measurements

Sphere gaps can be arranged either (*i*) vertically with lower sphere grounded, or (*ii*) horizontally with both spheres connected to the source voltage or one sphere grounded. In horizontal configurations, it is generally arranged such that both spheres are symmetrically at high voltage above the ground. The two spheres used are identical in size and shape. The schematic arrangement is shown in Figs. 7.18a and 7.18b. The voltage to be measured is applied between the two spheres and the distance



(a) Vertical arrangement of sphere gap

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

Fig. 7.18a Sphere gap for voltage measurement

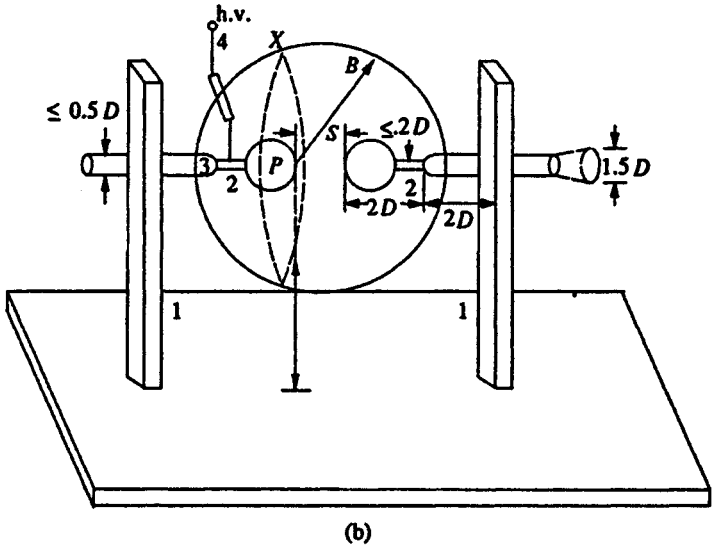


Fig. 7.18b Horizontal arrangement of sphere gap
(Legend as in Fig. 7.18a)

or spacing S between them gives a measure of the sparkover voltage. A series resistance is usually connected between the source and the sphere gap to (*i*) limit the breakdown current, and (*ii*) to suppress unwanted oscillations in the source voltage when breakdown occurs (in case of impulse voltages). The value of the series resistance may vary from 100 to 1000 kilo ohms for a.c. or d.c. voltages and not more than 500 Ω in the case of impulse voltages.

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

In the case of impulse voltages, to obtain 50% flashover voltage, two voltage limits, differing by not more than 2% are set such that on application of lower limit value either 2 or 4 flashovers take place and on application of upper limit value 8 or 6 flashovers take place respectively. The mean of these two limits is taken as 50% flashover voltage. In any case, a preliminary sparkover voltage measurement is to be made before actual measurements are made.

The flashover voltage for various gap distances and standard diameters of the spheres used are given in Tables 7.3 and 7.4 respectively. The values of sparkover voltages are specified in BS : 358, IEC Publication 52 of 1960 and IS : 1876 of 1962. The clearances necessary are shown in Figs. 7.18a and 7.18b for measurements to be within ±3%. The values of A and B indicated in the above figures are given in Table 7.5.

Table 7.3 Peak value of sparkover voltage in kV for a.c., d.c. voltages of either polarity, and for full negative standard impulse voltages (one sphere earthed) (a) and positive polarity impulse voltages and impulse voltages with long tails (b) at temperature: 25°C and pressure: 760 torr

Gap spacing (cm)	Sphere diameter (cm)															
	5		10		15		25		50		100		150		200	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0.5	17.4	17.4	16.9	16.8	16.9	16.9										
1.0	32.0	32.0	31.7	31.7	31.4	31.4	31.2	31.4								
1.5	44.7	45.5	44.7	45.1	44.7	45.1	44.7	44.7								
2.0	57.5	58.0	58.0	58.0	58.0	58.0	58.0	58.0								
2.5			71.5	71.5	71.5	71.5	71.5	71.5	71.5	71.5						
3.0			85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0						
3.5			95.5	96.0	97.0	97.0	97.0	97.0	97.0	97.0						
4.0			106.0	108.0	108.0	110.0	110.0	110.0	110.0	110.0						
5.0			(123.0)	(127.0)	127.0	132.0	135.0	136.0	136.0	136.0						
7.5					(181.0)	(187.0)	195.0	196.0	199.0	199.0						
10.0							257	268	259	259	262	262	262	262	262	262
12.5							277	294	315	317						
15.0							(309)	(331)	367	374	383	384	384	384	384	384
17.5							(336)	(362)	413	425						
20.0									452	472	500	500	500	500	500	500
25.0									520	545	605	610				
30.0									(575)	(610)	700	715	730	735	735	740
35.0									(725)	(755)	785	800				
40.0											862	885	940	950	960	965
45.0											925	965				
50.0											1000	1020	1110	1130	1160	1170
75.0											(1210)	(1260)	1420	1460	1510	1590
100.0															1870	1900

