1

Breakdown Mechanism of Gaseous, Liquid and Solid Materials

1.0 INTRODUCTION

With ever increasing demand of electrical energy, the power system is growing both in size and complexities. The generating capacities of power plants and transmission voltage are on the increase because of their inherent advantages. If the transmission voltage is doubled, the power transfer capability of the system becomes four times and the line losses are also relatively reduced. As a result, it becomes a stronger and economical system. In India, we already have 400 kV lines in operation and 800 kV lines are being planned. In big cities, the conventional transmission voltages (110 kV–220 kV etc.) are being used as distribution voltages because of increased demand. A system (transmission, switchgear, etc.) designed for 400 kV and above using conventional insulating materials is both bulky and expensive and, therefore, newer and newer insulating materials are being investigated to bring down both the cost and space requirements. The electrically live conductors are supported on insulating materials and sufficient air clearances are provided to avoid flashover or short circuits between the live parts of the system and the grounded structures. Sometimes, a live conductor is to be immersed in an insulating liquid to bring down the size of the container and at the same time provide sufficient insulation between the live conductor and the grounded container. In electrical engineering all the three media, viz. the gas, the liquid and the solid are being used and, therefore, we study here the mechanism of breakdown of these media.

1.1 MECHANISM OF BREAKDOWN OF GASES

At normal temperature and pressure, the gases are excellent insulators. The current conduction is of the order of 10^{-10} A/cm^2. This current conduction results from the ionisation of air by the cosmic radiation and the radioactive substances present in the atmosphere and the earth. At higher fields, charged particles may gain sufficient energy between collision to cause ionisation on impact with neutral molecules. It is known that during an elastic collision, an electron loses little energy and rapidly builds up its kinetic energy which is supplied by an external electric field. On the other hand, during elastic collision, a large part of the kinetic energy is transformed into potential energy by ionising the molecule struck by the electron. Ionisation by electron impact under strong electric field is the most important process leading to breakdown of gases.

This ionisation by radiation or photons involves the interaction of radiation with matter. Photoionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionisation energy and is represented as $A + h\nu \rightarrow A^+ + e$ where A represents a neutral atom or molecule in the gas and $h\nu$ the photon energy. Photoionization is a secondary ionization process and is essential in the streamer breakdown mechanism and in some corona discharges. If the photon energy is less than the ionization energy, it may still be absorbed thus raising the atom to a higher energy level. This is known as *photoexcitation*.

The life time of certain elements in some of the excited electronic states extends to seconds. These are known as metastable states and these atoms are known as *metastables*. Metastables have a relatively high potential energy and are, therefore, able to ionize neutral particles. Let A be the atom to be ionized and B^m the metastable, when B^m collides with A, ionization may take place according to the reaction.

$$A + B^m \longrightarrow A^+ + B + e$$

Ionization by metastable interactions comes into operation long after excitation and it has been shown that these reactions are responsible for long-time lags observed in some gases.

Thermal Ionisation: The term thermal ionisation in general applies to the ionizing actions of molecular collisions, radiation and electron collisions occurring in gases at high temperatures. When a gas is heated to high temperature, some of the gas molecules acquire high kinetic energy and these particles after collision with neutral particles ionize them and release electrons. These electrons and other high-velocity molecules in turn collide with other particles and release more electrons. Thus, the gas gets ionized. In this process, some of the electrons may recombine with positive ions resulting into neutral molecule. Therefore, a situation is reached when under thermodynamic equilibrium condition the rate of new ion formation must be equal to the rate of recombination. Using this assumption, Saha derived an expression for the degree of ionization β in terms of the gas pressure and absolute temperature as follows:

$$\frac{\beta^2}{1-\beta^2} = \frac{1}{p}\frac{(2\pi m_e)^{3/2}}{h}(KT)^{5/2}\, e^{-W/KT}$$

or

$$\frac{\beta^2}{1-\beta^2} = \frac{2.4\times10^{-4}}{p}\,T^{5/2}\, e^{-W_i/KT}$$

where p is the pressure in Torr, W_i the ionization energy of the gas, K the Boltzmann's constant, β the ratio n_i/n and n_i the number of ionized particles of total n particles. Since β depends upon the temperature it is clear that the degree of ionization is negligible at room temperature. Also, if we substitute the values of p, W_i, K and T, it can be shown that thermal ionization of gas becomes significant only if temperature exceeds 1000° K.

1.2 TOWNSEND'S FIRST IONIZATION COEFFICIENT

Consider a parallel plate capacitor having gas as an insulating medium and separated by a distance d as shown in Fig. 1.1. When no electric field is set up between the plates, a state of equilibrium exists between the state of electron and positive ion generation due to the decay processes. This state of equilibrium will be disturbed moment a high electric field is applied. The variation of current as a function of voltage

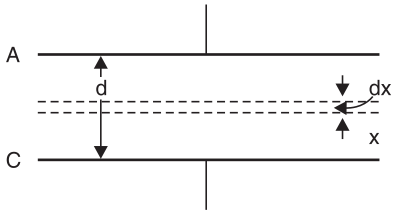


Fig. 1.1 Parallel plate capacitor

was studied by Townsend. He found that the current at first increased proportionally as the voltage is increased and then remains constant, at I_0 which corresponds to the saturation current. At still higher voltages, the current increases exponentially. The variation of current as a function of voltage is shown in Fig. 1.2. The exponential increase in current is due to ionization of gas by electron collision. As the voltage increases *V/d* increases and hence the electrons are accelerated more and more and between collisions these acquire higher kinetic energy and, therefore, knock out more and more electrons.

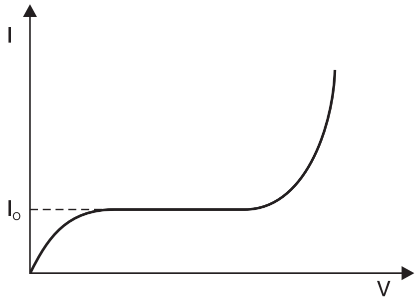


Fig. 1.2 Variation of current as a function of voltage

To explain the exponential rise in current, Townsend introduced a coefficient α known as *Townsend's first ionization coefficient* and is defined as the number of electrons produced by an electron per unit length of path in the direction of field. Let n_0 be the number of electons leaving the cathode and when these have moved through a distance x from the cathode, these become n. Now when these n electrons move through a distance dx produce additional dn electrons due to collision. Therefore,

$$dn = \alpha\, n\, dx$$

or
$$\frac{dn}{n} = \alpha\, dx$$

or
$$\ln n = \alpha x + A$$

Now at $x = 0$, $n = n_0$. Therefore,

$$\ln n_0 = A$$

or
$$\ln n = \alpha x + \ln n_0$$

or
$$\ln \frac{n}{n_0} = \alpha x$$

At $x = d$, $n = n_0\, e^{\alpha d}$. Therefore, in terms of current

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

The term $e^{\alpha d}$ is called the *electron avalanche* and it represents the number of electrons produced by one electron in travelling from cathode to anode.

1.3 CATHODE PROCESSES—SECONDARY EFFECTS

Cathode plays an important role in gas discharges by supplying electrons for the initiation, sustainance and completion of a discharge. In a metal, under normal condition, electrons are not allowed to leave the surface as they are tied together due to the electrostatic force between the electrons and the ions in the lattice. The energy required to knock out an electron from a Fermi level is konwn as the *work function* and is a characteristic of a given material. There are various ways in which this energy can be supplied to release the electron.

Thermionic Emission: At room temperature, the conduction electrons of the metal do not have sufficient thermal energy to leave the surface. However, if the metals are heated to temperature 1500°K and above, the electrons will receive energy from the violent thermal lattice in vibration sufficient to cross the surface barrier and leave the metal. After extensive investigation of electron emission from metals at high temperature, Richardson developed an expression for the saturation current density J_s as

$$J_s = \frac{4\pi m_e\, K^2}{h^3}\, T^2 e^{-W\alpha/KT} \;\; A/m^2$$

where the various terms have their usual significance.

Let $$A = \frac{4\pi m_e\, K^2}{h^3}$$

the above expression becomes

$$J_s = AT^2 e^{-W/KT}$$

which shows that the saturation current density increases with decrease in work function and increase in temperature. Substituting the values of m_e, K and h, A is found to be $120 \times 10^4\ A/m^2\, K^2$. However, the experimentally obtained value of A is lower than what is predicted by the equation above. The discrepancy is due to the surface imperfections and surface impurities of the metal. The gas present between the electrode affects the thermionic emission as the gas may be absorbed by the metal and can also damage the electrode surface due to continuous impinging of ions. Also, the work function is observed to be lowered due to thermal expansion of crystal structure. Normally metals with low work function are used as cathode for thermionic emission.

Field Emission: If a strong electric field is applied between the electrodes, the effective work function of the cathode decreases and is given by

$$W' = W - \varepsilon^{3/2}\, E^{1/2}$$

and the saturation current density is then given by

$$J_s = AT^2\, e^{-W'/KT}$$

This is known as *Schottky effect* and holds good over a wide range of temperature and electric fields. Calculations have shown that at room temperature the total emission is still low even when fields of the order of 10^5 V/cm are applied. However, if the field is of the order of 10^7 V/cm, the emission current has been observed to be much larger than the calculated thermionic value. This can be explained only through quantum mechanics at these high surface gradients, the cathode surface barrier becomes very thin and quantum tunnelling of electrons occurs which leads to field emission even at room temperature.

Electron Emission by Positive Ion and Excited Atom Bombardment

Electrons may be emitted by the bombardment of positive ion on the cathode surface. This is known as *secondary emission*. In order to effect secondary emission, the positive ion must have energy more than twice the work function of the metal since one electron will neutralize the bombarding positive ion and the other electron will be released. If W_k and W_p are the kinetic and potential energies, respectively of the positive ion then for secondary emission to take place $W_k + W_p \geq 2W$. The electron emission by positive ion is the principal secondary process in the Townsend spark discharge mechanism. Neutral excited atoms or molecules (metastables) incident upon the cathode surface are also capable of releasing electron from the surface.

1.4 TOWNSEND SECOND IONISATION COEFFICIENT

From the equation

$$I = I_0\, e^{\alpha x}$$

We have, taking log on both the sides.

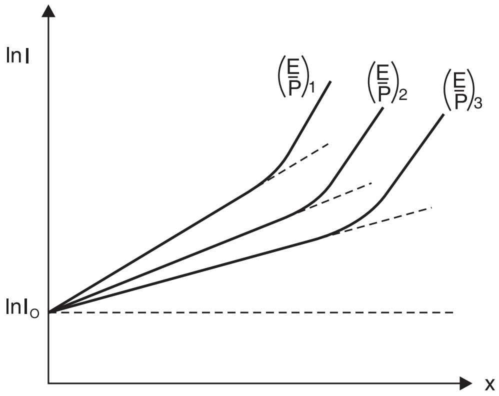


Fig. 1.3 Variation of gap current with electrode spacing in uniform E

$$\ln I = \ln I_0 + \alpha x$$

This is a straight line equation with slope α and intercept $\ln I_0$ as shown in Fig. 1.3 if for a given pressure p, E is kept constant.

Townsend in his earlier investigations had observed that the current in parallel plate gap increased more rapidly with increase in voltage as compared to the one given by the above equation. To explain this departure from linearity, Townsend suggested that a second mechanism must be affecting the current. He postulated that the additional current must be due to the presence of positive ions and the photons. The positive ions will liberate electrons by collision with gas molecules and by bombardment against the cathode. Similarly, the photons will also release electrons after collision with gas molecules and from the cathode after photon impact.

Let us consider the phenomenon of self-sustained discharge where the electrons are released from the cathode by positive ion bombardment.

Let n_0 be the number of electrons released from the cathode by ultraviolet radiation, n_+ the number of electrons released from the cathode due to positive ion bombardment and n the number of electrons reaching the anode. Let ν, known as *Townsend second ionization co-efficient* be defined as the number of electrons released from cathode per incident positive ion, Then

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

Now total number of electrons released from the cathode is $(n_0 + n_+)$ and those reaching the anode are n, therefore, the number of electrons released from the gas $= n - (n_0 + n_+)$, and corresponding to each electron released from the gas there will be one positive ion and assuming each positive ion releases ν effective electrons from the cathode then

$$n_+ = \nu\,[n - (n_0 + n_+)]$$

or $$n_+ = \nu n - \nu n_0 - \nu n_+$$

or $$(1 + \nu)\, n_+ = \nu(n - n_0)$$

or $$n_+ = \frac{\nu(n - n_0)}{1 + \nu}$$

Substituting n_+ in the previous expression for n, we have

$$n = \left[n_0 + \frac{\nu(n - n_0)}{1 + \nu}\right] e^{\alpha d} = \frac{(1 + \nu)\, n_0 + \nu n - \nu n_0}{1 + \nu}\, e^{\alpha d}$$

$$= \frac{n_0 + \nu n}{1 + \nu}\, e^{\alpha d}$$

or $$(n + \nu n) = n_0\, e^{\alpha d} + \nu n e^{\alpha d}$$

or $$n + \nu n - \nu n e^{\alpha d} = n_0 e^{\alpha d}$$

or $$n[1 + \nu - \nu e^{\alpha d}] = n_0 e^{\alpha d}$$

or $$n = \frac{n_0 e^{\alpha d}}{1 + \nu n(1 - e^{\alpha d})} = \frac{n_0 e^{\alpha d}}{1 - \nu\,(e^{\alpha d} - 1)}$$

In terms of current

$$I = \frac{I_0\, e^{\alpha d}}{1 - \nu(e^{\alpha d} - 1)}$$

Earlier Townsend derived an expression for current as

$$I = I_0\, \frac{(\alpha - \beta)\, e^{(\alpha - \beta)d}}{\alpha - \beta\, e^{(\alpha - \beta)d}}$$

where β represents the number of ion pairs produced by positive ion travelling 1 cm path in the direction of field. Townsend's original suggestion that the positive ion after collision with gas molecule releases electron does not hold good as ions rapidly lose energy in elastic collision and ordinarily are unable to gain sufficient energy from the electric field to cause ionization on collision with gas molecules or atoms.

In practice positive ions, photons and metastable, all the three may participate in the process of ionization. It depends upon the experimental conditions. There may be more than one mechanism producing secondary ionization in the discharge gap and, therefore, it is customary to express the net secondary ionization effect by a single coefficient ν and represent the current by the above equation keeping in mind that ν may represent one or more of the several possible mechanism.

$$\nu = \nu_1 + \nu_2 + \nu_3 + \ldots\ldots$$

It is to be noted that the value of ν depends upon the work function of the material. If the work function of the cathode surface is low, under the same experimental conditions will produce more emission. Also, the value of ν is relatively small at low value of E/p and will increase with increase in E/p. This is because at higher values of E/p, there will be more number of positive ions and photons of sufficiently large energy to cause ionization upon impact on the cathode surface. It is to be noted that the influence of ν on breakdown mechanism is restricted to Townsend breakdown mechanism *i.e.*, to low-pressure breakdown only.

1.5 TOWNSEND BREAKDOWN MECHANISM

When voltage between the anode and cathode is increased, the current at the anode is given by

$$I = \frac{I_0 e^{\alpha d}}{1 - \nu\,(e^{\alpha d} - 1)}$$

The current becomes infinite if

$$1 - \nu(e^{\alpha d} - 1) = 0$$

or $$\nu(e^{\alpha d} - 1) = 1$$

or $$\nu e^{\alpha d} \approx 1$$

Since normally $$e^{\alpha d} >> 1$$

the current in the anode equals the current in the external cirrcuit. Theoretically the current becomes infinitely large under the above mentioned condition but practically it is limited by the resistance of the external circuit and partially by the voltage drop in the arc. The condition $\nu e^{\alpha d} = 1$ defines the condition for beginning of spark and is known as the *Townsend criterion* for spark formation or Townsend breakdown criterion. Using the above equations, the following three conditions are possible.

