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 **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.

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*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

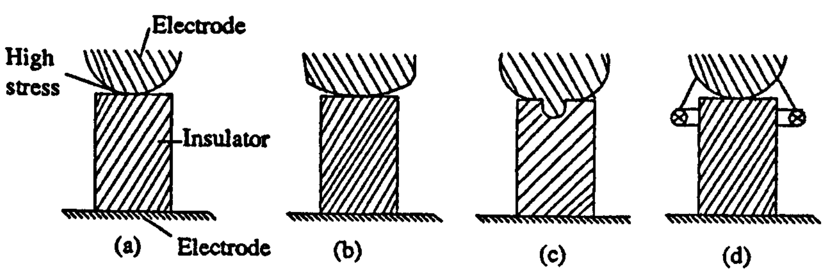


Fig. 1.1 Control of stress at an electrode edge

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

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

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 $\mathbf{E}$,

then,

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

When several conductors are present with charges $Q_1, Q_2, ... Q_n$ 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

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

where $C_{11}, C_{22}, ..., C_{ii}, ..., C_{nn}$ are called capacitance coefficients, and $C_{12}, C_{21}, ..., C_{ij}, C_{ji}$ 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

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

where $\mathbf{E}_{t1}$ and $\mathbf{E}_{t2}$ are the tangential components of the electric field, $\mathbf{E}_{n1}$ and $\mathbf{E}_{n2}$ 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.

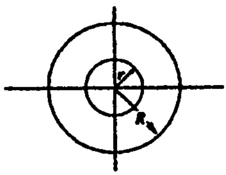
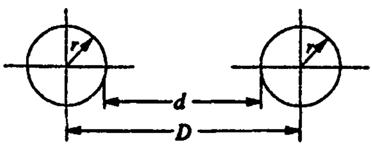
1.5.4 Estimation of Electric Field in Some Geometric Boundaries

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.

1.6 SURGE VOLTAGES, THEIR DISTRIBUTION AND CONTROL

The design of power apparatus particularly at high voltages is governed by their transient behaviour. The transient high voltages or surge voltages originate in power systems due to lightning and switching operations. The effect of the surge voltages is severe in all power apparatuses. The response of a power apparatus to the impulse or surge voltage depends on the capacitances between the coils of windings and between the different phase windings of the multi-phase machines. The transient voltage distribution in the windings as a whole are generally very non-uniform and are complicated by travelling wave voltage oscillations set up within the windings. In the actual design of an apparatus, it is, of course, necessary to consider the maximum voltage differences occurring, in each region, at any instant of time after the application of an impulse, and to take into account their durations especially when they are less than one microsecond.

An experimental assessment of the dielectric strength of insulation against the power frequency voltages and surge voltages, on samples of basic materials, on more or less complex assemblies, or on complete equipment must involve high voltage testing. Since the design of an electrical apparatus is based on the dielectric strength, the design cannot be completely relied upon, unless experimentally tested. High voltage testing is done by generating the voltages and measuring them in a laboratory.

When high voltage testing is done on component parts, elaborate insulation assemblies, and complete full-scale prototype apparatus (called development testing), it is possible to build up a considerable stock of design information; although expensive, such data can be very useful. However, such data can never really be complete to cover all future designs and necessitates use of large factors of safety. A different approach to the problem is the exact calculation of dielectric strength of any insulation arrangement. In an ideal design each part of the dielectric would be uniformly stressed at the maximum value which it will safely withstand. Such an ideal condition is impossible to achieve in practice, for dielectrics of different electrical strengths, due to the practical limitations of construction. Nevertheless it provides information on stress concentration factors — the ratios of maximum local voltage gradients to the mean value in the adjacent regions of relatively uniform stress. A survey of typical power apparatus designs suggests that factors ranging from 2 to 5 can occur in practice; when this factor is high, considerable quantities of insulation must be used. Generally, improvements can be effected in the following ways:

(*i*) by shaping the conductors to reduce stress concentrations,
(*ii*) by insertion of higher dielectric strength insulation at high stress points, and
(*iii*) by selection of materials of appropriate permittivities to obtain more uniform voltage gradients.

The properties of different insulating media and their applications are presented in Chapters 2, 3, 4 and 5. The generation and measurement of high voltages and currents are discussed in Chapters 6 and 7, and high voltage test methods and the design of high voltage laboratories are detailed in Chapters 9, 10 and 11. The various aspects of insulation co-ordination in high voltage power systems are discussed in Chapter 8.

REFERENCES

1. Alston, L.L., *High Voltage Technology*, Oxford University Press, Oxford (1967).
2. Seely, S., *Electromagnetic Fields*, McGraw-Hill, New York (1960).
3. Kuffel, E. and Zaengl, W.S., *High Voltage Engineering Fundamentals*, Pergamon Press, Oxford (1984).