WORKED EXAMPLES

Example 7.1: A generating voltmeter has to be designed so that it can have a range from 20 to 200 kV d.c. If the indicating meter reads a minimum current of 2 μA and maximum current of 25 μA, what should the capacitance of the generating voltmeter be ?

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

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

where, V = applied voltage,

C_m = capacitance of the meter, and

ω = angular speed of the drive

Substituting,

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

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

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

$$= 20.0 \text{ μA}$$

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

Example 7.2: Design a peak reading voltmeter along with a suitable micro-ammeter such that it will be able to read voltages, up to 100 kV (peak). The capacitance potential divider available is of the ratio 1000 : 1.

Solution: Let the peak reading voltmeter be of the Haefely type shown in Fig. 7.17a.

Let the micro-ammeter have the range 0 – 10 μA.

The voltage available at the C_2 arm $= 100 \times 10^3 \times \dfrac{1}{1000}$

$$= 100 \text{ V (peak)}$$

The series resistance R in series with the micro ammeter

$$= \frac{100}{10 \times 10^{-6}}$$

$$= 10^7 \Omega$$

$C_S R$ = 1 to 10 s

Taking the higher value of 10 s, $C_S = \dfrac{10}{10^7}$

$$= 1 \text{ μF}$$

The values of C_S and R are 1 μF and $10^7 \Omega$.

Example 7.3: Calculate the correction factors for atmospheric conditions, if the laboratory temperature is 37°C, the atmospheric pressure is 750 mm Hg, and the wet bulb temperature is 27°C.

Solution: Air density factor, $d = \frac{p}{760} \frac{293}{(273 + t)}$

At $t = 37°C$ $\quad d = \frac{750}{760} \frac{293}{310}$

$= 0.9327$

From Table 7.6 air density correction factor $K = 0.9362$. From Fig. 10.1, the absolute humidity (by extrapolation) corresponding to the given temperature is 18 g/m^3. From Fig. 10.2, the humidity correction factor for 50 Hz (curve *a*) is 0.925.
(Note: No humidity correction is needed for sphere gaps.)

Example 7.4: A resistance divider of 1400 kV (impulse) has a high voltage arm of 16 kilo-ohms and a low voltage arm consisting 16 members of 250 ohms, 2 watt resistors in parallel. The divider is connected to a CRO through a cable of surge impedance 75 ohms and is terminated at the other end through a 75 ohm resistor. Calculate the exact divider ratio.

Solution: h.v. arm resistance, $R_1 = 16{,}000$ ohms

l.v. arm resistance, $\quad R_2 = \frac{250}{16}$ ohms

Terminating resistance, $\quad R_2' = 75$ ohms

hence, the divider ratio, $\quad a = 1 + R_1/R_2 + R_1/R_2'$

$= 1 + 16{,}000 \times 16/250$

$= 1 + 16{,}000/75$

$= 1 + 1024 + 213.3 = 1238.3$

Example 7.5: The H. V. arm of an *R-C*, divider has 15 numbers of 120 ohm resistors with a 20 pF capacitor to ground from each of the junction points. The L.V. arm resistance is 5 ohms. Determine the capacitance needed in the L.V. arm for correct compensation.

Solution: Ground capacitance per unit = $C_g' = 20$ pF

Effective ground capacitance = $C_e = (2/3)\, C_g$

$= 2/3\ (15 \times 20)$

(Refer Fig. 7.34)

$= 200$ pF

This capacitance is assumed to be between the center tap of the H.V. arm and the ground as shown in Fig. 7.28.

Here, $\quad R_1/2 = 15 \times 120/2 = 900$ ohms

$R_2 = 5$ ohms.

Then, the effective time constant of the divider,

$= (R_1/2 \cdot (2/3)\, C_g) = R_1 C_e/2$