(1) $\nu e^{\alpha d} = 1$

The number of ion pairs produced in the gap by the passage of arc electron avalanche is sufficiently large and the resulting positive ions on bombarding the cathode are able to relase one secondary electron and so cause a repetition of the avalanche process. The discharge is then said to be self-sustained as the discharge will sustain itself even if the source producing I_0 is removed. Therefore, the condition $\nu e^{\alpha d} = 1$ defines the threshold sparking condition.

(2) $\nu e^{\alpha d} > 1$

Here ionization produced by successive avalanche is cumulative. The spark discharge grows more rapidly the more $\nu e^{\alpha d}$ exceeds unity.

(3) $\nu e^{\alpha d} < 1$

Here the current I is not self-sustained *i.e.,* on removal of the source the current I_0 ceases to flow.

1.6 STREAMER OR KANAL MECHANISM OF SPARK

We know that the charges in between the electrodes separated by a distance d increase by a factor $e^{\alpha d}$ when field between electrodes is uniform. This is valid only if we assume that the field $E_0 = V/d$ is not affected by the space charges of electrons and positive ions. Raether has observed that if the charge concentration is higher than 10^6 but lower than 10^8 the growth of an avalanche is weakened *i.e., dn/dx* $< e^{\alpha d}$. Whenever the concentration exceeds 10^8, the avalanche current is followed by steep rise in current and breakdown of the gap takes place. The weakening of the avalanche at lower concentration and rapid growth of avalanche at higher concentration have been attributed to the modification of the

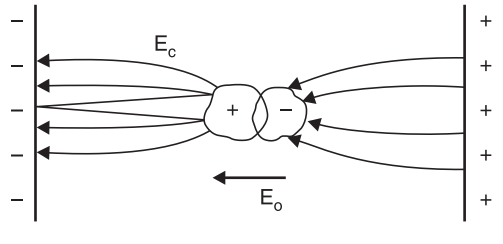


Fig. 1.4 Field redistribution due to space charge

electric field E_0 due to the space charge field. Fig. 1.4 shows the electric field around an avalanche as it progresses along the gap and the resultant field *i.e.*, the superposition of the space charge field and the original field E_0. Since the electrons have higher mobility, the space charge at the head of the avalanche is considered to be negative and is assumed to be concentrated within a spherical volume. It can be seen from Fig. 1.4 that the filed at the head of the avalanche is strengthened. The field between the two assumed charge centres *i.e.*, the electrons and positive ions is decreased as the field due to the charge centres opposes the main field E_0 and again the field between the positive space charge centre and the cathode is strengthened as the space charge field aids the main field E_0 in this region. It has been observed that if the charge carrier number exceeds 10^6, the field distortion becomes noticeable. If the distortion of field is of 1%, it would lead to a doubling of the avalanche but as the field distortion is only near the head of the avalanche, it does not have a significance on the discharge phenomenon. However, if the charge carrier exceeds 10^8, the space charge field becomes almost of the same magnitude as the main field E_0 and hence it may lead to initiation of a streamer. The space charge field, therefore, plays a very important role in the mechanism of electric discharge in a non-uniform gap.

Townsend suggested that the electric spark discharge is due to the ionization of gas molecule by the electron impact and release of electrons from cathode due to positive ion bombardment at the cathode. According to this theory, the formative time lag of the spark should be at best equal to the electron transit time t_r. At pressures around atmospheric and above $p.d. > 10^3$ Torr-cm, the experimentally determined time lags have been found to be much shorter than t_r. Study of the photographs of the avalanche development has also shown that under certain conditions, the space charge developed in an avalanche is capable of transforming the avalanche into channels of ionization known as *streamers* that lead to rapid development of breakdown. It has also been observed through measurement that the transformation from avalanche to streamer generally takes place when the charge within the avalanche head reaches a critical value of

$$n_0 e^{\alpha x} \approx 10^8 \quad \text{or} \quad \alpha x_c \approx 18 \text{ to } 20$$

where X_c is the length of the avalanche parth in field direction when it reaches the critical size. If the gap length $d < X_c$, the initiation of streamer is unlikely.

The short-time lags associated with the discharge development led Raether and independently Meek and Meek and Loeb to the advancement of the theory of streamer of Kanal mechanism for spark formation, in which the secondary mechanism results from photoionization of gas molecules and is independent of the electrodes.

Raether and Meek have proposed that when the avalanche in the gap reaches a certain critical size the combined space charge field and externally applied field E_0 lead to intense ionization and excitation of the gas particles in front of the avalanche head. There is recombination of electrons and positive ion resulting in generation of photons and these photons in turn generate secondary electrons by the photoionization process. These electrons under the influence of the electric field develop into secondary avalanches as shown in Fig. 1.5. Since photons travel with velocity of light, the process leads to a rapid development of conduction channel across the gap.

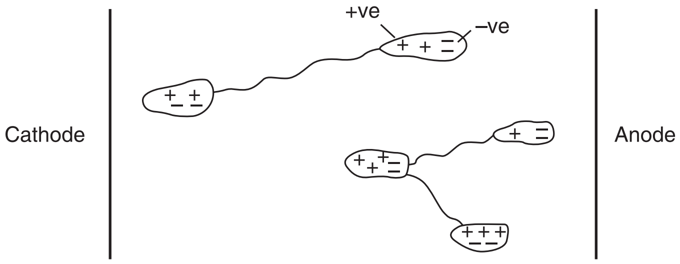


Fig. 1.5 Secondary avalanche formation by photoelectrons

Raether after thorough experimental investigation developed an empirical relation for the streamer spark criterion of the form

$$\alpha x_c = 17.7 + \ln x_c + \ln \frac{E_r}{E_0}$$

where E_r is the radial field due to space charge and E_0 is the externally applied field.

Now for transformation of avalanche into a streamer $E_r \approx E$

Therefore, $\alpha x_c = 17.7 + \ln x_c$

For a uniform field gap, breakdown voltage through streamer mechanism is obtained on the assumption that the transition from avalanche to streamer occurs when the avalanche has just crossed the gap. The equation above, therefore, becomes

$$\alpha d = 17.7 + \ln d$$

When the critical length $x_c \geq d$ minimum breakdown by streamer mechanism is brought about. The condition $X_c = d$ gives the smallest value of α to produce streamer breakdown.

Meek suggested that the transition from avalanche to streamer takes place when the radial field about the positive space charge in an electron avalanche attains a value of the order of the externally applied field. He showed that the value of the radial field can be otained by using the expression.

$$E_r = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha x}}{(x/P)^{1/2}} \text{ volts/cm.}$$

where x is the distance in cm which the avalanche has progressed, p the gas pressure in Torr and α the Townsend coefficient of ionization by electrons corresponding to the applied field E. The minimum breakdown voltage is assumed to correspond to the condition when the avalanche has crossed the gap of length d and the space charge field E_r approaches the externally applied field *i.e.*, at $x = d$, $E_r = E$. Substituting these values in the above equation, we have

$$E = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha d}}{(d/p)^{1/2}}$$

Taking ln on both the sides, we have

$$\ln E = -14.5 + \ln \alpha - \frac{1}{2} \ln \frac{d}{p} + \alpha d$$

$$\ln E - \ln p = -14.5 + \ln \alpha - \ln p - \frac{1}{2} \text{1n} \frac{d}{p} + \alpha d$$

$$1\text{n}\,\frac{E}{p} = -14.5 + \ln\frac{\alpha}{p} - \frac{1}{2}\ln\frac{d}{p} + \alpha d$$

The experimentally determined values of α/p and the corresponding E/p are used to solve the above equation using trial and error method. Values of α/p corresponding to E/p at a given pressure are chosen until the equation is satisfied.

1.7. THE SPARKING POTENTIAL—PASCHEN'S LAW

The Townsend's Criterion

$$\nu(e^{\alpha d} - 1) = 1$$

enables the evaluation of breakdown voltage of the gap by the use of appropriate values of α/p and ν corresponding to the values E/p when the current is too low to damage the cathode and also the space charge distortions are minimum. A close agreement between the calculated and experimentally determined values is obtained when the gaps are short or long and the pressure is relatively low.

An expression for the breakdown voltage for uniform field gaps as a function of gap length and gas pressure can be derived from the threshold equation by expressing the ionization coefficient α/p as a function of field strength E and gas pressure p *i.e.*,

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

Substituting this, we have

$$e^{f(E/p)\,pd} = \frac{1}{\nu} + 1$$

Taking ln both the sides, we have

$$f\left(\frac{E}{p}\right)pd = \ln\left[\frac{1}{\nu} + 1\right] = K \text{ say}$$

For uniform field $E = \dfrac{V_b}{d}$.

Therefore, $$f\left(\frac{V_b}{pd}\right).\,pd = K$$

or $$f\left(\frac{V_b}{pd}\right) = \frac{K}{pd}$$

or $$V_b = F\,(p.d)$$

This shows that the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and the gap length for a particular gas and electrode material. This relation is known as *Paschen's law*. This relation does not mean that the breakdown voltage is directly proportional to product *pd* even though it is found that for some region of the product *pd* the relation is linear *i.e.*, the breakdown voltage varies linearly with the product *pd*. The variation over a large range is shown in Fig. 1.6.

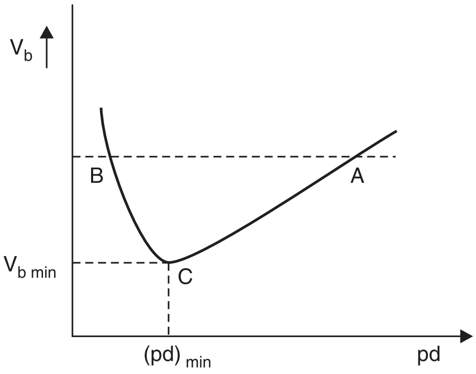


Fig. 1.6 Paschen's law curve

Let us now compare Paschen's law and the Townsend's criterion for spark potential. We draw the experimentally obtained relation between the ionization coefficient α/p and the field strength $f(E/p)$ for a given gas. Fig. 1.7. Here point $\left(\frac{E_b}{p}\right)_c$ represents the onset of ionization.

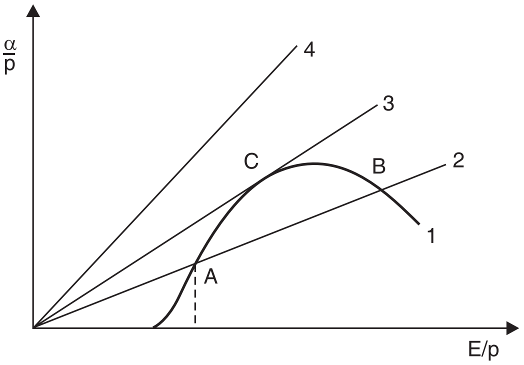


Fig. 1.7 The relation between Townsend's criterion for spark = *k* and Paschen's criterion

Now the Townsend's criterion $\alpha d = K$ can be re-written as

$$\frac{\alpha}{p} \cdot \frac{V}{E} = \frac{K}{p} \quad \text{or} \quad \frac{\alpha}{p} = \frac{K}{V} \cdot \frac{E}{P}$$

This is equation to a straight line with slope equal to K/V depending upon the value of K. The higher the voltage the smaller the slope and therefore, this line will intersect the ionization curve at two points *e.g.*, A and B in Fig. 1.7. Therefore, there must exist two breakdown voltages at a constant pressure (p = constant), one corresponding to the small value of gap length *i.e.*, higher E ($E = V/d$) *i.e.*, point B and the other to the longer gap length *i.e.*, smaller E or smaller E/p *i.e.*, the point A. At low values of voltage V the slope of the straight line is large and, therefore, there is no intersection between the line and the curve 1. This means no breakdown occurs with small voltages below Paschen's minimum irrespective of the value of *pd*. The point C on the curve indicates the lowest breakdown voltage or the minimum sparking potential. The spark over voltages corresponding to points A, B, C are shown in the Paschen's curve in Fig. 1.6.

The fact that there exists a minimum sparking potential in the relation between the sparking potential and the gap length assuming p to be constant can be explained quantitatively by considering the efficiency of ionization of electrons traversing the gap with different electron energies. Assuming that the Townsend's second ionization coefficient ν is small for values $pd > (pd)$min., electrons crossing the gap make more frequent collision with the gas molecules than at (pd)min. but the energy gained between the successive collision is smaller than at (pd). Hence, the probability of ionization is lower unless the voltage is increased. In case of $(pd) < (pd)$ min., the electrons cross the gap without making any collision and thus the sparking potential is higher. The point (pd)min., therefore, corresponds to the highest ionization efficiency and hence minimum sparking potential.

An analytical expression for the minimum sparking potential can be obtained using the general expression for α/p.

$$\frac{\alpha}{p} = Ae^{Bp/E} \qquad \text{or} \qquad \alpha = pAe^{-Bpd/V_b}$$

or

$$e^{-Bpd/V_b} = \frac{pA}{\alpha} \qquad \text{or} \qquad \frac{1}{\alpha} = \frac{e^{Bpd/V_b}}{pA}$$

or

$$d \cdot \frac{1}{\alpha d} = \frac{e^{B^{pd}/V_b}}{pA}$$

We know that

$$\alpha d = 1\text{n}\left(1 + \frac{1}{\nu}\right)$$

Therefore,

$$d = \frac{e^{Bpd/V_b}}{pA} 1\text{n}\left(1 + \frac{1}{\nu}\right)$$

Assuming ν to be constant, let $1\text{n}\left(1 + \frac{1}{\nu}\right) = k$

Then

$$d = \frac{e^{Bpd/V_b}}{pA} K$$

In order to obtain minimum sparking potential, we rearrange the above expression as

$$V_b = f(pd)$$

Taking 1n on both sides, we have

$$\frac{Bpd}{V_b} = \ln \frac{Apd}{K}$$

or

$$V_b = \frac{Bpd}{\ln Apd/k}$$

Differentiating V_b w.r.t. to pd and equating the derivative to zero

$$\frac{dV_b}{d\,(pd)} = \frac{\ln \frac{Apd}{K} \cdot B - Bpd \cdot \frac{K}{Apd} \cdot \frac{A}{K}}{\left(1\text{n}\,\frac{Apd}{K}\right)^2} = \frac{B \ln \frac{Apd}{K}}{\left(1\text{n}\,\frac{Apd}{K}\right)^2} - \frac{B}{\left(1\text{n}\,\frac{Apd}{K}\right)^2} = 0$$

or

$$\frac{1}{\ln \frac{Apd}{K}} = \frac{1}{\left(\ln \frac{Apd}{K}\right)^2}$$

or $$1\text{n}\,\frac{Apd}{K} = 1$$

or $$1\text{n}\,\frac{Apd}{K} = e$$

or $$(pd)_{\text{min}} = \frac{e}{A}K$$

or $$V_{b\,\text{min}} = \frac{B\,e^{K/A}}{1} = \frac{B}{A}\,.\,eK$$

$$V_{b\text{min}} = 2.718\ \frac{B}{A}1\text{n}\left(1+\frac{1}{\nu}\right)$$

If values of A, B and ν are known both the (pd) min and $V_{b\text{min}}$ can be obtained. However, in practice these values are obtained through measurements and values of some of the gases are given in the following Table 1.1.

Table 1.1. Minimum Sparking Constant for various gases

Gas	*(pd)min*	V_b *min volts*
Air	0.55	352
Nitrogen	0.65	240
Hydrogen	1.05	230
SF_6	0.26	507
CO_2	0.57	420
O_2	0.70	450
Neon	4.0	245
Helium	4.0	155

Typical values for A, B and ν for air are $A = 12$, $B = 365$ and $\nu = 0.02$.

Schuman has suggested a quadratic formulation between α/p and E/p under uniform field over a wide but restricted range as

$$\text{s}\frac{\alpha}{p} = C\left[\frac{E}{p} - \left(\frac{E}{p}\right)\right]^2$$

where $(E/p)_c$ is the minimum value of E at which the effective ionization begins and p is the pressure, C a constant.

We know that Townsend's spark criterion for uniform fields is $\alpha d = k$ where $k = (1 + 1/\nu)$.

Therefore, the equation above can be re-written as

$$\frac{K}{dp} = C\left[\frac{E}{p} - \left(\frac{E}{p}\right)_c\right]^2$$

or $$\left(\frac{K}{C}\cdot\frac{1}{pd}\right)^{1/2} = \frac{E}{p} - \left(\frac{E}{p}\right)_c$$

or $$\frac{E}{p} = \left(\frac{E}{p}\right)_c + \left(\frac{K/C}{pd}\right)^{1/2}$$

$$\frac{V}{dp} = \left(\frac{E}{p}\right)_c + \left(\frac{K/C}{pd}\right)^{1/2}$$

or
$$V_b = \left(\frac{E}{p}\right)_c pd + \left(\frac{K}{c}\right)^{1/2} . \sqrt{pd}$$

Sohst and Schröder have suggested values for E_c = 24.36 kV/cm K/C = 45.16 (kV)^2 /cm for air at p = 1 bar and temperature 20°C.

Substituting these values in the above equation, we have

$$V_b = 6.72\sqrt{pd} + 24.36\ (pd)\ kV$$

The breakdown voltages suggested in tables or obtained through the use of empirical relation normally correspond to ambient temperature and pressure conditions, whereas the atmospheric air provides basic insulation between various electrical equipments. Since the atmospheric conditions (Temperature, pressure) vary widely from time to time and from location to location, to obtain the actual breakdown voltage, the voltage obtained from the STP condition should be multiplied by the air density correction factor. The air density correction factor is given as

$$\delta = \frac{3.92\, b}{273 + t}$$

where b is the atmospheric pressure in cm of Hg and t the temperature in °C.

1.8 PENNING EFFECT

Paschen’s law does not hold good for many gaseous mixtures. A typical example is that of mixture of Argon in Neon. A small percentage of Argon in Neon reduces substantially the dielectric strength of pure Neon. In fact, the dielectric strength is smaller than the dielectric strengths of either pure Neon or Argon. The lowering of dielectric strength is due to the fact that the lowest excited stage of neon is metastable and its excitation potential (16 ev) is about 0.9 ev greater than the ionization potential of Argon. The metastable atoms have a long life in neon gas, and on hitting Argon atoms there is a very high probability of ionizing them. This phenomenon is known as Penning Effect.

1.9 CORONA DISCHARGES

If the electric field is uniform and if the field is increased gradually, just when measurable ionization begins, the ionization leads to complete breakdown of the gap. However, in non-uniform fields, before the spark or breakdown of the medium takes place, there are many manifestations in the form of visual and audible discharges. These discharges are known as *Corona discharges*. In fact Corona is defined as a self-sustained electric discharge in which the field intensified ionization is localised only over a portion of the distance (non-uniform fields) between the electrodes. The phenomenon is of particular importance in high voltage engineering where most of the fields encountered are non-uniform fields unless of course some design features are involved to make the filed almost uniform. Corona is responsible for power loss and interference of power lines with the communication lines as corona frequency lies between 20 Hz and 20 kHz. This also leads to deterioration of insulation by the combined action of the discharge ion bombarding the surface and the action of chemical compounds that are formed by the corona discharge.

When a voltage higher than the critical voltage is applied between two parallel polished wires, the glow is quite even. After operation for a short time, reddish beads or tufts form along the wire, while around the surface of the wire there is a bluish white glow. If the conductors are examined through a stroboscope, so that one wire is always seen when at a given half of the wave, it is noticed that the reddish tufts or beads are formed when the conductor is negative and a smoother bluish white glow when the conductor is positive. The a.c. corona viewed through a stroboscope has the same apperance as direct current corona. As corona phenomenon is initiated a hissing noise is heard and ozone gas is formed which can be detected by its chracteristic colour.

When the voltage applied corresponds to the critical disruptive voltage, corona phenomenon starts but it is not visible because the charged ions in the air must receive some finite energy to cause further ionization by collisions. For a radial field, it must reach a gradient (visual corona gradient) g_u at the surface of the conductor to cause a gradient g_0, finite distance away from the surface of the conductor. The distance between g_0 and g_v is called the energy distance. According to Peek, this distance is equal to ($r + 0.301 \sqrt{r}$) for two parallel conductors and ($r + 0.308 \sqrt{r}$) for coaxial conductors. From this it is clear that g_v is not constant as g_0 is, and is a function of the size of the conductor. The electric field intensity for two parallel wires is given as

$$E = 30 \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right) \delta \text{ kV/cm}$$

and for a coaxial wire

$$E = 30 \left(1 + \frac{0.308}{\sqrt{r\delta}}\right) \delta$$

Investigation with point-plane gaps in air have shown that when point is positive, the corona current increases steadily with voltage. At sufficiently high voltage, current amplification increases rapidly with voltage upto 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 known as *burst corona*. The average current then increases steadily with applied voltage, leading to breakdown.

With point-plane gap in air when negative polarity voltage is applied to the point and the voltage exceeds the onset value, the current flows in vary regular pulses known as *Trichel pulses*. The onset voltage is independent of the gap length and is numerically equal to the onset of streamers under positive voltage for the same arrangement. The pulse frequency increases with voltage and is a function of the radius of the cathode, the gap length and the pressure. A decrease in pressure decreases the frequency of the pulses. It should be noted that the breakdown voltage with negative polarity is higher than with positive polarity except at low pressure. Therefore, under alternating power frequency voltage the breakdown of non-uniform field gap invariably takes place during the positive half cycle of the voltage wave.

Fig. 1.8 gives comparision between the positive and negative point-plane gap breakdown characteristics measured in air as a function of gas pressure.

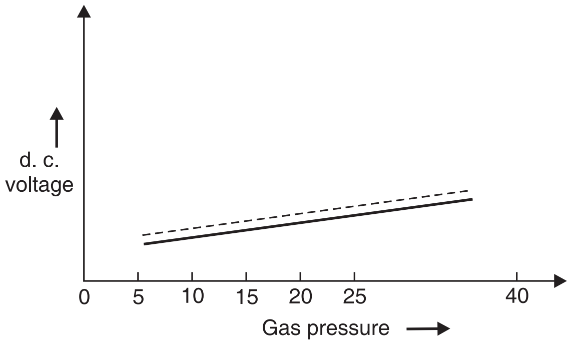


Fig. 1.8. Point-plane breakdown for +ve and –ve polarities

When the spacing is small the breakdown characteristics for the two polarities nearly coincide and no corona stabilised region is observed. As the spacing is increased, the positive characteristics display the distinct high corona beakdown upto a pressure of about 7 bars, followed by a sudden drop in breakdown strengths. Under the negative polarity, the corona stabilised region extends to much higher pressures.

Fig. 1.9 shows the corona inception and breakdown voltages of the sphere-plane arrangement. From the figure, it is clear that—

(*i*) For small spacings (Zone–I), the field is uniform and the breakdown voltage depends mainly on the gap spacing.

(*ii*) In zone–II, where the spacing is relatively larger, the electric field is non-uniform and the breakdown voltage depends on both the sphere diameter and the spacing.

(*iii*) For still larger spacings (Zone-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.

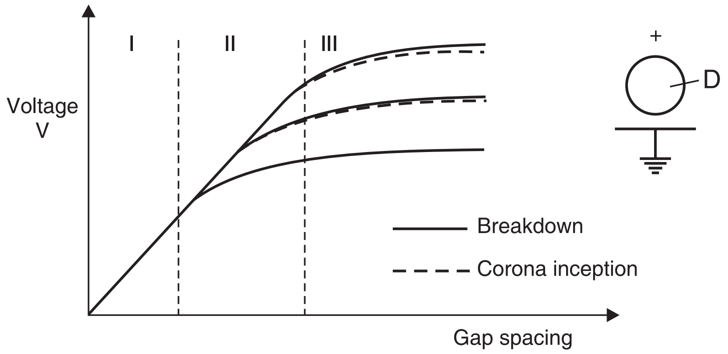


Fig. 1.9 Breakdown and corona inception characteristics for spheres of different diameters in sphere-plane gap geometry

1.10 TIME-LAG

In order to breakdown a gap, certain amount of energy is required. Also it depends upon the availability of an electron between the gap for initiation of the avalanche. Normally the peak value of a.c. and d.c. are smaller as compared to impulse wave as the duration of the former are pretty large as compared to the letter and the energy content is large. Also with d.c. and a.c. as the duration is large there are usually sufficient initiatory electrons created by cosmic ray and naturally occuring radioactive sources.

Suppose V_d is the maximum value of d.c. voltage applied for a long time to cause breakdown of a given gap. Fig. 1.10.

Let the same gap be subjected to a step voltage of peak value $V_{d1} > V_d$ and of a duration such that the gap breaks down in time t. If the breakdown

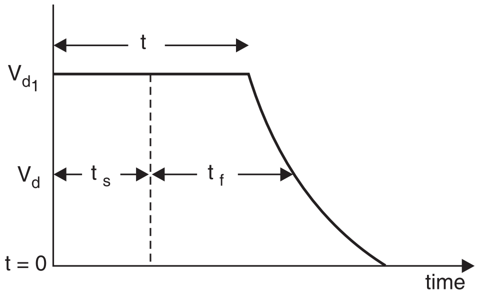


Fig. 1.10 Time lag components under a step voltage

were purely a function of voltage magnitude, the breakdown should have taken place the moment the step voltage had just crossed the voltage V_d.

The time that elapses between the application of the voltage to a gap sufficient to cause breakdown, and the breakdown, is called the *time lag*. In the given case shown in Fig. 1.10, t is the time lag. It consists of two components. One is the that elapses during the voltage applications until a primary electron appears to initiate the discharge and is known as the *statistical time lag* t_s and the other is the time required for the breakdown to develop once initiated and is known as the *formative time lag* t_f.

The statistical time lag depends upon (*i*) The amount of pre-ionization present in between the gap (*ii*) Size of the gap (*iii*) The amount of over voltage ($V_{d1} - V_d$) applied to the gap. The larger the gap the higher is going to be the statistical time lag. Similarly, a smaller over voltage results in higher statistical time lag. However, the formative time lag depends mainly on the mechanism of breakdown. In cases when the secondary electrons arise entirely from electron emission at the cathode by positive ions, the transit time from anode to cathode will be the dominant factor determining the formative time. The formative time lag increases with increase in gap length and field non-uniformity, decreases with increase in over voltage applied.

1.10.1 Breakdown in Electronegative Gases

SF_6, has excellent insulating strength because of its affinity for electrons (electronegativity) *i.e.*, whenever a free electron collides with the neutral gas molecule to form negative ion, the electron is absorbed by the neutral gas molecule. The attachment of the electron with the neutral gas molecule may occur in two ways:

$$SF_6 + e \longrightarrow SF_6^-$$

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

The negative ions formed are relatively heavier as compared to free electrons and, therefore, under a given electric field the ions do not attain sufficient energy to lead cumulative ionization in the gas. Thus, these processes represent an effective way of removing electrons from the space which otherwise would have contributed to form electron avalanche. This property, therefore, gives rise to very high dielectric strength for SF_6. The gas not only possesses a good dielectric strength but it has the unique property of fast recombination after the source energizing the spark is removed.

The dielectric strength of SF_6 at normal pressure and temperature is 2–3 times that of air and at 2 atm its strength is comparable with the transformer oil. Although SF_6 is a vapour, it can be liquified at moderate pressure and stored in steel cylinders. Even though SF_6 has better insulating and arc-quencling properties than air at an equal pressure, it has the important disadvantage that it can not be used much above 14 kg/cm^2 unless the gas is heated to avoid liquifaction.

1.10.2 Application of Gases in Power System

The gases find wide application in power system to provide insulation to various equipments and substations. The gases are also used in circuit breakers for arc interruption besides providing insulation between breaker contacts and from contact to the enclosure used for contacts. The various gases used are (*i*) air (*ii*) oxygen (*iii*) hydrogen (*iv*) nitrogen (*v*) CO_2 and (*vi*) electronegative gases like sulphur hexafluoride, arcton etc.

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

(*i*) High dielectric strength.

(*ii*) Thermal and chemical stability.

(*iii*) Non-inflammability.

(*iv*) High thermal conductivity. This assists cooling of current carrying conductors immersed in the gas and also assists the arc-extinction process.

(*v*) Arc extinguishing ability. It should have a low dissociation temperature, a short thermal time constant (ratio of energy contained in an arc column at any instant to the rate of energy dissipation at the same instant) and should not produce conducting products such as carbon during arcing.

(*vi*) Commercial availability at moderate cost. Of the simple gases air is the cheapest and most widely used for circuit breaking. Hydrogen has better arc extinguishing property but it has lower dielectric strength as compared with air. Also if hydrogen is contaminated with air, it forms an explosive mixture. Nitrogen has similar properties as air, CO_2 has almost the same dielectric strength as air but is a better arc extinguishing medium at moderate currents. Oxygen is a good extinguishing medium but is chemically active. SF_6 has outstanding arc-quenching properties and good dielectric strength. Of all these gases, SF_6 and air are used in commercial gas blast circuit breakers.

Air at atmospheric pressure is ‘free’ but dry air costs a lot when stored at say 75 atmosphere. The compressed air supply system is a vital part of an air blast C.B. Moisture from the air is removed by refrigeration, by drying agents or by storing at several times the working pressure and then expanding it to the working pressure for use in the C.B. The relative cost of storing the air reduces with increase in pressure. If the air to be used by the breaker is at 35 kg/cm^2 it is common to store it at 210 kg/cm^2.

Air has an advantage over the electronegative gases in that air can be compressed to extremely high pressures at room temperature and then its dielectric strength even exceeds that of these gases.

The SF_6 gas is toxic and its release in the form of leakage causes environmental problems. Therefore, the electrical industry has been looking for an alternative gas or a mixture of SF_6 with some other gas as an insulating and arc interrupting medium. It has been observed that a suitable mixture of SF_6 with N_2 is a good replacement for SF_6. This mixture is not only finding acceptability for providing insulation *e.g.*, gas insulated substation and other equipments, it is able to quench high current magnitude arcs. The mixture is not only cost effective, it is less sensitive to find non-uniformities present within the equipment. Electric power industry is trying to find optimum SF_6 to N_2 mixture ratio for various components of the system *viz.*, GIS, C.B., capacitors, CT, PT and cables. A ratio 70% of SF_6 and 30% of N_2 is found to be optimum for circuit breaking. With this ratio, the C.B. has higher recovery rate than pure SF_6 at the same partial pressure. The future of using SF_6 with N_2 or He for providing insulation and arc interruption is quite bright.

1.11 BREAKDOWN IN LIQUID DIELECTRICS

Liquid dielectrics are used for filling transformers, circuit breakers and as impregnants in high voltage cables and capacitors. For transformer, the liquid dielectric is used both for providing insulation between the live parts of the transformer and the grounded parts besides carrying out the heat from the transformer to the atmosphere thus providing cooling effect. For circuit breaker, again besides providing insulation between the live parts and the grounded parts, the liquid dielectric is used to quench the arc developed between the breaker contacts. The liquid dielectrics mostly used are petroleum oils. Other oils used are synthetic hydrocarbons and halogenated hydrocarbons and for very high temperature applications sillicone oils and fluorinated hyrocarbons are also used.

The three most important properties of liquid dielectric are (*i*) The dielectric strength (*ii*) The dielectric constant and (*iii*) The electrical conductivity. Other important properties are viscosity, thermal stability, specific gravity, flash point etc. The most important factors which affect the dielectric strength of oil are the, presence of fine water droplets and the fibrous impurities. The presence of even 0.01% water in oil brings down the dielectric strength to 20% of the dry oil value and the presence of fibrous impurities brings down the dielectric strength much sharply. Therefore, whenever these oils are used for providing electrical insulation, these should be free from moisture, products of oxidation and other contaminants.

The main consideration in the selection of a liquid dielectric is its chemical stability. The other considerations are the cost, the saving in space, susceptibility to environmental influences etc. The use of liquid dielectric has brought down the size of equipment tremendously. In fact, it is practically impossible to construct a 765 kV transformer with air as the insulating medium. Table 1.2. shows the properties of some dielectrics commonly used in electrical equipments.

Table 1.2. Dielectric properties of some liquids

S.No.	*Property*	*Transformer Oil*	*Capacitor Oil*	*Cable Oil*	*Silicone Oil*
1.	Relative permittivity 50 Hz	2.2 – 2.3	2.1	2.3 – 2.6	2.7 – 3.0
2.	Breakdown strength at 20°C 2.5 mm 1 min	12 kV/mm	18 kV/mm	25 kV/mm	35 kV/mm
3.	(*a*) Tan δ 50 Hz	10^{-3}	2.5×10^{-4}	2×10^{-3}	10^{-3}
	(*b*) 1 kHz	5×10^{-4}	10^{-4}	10^{-4}	10^{-4}
4.	Resistivity ohm-cm	$10^{12} – 10^{13}$	$10^{13} – 10^{14}$	$10^{12} – 10^{13}$	2.5×10^{14}
5.	Maximum permissible water content (ppm)	50	50	50	< 40
6.	Acid value mg/gm of KOH	NIL	NIL	NIL	NIL
7.	Sponification mg of KOH/gm of oil	0.01	0.01	0.01	< 0.01
8.	Specific gravity at 20°C	0.89	0.89	0.93	1.0–1.1

Liquids which are chemically pure, structurally simple and do not contain any impurity even in traces of 1 in 10^9, are known as *pure liquids*. In contrast, commercial liquids used as insulating liquids are chemically impure and contain mixtures of complex organic molecules. In fact their behaviour is quite erratic. No two samples of oil taken out from the same container will behave identically.

The theory of liquid insulation breakdown is less understood as of today as compared to the gas or even solids. Many aspects of liquid breakdown have been investigated over the last decades but no general theory has been evolved so far to explain the breakdown in liquids. Investigations carried out so far, however, can be classified into two schools of thought. The first one tries to explain the breakdown in liquids on a model which is an extension of gaseous breakdown, based on the avalanche ionization of the atoms caused by electon collisiron in the applied field. The electrons are assumed to be ejected from the cathode into the liquid by either a field emission or by the field enhanced thermionic effect (Shottky's effect). This breakdown mechanism explains breakdown only of highly pure liquid and does not apply to explain the breakdown mechanism in commercially available liquids. It has been observed that conduction in pure liquids at low electric field (1 kV/cm) is largely ionic due to dissociation of impurities and increases linearily with the field strength. At moderately high fields the conduction saturates but at high field (electric), 100 kV/cm the conduction increases more rapidly and thus breakdown takes place. Fig. 1.11 (*a*) shows the variation of current as a function of electric field for hexane. This is the condition nearer to breakdown. However, if the figure is redrawn starting with low fields, a current-electric field characteristic as shown in Fig. 1.11 (*b*) will be obtained. This curve has three distinct regions as discussed above.

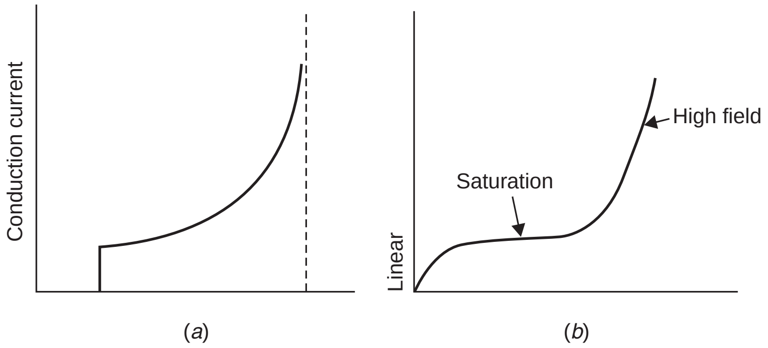


Fig. 1.11 Variation of current as a function of electric field
(*a*) High fields (*b*) Low fields

The second school of thought recognises that the presence of foreign particles in liquid insulations has a marked effect on the dielectric strength of liquid dielectrics. It has been suggested that the suspended particles are polarizable and are of higher permittivity than the liquid. These particles experience an electrical force directed towards the place of maximum stress. With uniform field electrodes the movement of particles is presumed to be initiated by surface irregularities on the electrodes, which give rise to local field gradients. The particles thus get accumulated and tend to form a bridge across the gap which leads finally to initiation of breakdown. The impurities could also be in the form of gaseous bubbles which obviously have lower dielectric strength than the liquid itself and hence on breakdown of bubble the total breakdown of liquid may be triggered.

Electronic Breakdown

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

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

where λ is the mean free path, $h\nu$ is the energy of ionization and C is a constant. Table 1.3 gives typical values of dielectric strengths of some of the highly purified liquids.

Table 1.3. Dielectric strengths of pure liquids

Liquid	*Strength (MV/cm)*
Benzene	1.1
Goodoil	1.0–4.0
Hexane	1.1–1.3
Nitrogen	1.6–1.88
Oxygen	2.4
Silicon	1.0–1.2

The electronic theory whereas predicts the relative values of dielectric strength satisfactorily, the formative time lags observed are much longer as compared to the ones predicted by the electronic theory.

1.11.1 Suspended Solid Particle Mechanism

Commercial liquids will always contain solid impurities either as fibers or as dispersed solid particles. The permittivity of these solids (E_1) will always be different from that of the liquid (E_2). Let us assume these particles to be sphere of radisus r. These particles get polarized in an electric field E and experience a force which is given as

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

and this force is directed towards a place of higher stress if $\varepsilon_1 > \varepsilon_2$ and towards a place of lower stress if $\varepsilon_1 < \varepsilon_2$ when ε_1 is the permittivity of gas bubbles. The force given above increases as the permittivity of the suspended particles (ε_1) increases. If $\varepsilon_1 \to \infty$

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

Let $\varepsilon_1 \to \infty$

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

Thus, the force will tend the particle to move towards the strongest region of the field. In a uniform electric field which usually can be developed by a small sphere gap, the field is the strongest in the uniform field region. Here $dE/dx \to 0$ so that the force on the particle is zero and the particle remains in equilibrium. Therefore, the particles will be dragged into the uniform field region. Since the permittivity of the particles is higher than that of the liquid, the presence of particle in the uniform field region will cause flux concentration at its surface. Other particles if present will be attracted towards the higher flux concentration. If the particles present are large, they become aligned due to these forces and form a bridge across the gap. The field in the liquid between the gap will increase and if it reaches critical value, brakdown will take place. If the number of particles is not sufficient to bridge the gap, the particles will give rise to local field enhancement and if the field exceeds the dielectric strength of liquid, local breakdown will occur near the particles and thus will result in the formation of gas bubbles which have much less dielectric strength and hence finally lead to the breakdown of the liquid.

The movement of the particle under the influence of electric field is oposed by the viscous force posed by the liquid and since the particles are moving into the region of high stress, diffusion must also be taken into account. We know that the viscous force is given by (Stoke's relation) $F_V = 6\pi n r \nu$ where η is the viscosity of liquid, r the raidus of the particle and v the velocity of the particle.

Equating the electrical force with the viscous force we have

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

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

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

where $D = KT/6\pi\eta r$ a relation known as Stokes-Einstein relation. Here K is Boltzmann's constant and T the absolute temperature. At any instant of time, the particle should have one velocity and, therefore, equation $v = v_d$

We have

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

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

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

It is clear that the breakdown strength E depends upon the concentration of particles N, radius r of particle, viscosity η of liquid and temperature T of the liquid.

It has been found that liquid with solid impurities has lower dielectric strength as compared to its pure form. Also, it has been observed that larger the size of the particles impurity the lower the overall dielectric strength of the liquid containing the impurity.

1.11.2 Cavity Breakdown

It has been observed experimentally that the dielectric strength of liquid depnds upon the hydrostatic pressure above the gap length. The higher the hydrostatic pressure, the higher the electric strength, which suggests that a change in phase of the liquid is involved in the breakdown process. In fact, smaller the head of liquid, the more are the chances of partially ionized gases coming out of the gap and higher the chances of breakdown. This means a kind of vapour bubble formed is responsible for the breakdown. The following processes might lead to formation of bubbles in the liquids:

(*i*) Gas pockets on the surface of electrodes.

(*ii*) Due to irregular surface of electrodes, point charge concentration may lead to corona discharge, thus vapourizing the liquid.

(*iii*) Changes in temperature and pressure.

(*iv*) Dissociation of products by electron collisions giving rise to gaseous products.

It has been suggested that the electric field in a gas bubble which is immersed in a liquid of permittivity ε_2 is given by

$$E_b=\frac{3E_0}{\varepsilon_2+2}$$

Where E_0 is the field in the liquid in absence of the bubble. The bubble under the influence of the electric field E_0 elongates keeping its volume constant. When the field E_b equals the gaseous ionization field, discharge takes place which will lead to decomposition of liquid and breakdown may follow.

A more accurate expression for the bubble breakdown strength is given as

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

where σ is the surface tension of the liquid, ε_2 and ε_1 are the permittivities of the liquid and bubble, respectively, r the initial radius of the bubble and V_b the voltage drop in the bubble. From the expression it can be seen that the breakdown strength depends on the initial size of the bubble which of course depends upon the hydrostatic pressure above the bubble and temperature of the liquid. Since the above formation does not take into account the production of the initial bubble, the experimental values of breakdown were found to be much less than the calculated values. Later on it was suggested that only incompressible bubbles like water bubbles can elongate at constant volume according to the simple gas law $pV = RT$. Such a bubble under the influence of electric field changes its shape to that of a prolate spheroid and reaches a condition of instability when β, the ratio of the longer to the shorter diameter of the spheroid is about 1.85 and the critical field producing the instability will be given by

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

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

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

For transformer oil $\varepsilon_2 = 2.0$ and water globule with $r = 1$ µm, $\sigma = 43$ dynes/cm, the above equation gives $E_c = 226$ KV/cm.

Electroconvection Breakdown

It has been recognized that the electroconvection plays an important role in breakdown of insulating fluids subjected to high voltages. When a highly pure insulating liquid is subjected to high voltage, electrical conduction results from charge carriers injected into the liquid from the electrode surface. The resulting space charge gives rise to coulombic forces which under certain conditions causes hydrodynamic instability, yielding convecting current. It has been shown that the onset of instability is associated with a critical voltage. As the applied voltage approaches the critical voltage, the motion at first exhibits a structure of hexagonal cells and as the voltage is increased further the motion becomes turbulent. Thus, interaction between the space charge and the electric field gives rise to forces creating an eddy motion of liquid. It has been shown that when the voltage applied is near to breakdown value, the speed of the eddy motion is given by $\nu_e = \sqrt{\varepsilon_2 / \rho}$ where ρ is the density of liquid. In liquids, the ionic drift velocity is given by

$$\nu_d = KE$$

where K is the mobility of ions.

Let
$$M \frac{\nu_e}{\nu_d} = \sqrt{\frac{\varepsilon_2}{\rho} / KE}$$

The ratio M is usually greater than unity and sometimes much greater than unity (Table 1.4).

Table 1.4

Medium	*Ion*	ε	*M*
Air NTP	O^-_2	1.0	2.3×10^{-2}
Ethanol	Cl^-	2.5	26.5
Methanol	H^+	33.5	4.1
Nitrobenzene	Cl^-	35.5	22
Propylene Carbonate	Cl^-	69	51
Transformer Oil	H^+	2.3	200

Thus, in the theory of electroconvection, *M* plays a dominant role. The charge transport will be largely by liquid motion rather than by ionic drift. The criterion for instability is that the local flow velocity should be greater than drift velocity.

1.12 TREATMENT OF TRANSFORMER OIL

Even though new synthetic materials with better mechanical and thermal properties are being developed, the use of oil/paper complex for high voltages is still finding applications. Oil, besides being a good insulating medium, it allows better dispersion of heat. It allows transfer and absorption of water, air and residues created by the ageing of the solid insulation. In order to achieve operational requirements, it must be treated to attain high degree of purity.

Whatever be the nature of impurities whether solid, liquid or gaseous, these bring down the dielectric strength of oil materially. Oil at 20°C with water contents of 44 ppm will have 25% of its normal dielectric strength. The presence of water in paper not only increases the loss angle tan δ, it accelerates the process of ageing. Similarly, air dissolved in oil produces a risk of forming bubble and reduces the dielectric strength of oil.

Air Absorption: The process of air absorption can be compared to a diffusing phenomenon in which a gaseous substance in this case air is in contact with liquid (oil here).

If the viscosity of the liquid is low, the convection movements bring about a continuous intermixing whereby a uniform concentration is achieved. This phenomenon can, for example, be checked in a tank where the air content or the water content measured both at the top and the bottom are approximately equal.

Let $G(t)$ = Air content of the oil after time t

G_m = Air content under saturation condition

p = Probability of absorption per unit time

S = Surface of oil

V = Volume of oil

The absorption of air by oil can be given by the equation

$$\frac{dG}{dt} = p \,.\, \frac{S}{V}\,[G_m - G(t)]$$

with boundary condition at $t = 0$ $G = G_0$

Solving the above equation

$$\frac{dG}{G_m - G(t)} = p\,\frac{S}{V}\,dt$$

or $$1\text{n}\,\{G_m - G\,(t)\} = -\,p\,\frac{S}{V}\,t + A$$

At $t = 0$ $G = G_{0.}$ Therefore, $A = +\ 1\text{n} \leftarrow \{G_m - G_0\}$

or $$1\text{n}\,\frac{G_m - G(t)}{G_m - G_0} = -\,p\,\frac{S}{V}\,t$$

or $$G_m - G\,(t) = (G_m - G_0)\,e^{\,-pSt/V}$$

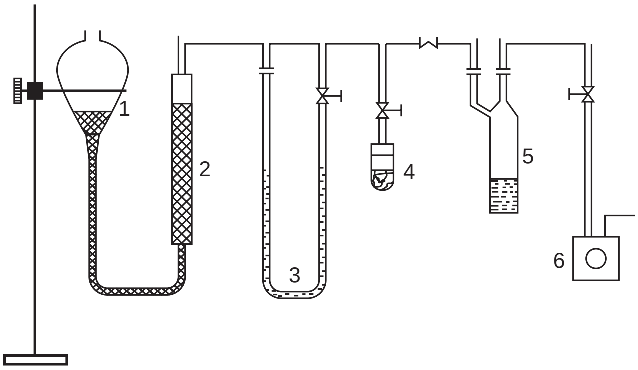
Fig. 1.12 (*a*) shows the schematic for the measurement of air absorption by insulating oil which has previously been degassed as a function of the absorption time. The oil is degassed and dried with the help of the vacuum pump (1) and then introduced into the installation until the desired pressure is reached. A part of this air is absorbed by the oil, the pressure being maintained at a constant (2) Value by reducing the volume in absorption meter (3) Thus, air content of oil by volume can be measured. Precision manometer (4) is used to calibrate the absorption meter. Phosphorus pentaoxide trap (5) takes in the remainder of the water vapour.

In case of a completely degassed oil *i.e.*, at $t = 0$ $G = 0$, we obtain

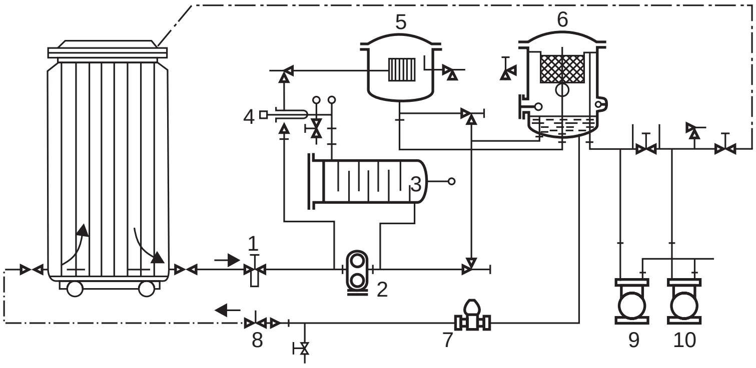
$$G(t) = G_m\,(1 - e^{-pSt/V})$$

To have an estimate of air absorbed by oil, let us consider a hermetically sealed bushing impregnated under vacuum contains 20 litres of degassed oil ($G_0 = 0$). Suppose the bushing is opened at 25°C and remains under atmospheric pressure for 10 hours, the oil surface $S = 10^3$ cm^2. Assume a typical value of $p = 0.4$ cm/hr, the percentage of air absorbed in given as

$$G\,(10\ hr) = 10(1 - e^{-10^3/10^4 \times 0.4 \times 10})$$



(*a*)



(*b*)

Fig. 1.12 (*a*), (*b*)

The molecules of oil are held together by their internal binding energy. In order that water molecule takes the place of oil molecule and is dissolved in the mixture, it is necessary to provide this molecule with a quantity of energy E in the form of heat.

Let N be the number of oil molecule n, the number of water molecules.

P_n the number of possibilities of combination for n water molecules among $(N + n)$ molecules.

i.e.,
$$P_n = \frac{N + n!}{N!\,n!}$$

S = Entropy of the oil
T = Absolute temperature of mixture
K = Boltzamann's constant
$E(T)$ = Energy required for a water molecule to take the palce of an oil molecule
W = Water content of the oil (p.p.m.)
W_m = Maximum water content of the oil, at saturation point

Thermal equilibrium will be reached when free energy F is minimum *i.e.,*

$$\frac{\partial F}{\partial n} = 0$$

where $F = E\,(T) - TS$

and $S = k \; 1\text{n} \; P_n$

Now
$$\frac{\partial F}{\partial n} = \frac{\partial E\,(T)}{\partial n} - T\,\frac{\partial S}{\partial n} = 0$$

Since
$$P_n = \frac{(N + n)!}{N!\,n!}$$

Taking 1n both sides, you have

$$\begin{aligned} 1\text{n}\; P_n &= 1\text{n}\;(N + n)! - 1\text{n}\; N\,! - 1\text{n}\; n\,! \\ &= 1\text{n}\;(N + n) + 1\text{n}\;(N + n - 1) + 1\text{n}\;(N + n - 2) \\ &\quad \ldots - 1\text{n}\; N\,! - 1\text{n}\; n - \ln\;(n - 1) - 1\text{n}\;(n - 2) - 1\text{n}\;(n - 3) \ldots \end{aligned}$$

Differentiating both sides,

$$\frac{1}{P_n}\frac{\partial P_n}{\partial n} = \frac{1}{N+n} + \frac{1}{N+n-1} + \ldots - \frac{1}{n} - \frac{1}{n-1} \ldots$$

$$\approx \frac{1}{N+n} - \frac{1}{n} = -\frac{N}{n\,(N+n)}$$

Since $$\frac{\partial S}{\partial n} = \frac{K}{P_n}\frac{\partial P_n}{\partial n} \approx -\frac{KN}{n\,(N+n)}$$

Substituting for $\partial S/\partial n$ in the equation

We have, $$\frac{\partial E\,(T)}{\partial n} - T\frac{\partial S}{\partial n} = 0$$

$$\frac{\partial E\,(T)}{\partial n} + T\frac{TKN}{n\,(N+n)} = 0$$

or $$\frac{\partial E}{\partial n} = -\frac{TKN}{n\,(N+n)}$$

$$\partial E = -\,TK\,\frac{N\,dn}{n\,(N+n)}$$

Since $N >> N + n \approx N$

Therefore, $$\partial E = -\,TK\,\frac{dn}{n}$$

or $$E = -\,TK \ln n + A$$

when $E = 0$, $n = N$. Therefore, $0 = -\,TK \ln N + A$ or $A = TK \ln N$

or $$E = TK \ln \frac{N}{n}$$

or $$\ln \frac{n}{N} = -\frac{E}{TK} \quad \text{or} \quad \frac{n}{N} \approx e^{-E/TK}$$

or $$n = N\,e^{-E/TK} \approx W_m$$

Following impurities should be considered for purification of oil (*i*) solid impurities (*ii*) free and dissolved water particles (*iii*) dissolved air. Some of the methods used to remove these impurities have been described below.

Filtration and Treatment Under Vacuum: Different types of filters have been used. Filter press with soft and hard filter papers is found to be more suitable for insulating oil. Due to hygroscopic properties of the paper, oil is predried before filtering. Therefore, this oil can not be used for high voltage insulation. The subsequent process of drying is carried out in a specially, designed tank under vacuum. The oil is distributed over a large surface by a so-called ‘‘Rasching-ring’’ degassing column. Through this process, both the complete drying and degassing are achieved simultaneously. By suitable selection of the various components of the plant *e.g.*, rate of flow of oil, degassing surface, vacuum pump etc., a desired degree of purity can be obtained.

Fig. 1.12 (*b*) shows a typical plant for oil treatment. The oil from a transformer or a storage tank is prefiltered (1) so as to protect the feeder pump (2). In (3), the oil is heated up and is allowed to flow through filter press (4) into degassing tank (5). The degassing tank is evacuated by means of vacuum pump (6) whereas the second vacuum pump (7) is either connected with the degassing tank in parallel with pump (6) or can be used for evacuating the transformer tank which is to be treated.

The operating temperature depends upon the quality and the vapour pressure of oil. In order to prevent an excessive evaporation of the aromatics, the pressure should be greater than 0.1 Torr. The filteration should be carried out at a suitable temperature as a higher temperature will cause certain products of the ageing process to be dissolved again in the oil.

Centrifugal Method: This method is helpful in partially extracting solid impurities and free water. It is totally ineffective as far as removal of water and dissolved gases is concerned and oil treated in this manner is even over-saturated with air as air, is thoroughly mixed into it during the process. However, if the centrifugal device is kept in a tank kept under vacuum, partial improvement can be obtained. But the slight increase in efficiency of oil achieved is out of proportion to the additional costs involved.

Adsorption Columns: Here the oil is made to flow through one or several columns filled with an adsorbing agent either in the form of grains or powder. Following adsorbing agents have been used:

(*i*) Fuller earth
(*ii*) Silica gel
(*iii*) Molecular sieves

Activated Fuller earths absorb carbonyl and hydroxyl groups which from the principal ageing products of oil and small amount of humidity. Best results of oil treatment are obtained by a combination of Fuller earth and subsequent drying under vacuum.

Silica gel and in particular molecular sieves whose pore diameter measures 4 Å show a strong affinity for water. Molecular sieves are capable of adsorbing water 20% of its original weight at 25°C and water vapour pressure of 1 Torr whereas sillica gel and Fuller earth take up 6 and 4 per cent respectively.

Molecular sieves are synthetically produced Zeolites which are activated by removal of the crystallisation water. Their adsorption capacity remains constant upto saturation point. The construction of an oil drying plant using molecular sieves is, therefore, simple. The plant consists of an adsorption column containing the sieves and of an oil circulating pump.

The adsorption cycle is followed by a desorption cycle once the water content of the sieves has exceeded 20 per cent. It has been found that the two processes adsorption and desorption are readily reversible. In order to attain disorption of the sieves, it is sufficient to dry them in air stream of 200°C.

Electrostatic Filters: The oil to be treated is passed between the two electrodes placed in a container. The electrostatic field charges the impurities and traces of water which are then attracted and retained by the foam coated electrodes. This method of drying oil is found to be economical if the water content of the oil is less than 2 ppm. It is, therefore, essential that the oil is dried before hand if the water content is large. Also, it is desirable that the oil flow should be slow if efficient filtering is required. Therefore, for industrial application where large quantity of oil is to be filtered, large number of filters will have to be connected in parallel which may prove uneconomical.

1.13 TESTING OF TRANSFORMER OIL

The oil is poured in a container known as *test-cell* which has internal dimensions of 55 mm × 90 mm × 100 mm high. The electrodes are polished spheres of 12.7 to 13 mm diameter, preferably of brass, arranged horizontally with their axis not less than 40 mm above the bottom of the cell. For the test, the distance between the spheres shall be 4 + 0.02 mm. A suitable gauge is used to adjust the gap. While preparing the oil sample, the test-cell should be thoroughly cleaned and the moisture and suspended particles should be avoided. Fig. 1.13 shows an experimental set-up for finding out the dielectric strength of the given sample of oil. The voltmeter is connected on to the primary side of the high voltage transformer but calibrated on the high voltage side.

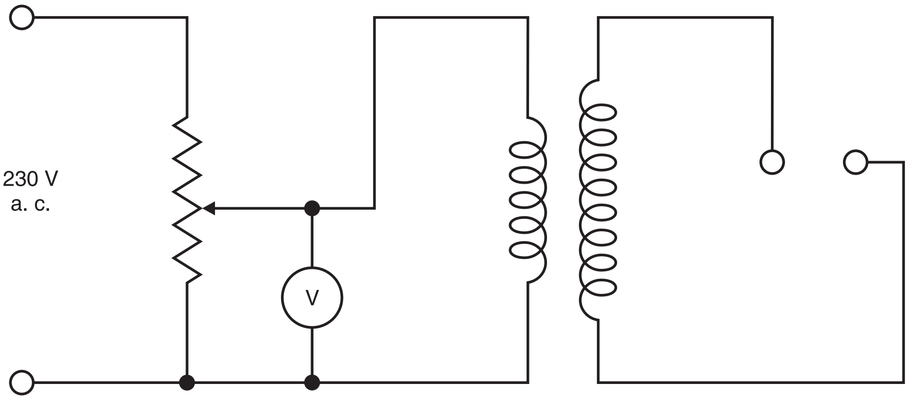


Fig. 1.13

The gap between the spheres is adjusted to 4 mm with the help of a gauge and the spheres are immersed in oil to a depth as mentioned earlier. The voltage is increased gradually and continuously till a flash over of the gap is seen or the MCB operates. Note down this voltage. This voltage is known as *rapidly-applied voltage*. The breakdown of the gap has taken place mainly due to field effect. The thermal effect is minimal as the time of application is short.

Next bring the voltage back to zero and start with 40% of the rapidly applied voltage and wait for one minute. See if the gap has broken. If not, increase the voltage everytime by 2.1/2% of the rapidly applied voltage and wait for one minute till the flash over is seen or the MCB trips. Note down this voltage.

Start again with zero voltage and increase the voltage to a value just obtained in the previous step and wait for a minute. It is expected that the breakdown will take place. A few trials around this point will give us the breakdown value of the dielectric strength. The acceptable value is 30 kV for 4 mm applied for one minute. In fact these days transformer oils with 65 kV for 4 mm 1 minute value are available. If it is less than 30 kV, the oil should be sent for reconditioning. It is to be noted that if the electrodes are immersed vertically in the oil, the dielectric strength measured may turn out to be lower than what we obtained by placing the electrodes in horizontal position which is the normal configuration. It is due to the fact that when oil decomposes carbon particles being lighter rise up and if the electrodes are in vertical configuration, these will bridge the gap and the breakdown will take place at a relatively lower value.

1.13.1 Application of Oil in Power Apparatus

Oil is normally used for providing insulation between the live parts of different phases and between phases and the grounded enclosure containing the oil and the main parts of the apparatus. Also it provides cooling effect to the apparatus placed within the enclosure. Besides providing insulation, the oil helps the C.B. to quench the arc produced between the breaker contacts when they begin to separate to eliminate the faulted section from the healthy section of the system.

In an oil circuit breaker, the heat of the oil decomposes the oil which boils at 658 K. The gases liberated are approx. (*i*) Hydrogen, 70%, (*ii*) Acetylene, 20%, (*iii*) Methane, 5% and (*iv*) Ethane, 5%. (the abbreviation for these gases could be used as HAME).

The temperature about the arc is too high for the three last-named gases to exist and the arc itself runs into a mixture of hydrogen, carbon and copper vapour at temperature above 6000 K. The hydrogen being a diatomic gas gets dissociated into the atomic state which changes the characteristics of the arc on account of its associated change in its thermal conductivity. The outcome of this is that the discharge suddenly contracts and acquires an appreciably higher core temperature. In certain cases, the thermal ionization may be so great that the discharge runs with a lower voltage which may stop the ionization due to the electric field strength. The transition from the field ionization to thermal ionization is most marked in hydrogen and, therefore, in oil circuit breakers.

The separation of the C.B. contacts which are carrying current gives rise to an arc without changing much the current wave form. Initially when the contacts just begin to separate the magnitude of current is very large but the contact resistance being very small, a small voltage appears across them. But the distance of separation being very very small, a large voltage gradient is set up which is good enough to cause ionization of the particles between the contacts. Also it is known that with the copper contacts which are generally used for the circuit breakers very little thermal ionization can occur at temperature below the melting point. For effective field emission, the voltage gradient required is 10^6 V/cm. From this it is clear that the arc is initiated by the field emission rather than the thermal ionization. This high voltage gradient exists only for a fraction of a micro-second. But in this short period, a large number of electrons would have been liberated from the cathode and these electrons while reaching anode, on their way would have collided with the atoms and molecules of the gases. Thus, each emitted electron tends to create others and these in turn derive energy from the field and multiply. In short, the work done by the initially-emitted electrons enables the discharge to be maintained. Finally, if the current is high, the discharge attains the form of an arc having a temperature high enough for thermal ionization, which results in lower voltage gradient. Thus, an arc is initiated due to field effect and then maintained due to thermal ionization.

1.14 BREAKDOWN IN SOLID DIELECTRICS

Solid insulating materials are used almost in all electrical equipments, be it an electric heater or a 500 MW generator or a circuit breaker, solid insulation forms an integral part of all electrical equipments especially when the operating voltages are high. The solid insulation not only provides insulation to the live parts of the equipment from the grounded structures, it sometimes provides mechanical support to the equipment. In general, of course, a suitable combination of solid, liquid and gaseous insulations are used.

The processes responsible for the breakdown of gaseous dielectrics are governed by the rapid growth of current due to emission of electrons from the cathode, ionization of the gas particles and fast development of avalanche process. When breakdown occurs the gases regain their dielectric strength very fast, the liquids regain partially and solid dielectrics lose their strength completely.

The breakdown of solid dielectrics not only depends upon the magnitude of voltage applied but also it is a function of time for which the voltage is applied. Roughly speaking, the product of the breakdown voltage and the log of the time required for breakdown is almost a constant *i.e.,*

$$V_b = 1\text{n}\ t_b = \text{constant}$$

The characteristics is shown in Fig. 1.14.

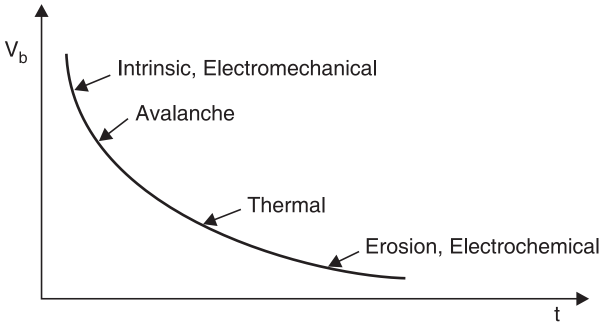


Fig. 1.14. Variation of V_b with time of application

The dielectric strength of solid materials is affected by many factors viz. ambient temperature, humidity, duration of test, impurities or structural defects whether a.c., d.c. or impulse voltages are being used, pressure applied to these electrodes etc. The mechanism of breakdown in solids is again less understood. However, as is said earlier the time of application plays an important role in breakdown process, for discussion purposes, it is convenient to divide the time scale of voltage application into regions in which different mechanisms operate. The various mechanisms are:

(*i*) Intrinisic Breakdown
(*ii*) Electromechanical Breakdown
(*iii*) Breakdown Due to Treeing and Tracking
(*iv*) Thermal Breakdown
(*v*) Electrochemical Breakdown

1.14.1 Intrinsic Breakdown

If the dielectric material is pure and homogeneous, the temperature and environmental conditions suitably controlled and if the voltage is applied for a very short time of the order of 10^{-8} second, the dielectric strength of the specimen increases rapidly to an upper limit known as *intrinsic dielectric strength*. The intrinsic strength, therefore, depends mainly upon the structural design of the material *i.e.*, the material itself and is affected by the ambient temperature as the structure itself might change slightly by temperature condition. In order to obtain the intrinsic dielectric strength of a material, the samples are so prepared that there is high stress in the centre of the specimen and much low stress at the corners as shown in Fig. 1.15.

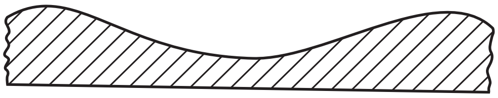


Fig. 1.15 Specimen designed for intrinsic breakdown

The intrinsic breakdown is obtained in times of the order of 10^{-8} sec. and, therefore, has been considered to be electronic in nature. The stresses required are of the order of one million volt/cm. The intrinsic strength is generally assumed to have been reached when electrons in the valance band gain sufficient energy from the electric field to cross the forbidden energy band to the conduction band. In pure and homogenous materials, the valence and the conduction bands are separated by a large energy gap at room temperature, no electron can jump from valance band to the conduction band. The conductivity of pure dielectrics at room temperature is, therfore, zero. However, in practice, no insulating material is pure and, therefore, has some impurities and/or imperfections in their structural designs. The impurity atoms may act as traps for free electrons in energy levels that lie just below the conduction band is small. An amorphous crystal will, therefore, always have some free electrons in the conduction band. At room temperature some of the trapped electrons will be excited thermally into the conduction band as the energy gap between the trapping band and the conduction band is small. An amorphous crystal will, therefore, always have some free electrons in the conduction band. As an electric field is applied, the electrons gain energy and due to collisions between them the energy is shared by all electrons. In an amorphous dielectric the energy gained by electrons from the electric field is much more than they can transfer it to the lattice. Therefore, the temperature of electrons will exceed the lattice temperature and this will result into increase in the number of trapped electrons reaching the conduction band and finally leading to complete breakdown.

When an electrode embeded in a solid specimen is subjected to a uniform electric field, breakdown may occur. An electron entering the conduction band of the dielectric at the cathode will move towards the anode under the effect of the electric field. During its movement, it gains energy and on collision it loses a part of the energy. If the mean free path is long, the energy gained due to motion is more than lost during collision. The process continues and finally may lead to formation of an electron avalanche similar to gases and will lead finally to breakdown if the avalanche exceeds a certain critical size.

1.14.2 Electromechanical Breakdown

When a dielectric material is subjected to an electric field, charges of opposite nature are induced on the two opposite surfaces of the material and hence a force of attraction is developed and the speciment is subjected to electrostatic compressive forces and when these forces exceed the mechanical withstand strength of the material, the material collapses. If the initial thickness of the material is d_0 and is compressed to a thickness d under the applied voltage V then the compressive stress developed due to electric field is

$$F = \frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2}$$

where ε_r is the relative permittivity of the specimen. If γ is the Young's modulus, the mechanical compressive strength is

$$\gamma \, 1\text{n} \frac{d_0}{d}$$

Equating the two under equilibrium condition, we have

$$\frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2} = \gamma \, 1\text{n} \frac{d_0}{d}$$

or $$V^2 = d^2 \cdot \frac{2\gamma}{\varepsilon_0\varepsilon_r} 1\text{n} \frac{d_0}{d} = Kd^2 \, 1\text{n} \frac{d_0}{d}$$

Differentiating with respect to d, we have

$$2V \frac{dV}{dd} = K\left[2d \, 1\text{n} \frac{d_0}{d} - d^2 \cdot \frac{d}{d_0} \cdot \frac{d_0}{d^2}\right] = 0$$

or $$2d \ln \frac{d_0}{d} = d$$

or $$\ln \frac{d_0}{d} = \frac{1}{2}$$

or $$\frac{d}{d_0} = 0.6$$

For any real value of voltage V, the reduction in thickness of the specimen can not be more than 40%. If the ratio V/d at this value of V is less than the intrinsic strength of the specimen, a further increase in V shall make the thickness unstable and the specimen collapses. The highest apparent strength is then obtained by substituting $d = 0.6\ d_0$ in the above expressions.

$$\frac{V}{d} = \sqrt{\frac{2\gamma}{\varepsilon_0 \varepsilon_r} \ln 1.67} \quad \text{or} \quad \frac{V}{d_0} = E_a = 0.6 \left[\frac{\gamma}{\varepsilon_0 \varepsilon_r} \right]^{1/2}$$

The above equation is approximate only as γ depends upon the mechanical stress. The possibility of instability occuring for lower average field is ignored *i.e.*, the effect of stress concentration at irregularities is not taken into account.

1.14.3 Breakdown due to Treeing and Tracking

We know that the strength of a chain is given by the strength of the weakest link in the chain. Similarly whenever a solid material has some impurities in terms of some gas pockets or liquid pockets in it the dielectric strength of the solid will be more or less equal to the strength of the weakest impurities. Suppose some gas pockets are trapped in a solid material during manufacture, the gas has a relative permittivity of unity and the solid material ε_r, the electric field in the gas will be ε_r times the field in the solid material. As a result, the gas breaks down at a relatively lower voltage. The charge concentration here in the void will make the field more non-uniform. The charge concentration in such voids is found to be quite large to give fields of the order of 10 MV/cm which is higher than even the intrinsic breakdown. These charge concentrations at the voids within the dielectric lead to breakdown step by step and finally lead to complete rupture of the dielectric. Since the breakdown is not caused by a single discharge channel and assumes a tree like structure as shown in Fig. 1.6, it is known as breakdown due to treeing. The treeing phenomenon can be readily demonstrated in a laboratory by applying an impulse voltage between point plane electrodes with the point embedded in a transparent solid dielectric such as perspex.

The treeing phenomenon can be observed in all dielectric wherever non-uniform fields prevail.

Suppose we have two electrodes separated by an insulating material and the assembly is placed in an outdoor environment. Some contaminants in the form of moisture or dust particles will get deposited on the surface of the insulation and leakage current starts between the electrode through the contaminants say moisture. The current heats the moisture and causes breaks in the moisture films. These small films then act as electrodes and sparks are drawn between the films. The sparks cause carbonization and volatilization of the insulation and lead to formation of permanent carbontracks on the surface of insulations. Therefore, tracking is the formation of a permanent conducting path usually carbon across the surface of insulation. For tracking to occur, the insulating material must contain organic substances. For this reason, for outdoor equipment, tracking severely limits the use of insulation having organic substances. The rate of tracking can be slowed down by adding filters to the polymers which inhibit carbonization.

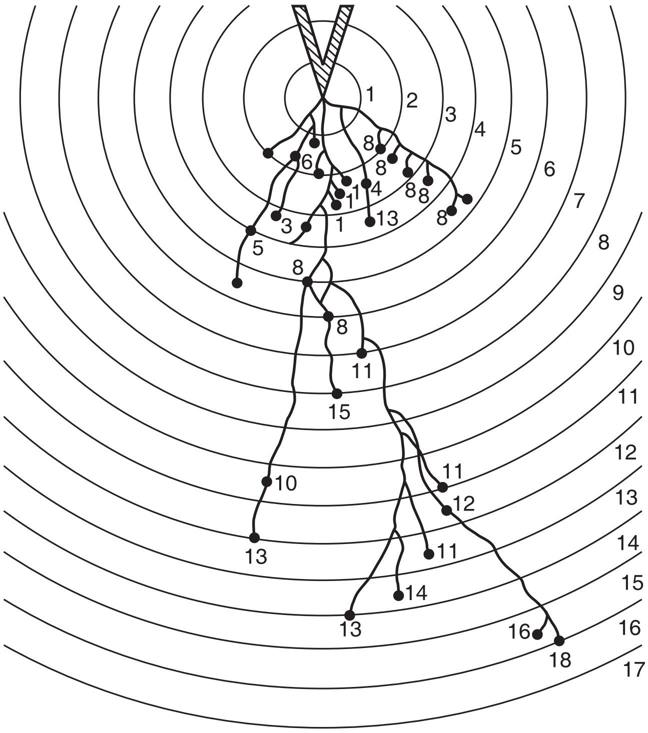


Fig. 1.16

1.14.4 Thermal Breakdown

When an insulating material is subjected to an electric field, the material gets heated up due to conduction current and dielectric losses due to polarization. The conductivity of the material increases with increase in termperature and a condition of instability is reached when the heat generated exceeds the heat dissipated by the material and the material breaks down. Fig. 1.17 shows various heating curves corresponding to different electric stresses as a function of specimen temperature. Assuming that the temperature difference between the ambient and the specimen temperature is small, Newton’s law of cooling is represented by a straight line.

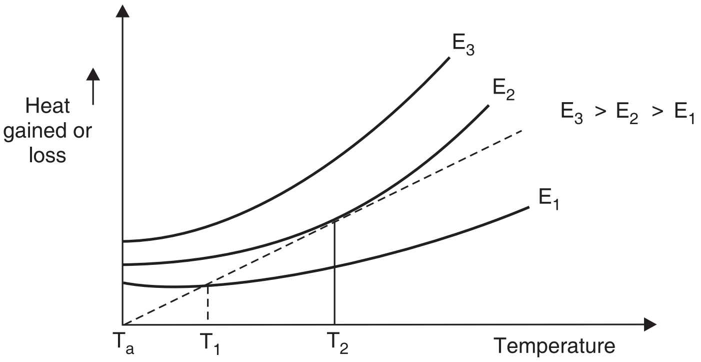


Fig. 1.17 Thermal stability or instability of different fields

The test specimen is at thermal equilibrium corresponding to field E_1 at temperature T_1 as beyond that heat generated is less than heat lost. Unstable equilibrium exists for field E_2 at T_2, and for field E_3 the state of equilibrium is never reached and hence the specimen breaks down thermally.

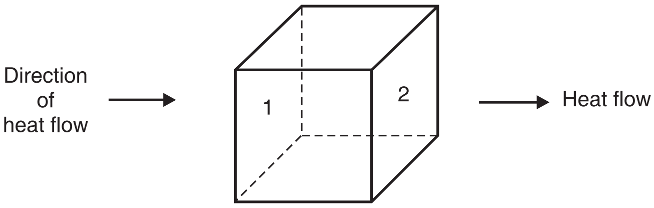


Fig. 1.18. Cubical speciman—Heat flow

In order to obtain basic equation for studying thermal breakdown, let us consider a small cube (Fig. 1.18) within the dielectric specimen with side Δx and temperature difference across its faces in the direction of heat flow (assume here flow is along x-direction) is ΔT. Therefore, the temperature gradient is

$$\frac{\Delta T}{\Delta x} \approx \frac{dT}{dx}$$

Let $\Delta x^2 = A$. The heat flow across face 1

$$KA\,\frac{dT}{dx}\,\text{Joules}$$

Heat flow across face 2

$$KA\,\frac{dT}{dx} - KA\,\frac{d}{dx}\left(\frac{dT}{dx}\right)\Delta x$$

Here the second term indicates the heat input to the differential specimen. Therefore, the heat absorbed by the differential cube volume

$$= \frac{KA\dfrac{d}{dx}\left(\dfrac{dT}{dx}\right)\Delta x}{\Delta V} = K\,\frac{d}{dx}\left(\frac{dT}{dx}\right)$$

The heat input to the block will be partly dissipated into the surrounding and partly it will raise the temperature of the block. Let C_V be the thermal capacity of the dielectric, σ the electrical conductivity, E the electric field intensity. The heat generated by the electric field = σE^2 watts, and suppose the rise in temperature of the block is ΔT, in time dt, the power required to raise the temperature of the block by ΔT is

$$C_V\,\frac{dT}{dt}\ \text{watts}$$

Therefore,
$$C_V\,\frac{dT}{dt} + K\,\frac{d}{dx}\left(\frac{dT}{dx}\right) = \sigma E^2$$

The solution of the above equation will give us the time required to reach the critical temperature T_c for which thermal instability will reach and the dielectric will lose its insulating properties. However, unfortunately the equation can be solved in its present from C_V, K and σ are all functions of temperature and in fact σ may also depend on the intensity of electrical field.

Therefore, to obtain solution of the equation, we make certain practical assumptions and we consider two extreme situations for its solution.

Case I: Assume that the heat absorbed by the block is very fast and heat generated due to the electric field is utilized in raising the temperature of the block and no heat is dissipated into the surroundings. We obtain, therefore, an expression for what is known as impulse thermal breakdown. The main equation reduces to

$$C_V \frac{dT}{dt} = \sigma E^2$$

The objective now is to obtain critical field strength E_c which will generate sufficient heat very fast so that above requirement is met. Let

$$E = \left(\frac{E_c}{t_c}\right) t$$

i.e., the field is a ramp function

$$\sigma E^2 = C_V \frac{dT}{dt} = C_V \frac{dT}{dE} \cdot \frac{dE}{dt}$$

and Let $\sigma = \sigma_0 \, e^{-u/KT}$

where K is Boltzamann's constant and σ_0 is the conductivity at ambinent temperature T_0.

Substituting these values in the simplified equation, we have

$$\sigma_0 e^{-u/KT} E^2 = C_V \frac{dE}{dt} \cdot \frac{dT}{dE}$$

Now $$\frac{dE}{dt} = \frac{E_c}{t_c}$$

Therefore, $$\sigma_0 e^{-u/KT} E^2 = C_V \frac{E_c}{t_c} \frac{dT}{dE}$$

or $$\sigma_0 E^2 \frac{t_c}{E_c} dE = C_V e^{u/KT} dT$$

or $$\frac{\sigma_0}{C_V} \frac{t_c}{E_c} \int_0^{E_c} E^2 dE = \int_{T_0}^{T_c} e^{\frac{u}{KT}} \, dT$$

The integral on the left hand side

$$\frac{\sigma_0}{C_V} \frac{t_c}{E_c} \int_0^{E_c} E^2 \, dE = \frac{\sigma_0}{C_V} \frac{t_c}{E_c} \cdot \frac{1}{3} E_c^3 = \frac{1}{3} t_c \frac{\sigma_0}{C_V} E_c{}^2$$

The integral on the right hand side

$$\int_{T_0}^{T_c} e^{\frac{u}{KT}} \, dt \to T_0{}^2 \frac{K}{u} e^{u/KT_0}$$

when $T_c >> T_0$

Therefore, $$E_c = \frac{3C_V}{\sigma_0 t_c} \cdot \frac{KT_0{}^2}{u} e^{u/KT_0}$$

From the above expression, it is clear that the critical condition requires a combination of critical time and critical field. However, the critical field is independent of the critical temperature due to the fast rise in temperature.

Case II: Here we assume that the voltage applied is the minimum voltage for indefinite time so that the thermal breakdown takes place. For this, we assume that we have a thick dielectric slab that is subjected to constant ambient temperature at its surface by using sufficiently large electrodes as shown in Fig. 1.19

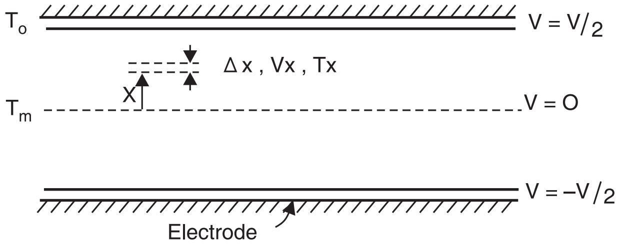


Fig. 1.19 Arrangement of electrode and specimen for minimum thermal B.D. voltage

Suppose that minimum voltage is applied which brings thermal breakdown. As a result after some time, a temperature distribution will be set up within the specimen with maximum temperature T_m at its centre and it decreases as we approach the surface.

In order to calculate maximum thermal voltage, let us consider a point inside the dielectric at a distance x from the central axis and let the voltage and temperature at the point are V_x and T_x, respectively. We further assume that all the heat generated in the dielectric will be carried away to its surroundings through the electrodes. Therefore, neglecting the term

$$C_V \frac{dT}{dt}$$

the main equation reduces to

$$\frac{d}{dx}\left(K \frac{dT}{dx}\right) = \sigma E^2$$

Now using the relations $\sigma E = J$ and $E = -\frac{\partial V}{\partial x}$

We have $$K \frac{d}{dx}\left(\frac{dT}{dx}\right) = -J \frac{\partial V}{\partial x}$$

Integrating both the sides w.r. to x

We have $$\int_0^x \frac{d}{dx}\left(K \frac{dT}{dx}\right) dx = -J \int_0^{V_x} \frac{\partial V}{\partial x} dx$$

or $$K \frac{dT}{dx} = -JV_x = -\sigma E V_x = -\sigma V_x \frac{dv}{dx}$$

Let $\sigma = \sigma_0 e^{-u/KT}$.

We have

$$K \frac{dT}{dx} = \sigma_0 e^{-u/KT} V_x \frac{\partial V}{\partial x}$$

or $$\frac{K}{\sigma_0} E^{u/KT} dT = V_x \frac{\partial V}{\partial x} dx$$

or

$$\frac{K}{\sigma_0}\int_{T_0}^{T_c} e^{u/KT}\, dT = \int_0^{V_{m/2}} V_x\, dV$$

This shows that the maximum thermal voltage depends upon the critical temperature T_c at the centre of dielectric at which the specimen loses is insulating properties. However, V_m is independent of the thickness of the insulating material but for thin specimens the thermal breakdown becomes touching asymptotically to a constant value for thick specimen. Under alternating currents the total heat generated will be

$$\sigma E^2 + V^2\, \omega c \tan \delta$$

and, therefore, this being higher than what we have in d.c. circuits, the maximum thermal breakdown voltage will be lower in a.c. supplies. In fact, higher the frequency the lower the thermal breakdown voltage.

Table 1.5 gives for thick specimen, thermal breakdown values for some dielectric under a.c. and d.c. voltages at 20°C.

Table 1.5. Thermal breakdown voltage

Material		*Maximum thermal voltage in MV/cm*	
		d.c.	*a.c.*
Ceramics	HV Steatite	—	9.8
	LF Steatite	—	1.5
	High grade porcelain		2.8
Organic materials	Ebonite	—	1.45–2.75
	Polythene		3.5
	Polystyrene		5.0
	Polystyrene at 1 MHz		0.05
	Acrylic resins		0.3–1.0
Crystals	Mica muscovite	24	7–18
	Rock salt	38	1.4
Quartz	Perpendiculars to axis	12000	—
	Paralle to axis	66	—
	Impure	—	2.2

1.14.5 Electrochemical Breakdown

Whenever cavities are formed in solid dielectrics, the dielectric strength in these solid specimen decreases. When the gas in the cavity breaks down, the surfaces of the specimen provide instantaneous anode and cathode. Some of the electrons dashing against the anode with sufficient energy shall break the chemical bonds of the insulation surface. Similarly, positive ions bombarding against the cathode may increase the surface temperature and produce local thermal instability. Similarly, chemical degradation may also occur from the active discharge products *e.g.*, O_3, NO_2 etc. formed in air. The net effect of all these processes is a slow erosion of the material and a consequent reduction in the thickness of the specimen. Normally, it is desired that with ageing, the dielectric strength of the specimen should not decrease. However, because of defects in manufacturing processes and/or design, the dielectric strength decreases with time of voltage application or even without voltage application and in many cases; the decrease in dielectric strength (E_b) with time follows the following empirical relation.

$$t \; E_b^{\,n} = \text{constant}$$

where the exponent n depends upon the dielectric material, the ambient temperature humidity and the quality of manufacture. This is the main reason why high a.c. voltage testing is not recommended. In fact, these days very low frequency testing is being suggested (0.1 HZ) which simulates the effects of both a.c. 50 HZ and d.c. voltages and yet the dielectric strength of the specimen is not affected much with VLF voltage application.

The breakdown of solid dielectric due to internal discharges or partial discharges has been elaborately explained in section 6.9 of the book.

1.14.6 Solid Dielectrics Used in Power Apparatus

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

1. High insulation resistance
2. High dielectric strength
3. Good mechanical properties *i.e.*, tenacity and elasticity
4. It should not be affected by chemicals around it
5. It should be non-hygroscopic because the dielectric strength of any material goes very much down with moisture content

Vulcanized rubber : Rubber in its natural form is highly insulating but it absorbs moisture readily and gets oxidized into a resinous material; thereby it loses insulating properties. When it is mixed with sulphur alongwith other carefully chosen ingredients and is subjected to a particular temperature it changes into vulcanized rubber which does not absorb moisture and has better insulating properties than even the pure rubber. It is elastic and resilient.

The electrical properties expected of rubber insulation are high breakdown strength and high insulation resistance. In fact the insulation strength of the vulcanized rubber is so good that for lower voltages the radial thickness is limited due to mechanical consideration.

The physical properties expected of rubber insulation are that the cable should withstand normal hazards of installation and it should give trouble-free service.

Vulcanized rubber insulated cables are used for wiring of houses, buildings and factories for low-power work.

There are two main groups of synthetic rubber material : (*i*) general purpose synthetics which have rubber-like properties and (*ii*) special purpose synthetics which have better properties than the rubber *e.g.*, fire resisting and oil resisting properties. The four main types are: (*i*) butyl rubber, (*ii*) silicon rubber, (*iii*) neoprene, and (*iv*) styrene rubber.

Butyl rubber: The processing of butyl rubber is similar to that of natural rubber but it is more difficult and its properties are comparable to those of natural rubber. The continuous temperature to which butyl rubber can be subjected is 85°C whereas for natural rubber it is 60°C. The current rating of butyl insulated cables is approximately same as those of paper or PVC insulated cables. Butyl rubber compound can be so manufactured that it has low water absorption and offers interesting possibilities for a non-metallic sheathed cable suitable for direct burial in the ground.

Silicone rubber: It is a mechanically weak material and needs external protection but it has high heat resistant properties. It can be operated at temperatures of the order of 150°C. The raw materials used for the silicon rubber are sand, marsh gas, salt, coke and magnesium.

Neoprene: Neoprene is a polymerized chlorobutadiene. Chlorobutadiene is a colourless liquid which is polymerized into a solid varying from a pale yellow to a darkish brown colour. Neoprene does not have good insulating properties and is used upto 660 V a.c. but it has very good fire resisting properties and therefore it is more useful as a sheathing material.

Styrene rubber: Styrene is used both for insulating and sheathing of cables. It has properties almost equal to the natural rubber.

Polyvinyl Chloride (PVC)

It is a polymer derived generally from acetylene and it can be produced in different grades depending upon the polymerization process. For use in cable industry the polymer must be compounded with a plasticizer which makes it plastic over a wide range of temperature. The grade of PVC depends upon the plasticizer. PVC is inferior to vulcanized in respect of elasticity and insulation resistance. PVC material has many grades.

General purpose type: It is used both for sheathing and as an insulating material. In this compound monomeric plasticizers are used. It is to be noted that a V.R. insulated PVC sheathed cable is not good for use.

Hard grade PVC: These are manufactured with less amount of plasticizer as compared with general purpose type. Hard grade PVC are used for higher temperatures for short duration of time like in soldering and are better than the general purpose type. Hard grade can not be used for low continuous temperatures.

Heat resisting PVC: Because of the use of monomeric plasticizer which volatilizes at temperature 80°C–100°C, general purpose type compounds become stiff. By using polymeric plasticizers it is possible to operate the material continuously around 100°C.

PVC compounds are normally costlier than the rubber compounds and the polymeric plasticized compounds are more expensive than the monomeric plasticized ones. PVC is inert to oxygen, oils, alkalis and acids and, therefore, if the environmental conditions are such that these things are present in the atmosphere, PVC is more useful than rubber.

Polythene

This material can be used for high frequency cables. This has been used to a limited extent for power cables also. The thermal dissipation properties are better than those of impregnated paper and the impulse strength compares favourably with an impregnated paper-insulated device. The maximum operating temperature of this material under short circuits is 100°C.

Cross-linked polythene: The use of polythene for cables has been limited by its low melting point. By cross-linking the molecules, in roughly the same way as vulcanising rubber, a new material is produced which does not melt but carbonizes at 250 to 300°C. By using chemical process it has been made technically possible to cross-link polythene in conventional equipment for the manufacture of rubber. This is why the product is said to be "vulcanised" or "cross-linked" polythene.

The polythene is inert to chemical reactions as it does not have double bonds and polar groups. Therefore, it was thought that polythene could be cross-linked only through special condition, *e.g.*, by irradiating polythene with electrons, thereby it could be given properties of cross-linking such as change of tensile strength and better temperature stability. Many irradiation processes have been developed in the cable making industry even though large amounts of high energy radiations are required and the procedure is expensive.

Polythene can also be irradiated with ultraviolet light, after adding to it a smal quantity of ultraviolet sensitive material such as benzophenone. Under the influence of ultraviolet light on benzophenone, a radical is formed of the same type as in the decomposition of peroxide by the radical mechanism. Organic peroxides have also been used successfully to crosslink the polythene.

Impregnated paper

A suitable layer of the paper is lapped on the conductor depending upon the operating voltage. It is then dried by the combined application of heat and vacuum. This is carried out in a hermetically sealed steam heated chamber. The temperature is 120°–130°C before vacuum is created. After the device is dried, an insulating compound having the same temperature as that of the chamber is forced into the chamber. All the pores of the paper are completely filled with this compound. After impregnation the device is allowed to cool under the compound so that the void formation due to compound shrinkage is minimized.

In case of pre-impregnated type the papers are dried and impregnated before they are applied on the conductor.

The compound used in case of impregnated paper is a semifluid and when the cables are laid on gradients the fluid tends to move from higher to lower gradient. This reduces the compound content at higher gradients and may result in void formation at higher gradients. This is very serious for cables operating at voltages higher than 3.3 kV. In many cases, the failures of the cables have been due to the void formation at the higher levels or due to the bursting of the sheath at the lower levels because of the excessive internal pressure of the head of compound.

Insulating press boards. If the thickness of paper is 0.8 mm or more, it is called paper board. When many layers of paper are laminated with an adhesive to get desired thickness, these are known as press boards and are used in bushings, transformers as insulating barriers or supporting materials. The electrical properties of press boards varies depending upon the resin content. The application of these press boards depends upon the thickness and density of paper used. For high frequency capacitors and cables usually low density paper (0.8 gm/cm^3) is used where medium density paper is used for power capacitors and high density papers are used in d.c. machines and energy storage capacitors. The electric strength of press board is higher than that of resins or porcelain. However, it is adversely affected by temperature above 20°C. The loss angle tan δ also decreases with increase in temperature. The main advantage of this material is that it provides good mechanical support even at higher temperatures upto 120°C.

Mica. Mica consists of crystalline mineral silicates of alumina and potash. It has high dielectric strength, low dielectric losses and good mechanical strength. All these properties make it useful for many electrical devices *e.g.,* commutator segment separator, aremature windings, electrical heating and cooling equipments and switchgear. Thin layers of mica are laminated with a suitable resin or varnish to make thick sheets of mica. Mica can be mixed with the required type of resin to obtain its application at different operating temperatures. Mica is used as a filler in insulating materials to improve their dielectric strength, reduce dielectric loss and improve heat resistance property.

Ceramics. Ceramics materials are produced from clay containing aluminium oxide and other inorganic materials. The thick parts of these substances is given the desired shape and form at room temperature and then baked at high temperature about (1450°C) to provide a solid inelastic final structure. Ceramics also known as porcelain in one of its forms have high mechanical strength and low permittivity ($\varepsilon_r < 12$) are widely used for insulators and bushings. These have 40% to 50% of clay, 30-20% of aluminium oxide and 30% of fieldspar. The ceramics with higher permittivity ($\varepsilon_r > 12$) are used in capacitors and transducers.

The specific insulation resistance of ceramics is comparatively low. The tan δ of these materials is high and increases with increase in temperature resulting in higher dielectric loss. The breakdown strength of porecelain compared to other insulating material is low but it remains unaffected over a wide range of temperature variation. Porcelain is chemically insert to alkalies and acids and, therefore, corrosion resistant and does not get contaminated. Alumina (Al_2O_3) has replaced quartz because of its better thermal conductivity, insulating property and mechanical strength. It is used for the fabrication of high current vacuum circuit breakers.

Glass. Glass is a thermoplastic inorganic material consisting of silicondioxide (SiO_2), which is available in nature in the form of quartz. Different types of metal oxides could be used for producing different types of glasses but for use in electrical engineering only non-alkaline glasses are suitable having alkaline content less than 0.8%.

The dielectric constant of glass varies between 3.6 and 10.0 and the density varies between 2000 kg/m^3 and 6000 kg/m^3. The loss angle tan δ is less than 10^{-3} and losses are higher for lower frequencies. Its dielectric strength varies between 300 and 500 kV/mm and it decreases with increase in temperature. Glass is used for X-ray equipments, electronic valves, electric bulbs etc.

Epoxy Resins. Epoxy resins are low molecular but soluble thermosetting plastics which exhibit sufficient hardening quality in their molecules. The chemical cross-linking of epoxy resins is normally carried out at room temperatures either by a catalytic mechanism or by bridging across epoxy molecule through the epoxy or hydroxyl group.

Epoxy resins have high dielectric and mechanical strength. They can be cast into desired shapes even at room temperature. They are highly elastic and it is found that when it is subjected to a pressure of 175000 psi, it returned to its original shape after the load is removed. The dielectric constant varies between 2.5 and 4.0. Epoxy resins basically being non-polar substances have high dc specific insulation resistance and low loss tan δ compared to polar materials like PVC. However, when the temperature exceeds 100°C the specific insulation resistance begins to decrease considerably and tan δ increases. Compared to porcelain the breakdown strength of epoxy resin is almost double at temperatures upto 100°C but decreases rapidly at higher temperatures.

As filler materials, the inorganic substances like quartz powder (SiO_2) are used for casting applications. In SF_6 gas insulated systems having epoxy resin spacers, aluminium oxide and also dolomite are used as filler materials. These are found to be more compatible to the decomposed products of SF_6 by partial discharge and arcing discharges.

It is to be noted that the cast or encapsulation should not contain voids or humidity especially in high voltage applications and the material is desired to be homogeneous. It is, therefore, desirable to dry and degas the individual components of the mixture and casting is preferably carried out in vacuum.

The epoxy resins casts are inert to ether, alcohol and benzol. However, most of them are soluble in mineral oils at about 70°C. It is for this reason that they are not found suitable for applications in filled transformers.

There are certain application which require insulating materials to operate between a high range of temperature *e.g.,* –270°C to 400°C. Some of the applications are space shuttle solar arrays, capacitors, transformers high speed locomotive, microprocessor chip carriers, cryogenic cables and other applications at cryogenic temperatures. For this some thermoplastic polymer films are used which have unique combination of electrical, mechanical and physical quantities and these materials are able to retain these properties over a wide range of temperatures where other insulating materials may fail. Perfluoro carbon films have high dielectric strength very low dielectric constant of 2 and low dielectric loss of 2×10^{-4} at 100 Hz and 7.5×10^{-4} at 100 MHz. These films are used under extreme conditions of temperature and environment. These films are used for insulation on high temperature wires, cables, motor coils phase and ground insulation and for capacitors. This is also used as a substrate for flexible printed circuits and flexible cables.

Another insulating film in which has the best thermal properties in this category of insulating materials is polyimide film under the trade name of Kapton manufactured by DuPont of America. These films can be used between a very wide range of temperature variation varying between –270°C and 350°C. Its continuous temperature rating is 240°C. It has high dielectric and tensile strength. The disadvantages of the film are

(*i*) high moisture absorption rate and (*ii*) it is affected by alkalies and strong inorganic acids.

Kepton films can be used capacitors, transformers formed coil insulation, motor state insulation and flexible printed circuits. The film is selectively costlier and is mainly used where its unique characteristics makes it the only suitable insulation. The use of this insulation for motors reduces the overall dimensions of the motors for the same ratings. It is, therefore, used in almost all situations whose space is a serious problem and the other nature insulation result in bigger dimension.

Another recently developed resins is poly carbonate (PC) which is good heat resistant; it is flexible and has good dielectric characteristic. It is not affected by oils, fats and dilute acids but is adversely affected by alkalies, esters and aromatic hydrocarbons. The film being cost effective and fast resistant, it is used for coil insulation, slot insulation for motors and for capacitor insulation. This is known as the lexon polymer.

General Electric Co. of USA has developed a film under the trade name Ultem which is a poly etherimine (PEI) film which has dielectric strength comparable to that of polyimide film and has higher thermal conductivity and lower moisture absorption and is relatively less costlier. It is used as insulation for transformers and motors.

1.14.7 Application of Insulating Materials

Insulating fluids (gases and liquids) provide insulation between phases and between phase and grounded parts of electrical equipments. These also carry out heat from the windings of the electrical equipments. However, solid insulating materials are used only to provide insulation only.

International Electrotechincal Commission has categories various insulating materials depending upon the temperature of operations of the equipments under the following categories.

Class Y	90°C Natural rubber, PVC, paper cotton, silk without impregnation.
Class A	105°C Same as class Y but impregnated
Class E	120°C Polyethylene, terephthalate, cellulose tricetrate, polyvinyl acetate enamel
Class B	130°C Bakelite, bituminised asbestos, fibre glass, mica, polyester enamel
Class F	155°C As class B but with epoxy based resin
Class H	180°C As class B with silicon resin binder silicone rubber, aromatic polyamide (nomex paper and fibre), polyimide film (enamel, varnish and film) and estermide enamel
Class C	Above 180°C, as class B but with suitable non-organic binders, teflon and other high temperature polymers.

While describing the dielectric and other properties of various insulating materials, their application for various electrical apparatus has also been mentioned in the previous paragraphs. However, a reverse process *i.e.,* what insulating materials are used for a particular apparatus depending upon its ratings and environmental condition where the apparatus is required to operate, is also desirable and a brief review is given here.

Power Transformers. For small rating, the coils are made of super-enamelled copper wire. For layer to layer, coil to coil and coil to ground (iron core) craft paper is used.

However, for large size transformers paper or glass tape is rapped on the rectangular conductors whereas for coil to coil or coil to ground, insulation is provided using thick radial spacers made of press board or glas fibre.

In oil-filled transformers, the transformer oil is the main insulation. However between various layers of low voltage and high voltage winding oil-impregnated press boards are placed.

SF_6 gas insulated power transformers make use of sheet aluminium conductors for windings and turn to turn insulation is provided by a polymer film. The transformer has annular cooling ducts through which SF_6 gas circulates for cooling the winding. SF_6 gas provides insulations to all major gaps in the transformer. This transformer is used where oil filled transform is not suitable *e.g.,* in cinema halls, high rise buildings and some especial circumstances: The end turns of a large power transformer are provided with extra insulation to avoid damage to coil when lighting or switching surges of high frequency are incident on the transformer winding.

The terminal bushings of large size power transformer are made of condenser type bushing. The terminal itself consists of a brass rod or tube which is wound with alternate layers of treated paper and tin foil, so proportioned, as to length, that the series of condensers formed by the tin foil cylinders and the intervening insulation have equal capacitances, thereby the dielectric stress is distributed uniformly.

Circuit Breakers. The basic construction of any circuit breaker requires the separation of contacts in an insulating fluid which serves two functions here:

(*i*) It extinguishes the arc drawn between the contacts when the CB, opens.

(*ii*) It provides adequate insulation between the contacts and from each contact to earth.

Many insulating fluids are used for arc extinction and the fluid chosen depends upon the rating and type of C.B. The insulating fluids commonly used for circuit breakers are

(*i*) Air at atmospheric pressure: Air break circuit breaker upto 11 kV.

(*ii*) Compressed air (Air blast circuit breaker between 220 kV and 400 kV)

(*iii*) Mineral oil which produces hydrogen for arc extrictrion (transformer oil)

  (*a*) Plain break oil, C.B. 11 kV–66 kV

  (*b*) Controlled break oil C.B. or bulk oil C.B. between 66 kV–220 kV

  (*c*) Minimum oil C.B. between 66 kV and 132 kV.

(*iv*) Ultra high vacuum C.B. upto 33 kV.

(*v*) SF_6 circuit breakers above 220 kV.

The controlled break and minimum oil circuit breakers enclose the breaker contacts in an arcing chamber made of insulating materials such as glassfibre reinforced synthetic resins etc.

Rotating Machines. For low voltage a.c. and d.c. machines, the winding wire are super enamelled wire and the other insulation used are vulcanised rubber and varnished cambric and paper. For high voltage and large power capacity machines, the space limitations demand the use of insulating materials having substantially greater dielectric strength. Mica is considered to be a good choice not only due to space requirements but because of its ability to withstand higher temperatures. However, the brittleness of mica makes it necessary to build up the required thickness by using thin flakes cemented together by varnish or bakelite generally with a backing of thin paper or cloth and then baking it under pressure. Epoxy resin bounded mica paper is widely used for both low and high voltage machines. Multilayer slot insulation is made of press board and polyester film. However, for machines with high operating temperatures kapton polymide is used for slot insulation. Mica has always been used for stator insulations. In addition to mica, conducting non-woven polyesters are used for corona protection both inside and at the edges of the slots. Glass fibre reinforced epoxy wedge profiles are used to provide support between the winding bars, slots and the core laminations.

Power Cables. The various insulating materials used are vulcanised rubber, PVC, Polyethylene and impregnated papers.

Vulcanised rubber, insulated cables are used for wiring of houses, buildings and factories for low power work.

PVC is inert to oxygen, oils, alkalies and acids and therefore, if the environmental conditions are such that these things are present in the atmosphere, PVC is more useful than rubber.

Polyethylene is used for high frequency cables. This has been used to a limited extent for power cables also. The thermal dissipation properties are better than those of impregnated poper. The maximum oprating temperature of this cable under short circuits is 100°C.

In case of impregnated paper, a suitable layer of the paper is lapped on the conductor depending upon the operating voltage. It is then dried by the combined application of heat and vacuum. The compound used in case of impregnated paper is semifluid and when the cables are laid on gradients the fluid tends to move from higher to lower gradients which reduces the compound content at higher gradients and may result in void formation at higher gradients. For this reason, impregnated paper cables are used upto 3.3 kV.

Following methods are used for elimination of void formation in the cables:

(*i*) The use of low viscosity mineral oil for the impregnation of the dielectric and the inclusion of oil channels so that any tendency of void formation (due to cyclic heating and cooling of impregnate) is eliminated.

(*ii*) The use of inert gas at high pressure within the metal sheath and indirect contact with the dielectric.

Because of the good thermal characteristics and high dielectric strength of the gas SF_6, it is used for insulating the cables also. SF_6 gas insulated cables can be matched to overhead lines and can be operated corresponding to their surge impedance loading. These cables can be used for transporting thousands of MVA even at UHV, whereas the conventional cables are limited to 1000 MVA and 500 kV.

Power Capacitors. Capacitor design economics suggests the use of individual unit assembled in appropriate series and parallel connected groups to obtain the desired bank voltage and reactive power ratings both in shunt and series capacitor equipments. Series capacitor duty usually requires that a unit designated for a series application be more conservatively rated than a shunt unit. However, there is no basic difference in the construction of the two capacitors.

The most commonly used capacitor for the purpose is the impregnated paper capacitor. This consists of a pair of aluminium foil electrodes separated by a number of Kraft paper tissues which are impregnated with chlorinated diphenyl and has a higher permittivity and results in reduction in the quantity of materials required for a given capacitance and the cost.

The working stress of an impregnated paper is 15 to 25 V/μ and papers of thickness 6–12μ are available and hence depending upon the operating voltage of the capacitor, a suitable thickness of the paper can be selected. Because of imperfection involved in the manufacturing process of the dielectric paper it is desirable to use at least two layers of tissues between metal foils so that the possibility of coincidence of weak spots is avoided.

The effective relative permittivity depends upon the paper and the impregnant. For chlorinated diphenyl impregnant the relative permittivity lies between 5 and 6. Normally through past experience, the area of the plate for a particular material of paper and impregnant per microfarad of capacitance is known and hence it is possible to obtain the number of turns of paper to be wound on a given diameter of mandrel for a specified foil width and for the particular lay-up of foil and paper.

The method of laying up the paper and metallic foil and the connection of lugs is shown in Fig. 1.20. Two layers of dielectric are used as without it rolling would short circuit the plates. As a result of this, two capacitors in parallel are formed by the roll. The foil and the paper interleaved in this fashion are wound on to a mandrel which is split to allow easy removal of the finished roll. If the section of the container is same as that of the roll, minimum overall value for the capacitor is obtained. As a result of this, quantity of free impregnant is a minimum thereby the risk of leakage of impregnant with variation in temperature is reduced. Sometimes a high resistance (for discharge) is connected across the terminals of the capacitor for safety reasons.

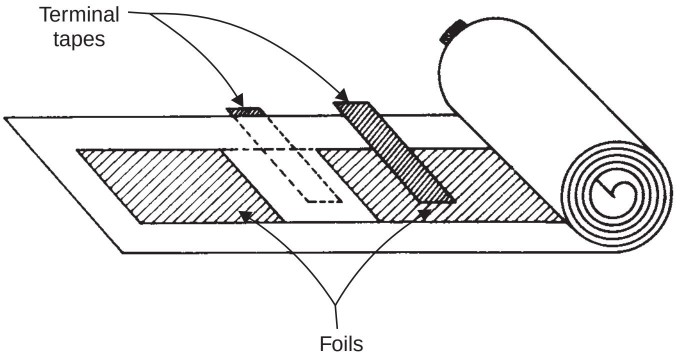


Fig. 1.20. Impregnated paper capacitor-terminal tape type

The replacement of linen by the Kraft paper and oil by askarel made it possible to have individual unit ratings upto 15 kVAr by 1930. After making some costly refinements in basic paper/askarel dielectric 100 kVAr rating capacitor were manufactured by 1960.

General Electric Company designed a 150 kVAr unit using a paper/poly propylene film/askarel dielectric.

Further advances in the manufacture of dielectric materials led to single unit of 600 kVAr even though the rating of a single unit based on economy ranges between 200 and 300 kVAr. Replacement of askarel with non-PCB fluids did not have much effect on unit sizes or ratings. The newer all polypropylene film dielectric units offer distinct advantages in reduced losses and probability of case rapture as well as improvement in unit ratings. The large size units have made it possible to reduce the physical equipment size and the site area requirements.

With further development, it has now been possible to have series and shout capacitor rating upto 550 kV and bank rating of upto 800 MVAr. The average price of smaller units in terms of 100 kVAr is Rs. 100 per kVAr or $2 per kVAr. It is to be noted that aluminium foil are used in these capacitors as it has high thermal and electrical conductivity, has high tensile strength, high melting point, is light in weight, low cost and is easily available.

Capacitor Bushings. Capacitor bushing is used for the terminals of high voltage transformers and switch gears. The power conductor is insulated from the flange by a capacitor bushing consisting of some dielectric material with metal foils cylinderical sheaths of different lengths and radii embedded in it as shown in Fig. 1.21 thus splitting up what essentially a capacitor having high voltage conductor and flange as it's plates, into a number of capacitors in series.

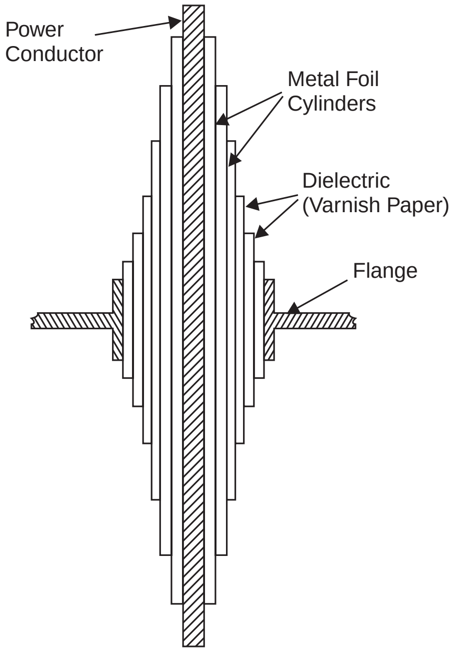


Fig. 1.21. Capacitor bushing

The capacitance of the capacitors formed by the metal foil cylinders is given by

$$C = \frac{\varepsilon l}{2 \ln \frac{R_2}{R_1}}$$

where l is the axial length of the capacitor R_1 and R_2 are the radii of its cylinderical plates. If these capacitor have the same capacitance, the potential difference between their plates will be equal. The equal capacitance between different layers is made possible by choosing suitable axial length together with ratio $\frac{R_2}{R_1}$. With this strategy the potential gradient in the dielectric is uniform but the edges of the foil sheets lie on a curve, thus giving unequal surfaces of dielectric between the edges of successive sheets. This is undesirable as this would result into flashovers by “Creeping” along the surface. However, if the differences between the lengths of successive sheets are made equal, the radial stress is not uniform and hence a compromise between the two conditions is usually adopted.

There are three types of papers used as insulating materials for capacitor bushings; oil impregnated paper, resin bonded paper and resin impregnated paper. The oil impregnated paper bushing is made by wrapping untreated paper after inserting foil sheets at the appropriate position and then impregnating with transformer oil after vacuum drying. Before impregnation, it is ensured that moisture and air voids are avoided. This bushing can work at a radial stress of 40 kV/cm.

In case of resin impregnated bushing creped paper tape is wrapped round the conductor and then dried in an autoclave under controlled heat and vacuum. Epoxyresin is then sprayed to fill the winding. The permissible radial stress in this case is 30 kV/cm.

In case of resin bonded paper bushing, the paper is first coated with epoxyresin and wrapped round a cylinderical form under heat and pressure after inserting foil sheets at appropriate position. The permissible radial stress in this case in 20 kV/cm.

1.15 BREAKDOWN IN VACUUM

A vacuum system is one in which the pressure maintained is at a value below the atmospheric pressure and is measured in terms of mm of mercury. One standard atmospheric pressure at 0°C is equal to 760 mm of mercury. One mm of Hg pressure is also known as *one torr* after the name of Torricelli who was the first to obtain pressures below atmosphere, with the help of mercury barometer. Sometimes 10^{-3} torr is known as one micron. It is now possible to obtain pressures as low as 10^{-8} torr.

In a Townsend type of discharge, in a gas, the mean free path of the particles is small and electrons get multiplied due to various ionization processes and an electron avalanche is formed. In a vacuum of the order of 10^{-5} torr, the mean free path is of the order of few metres and thus when the electrodes are separated by a few mm an electron crosses the gap without any collision. Therefore, in a vacuum, the current growth prior to breakdown can not take place due to formation of electron avalanches. However, if it could be possible to liberate gas in the vacuum by some means, the discharge could take place according to Townsend process. Thus, a vacuum arc is different from the general class of low and high pressure arcs. In the vacuum arc, the neutral atoms, ions and electrons do not come from the medium in which the arc is drawn but they are obtained from the electrodes themselves by evaporating its surface material. Because of the large mean free path for the electrons, the dielectric strength of the vacuum is a thousand times more than when the gas is used as the interrupting medium. In this range of vacuum, the breakdown strength is independent of the gas density and depends only on the gap length and upon the condition of electrode surface. Highly polished and thoroughly degassed electrodes show higher breakdown strength. Electrodes get roughened after use and thus the dielectric strength or breakdown strength decreases which can be improved by applying successive high voltage impulses which of course does not change the roughened surface but removes the loosely adhering metal particles from the electrodes which were deposited during arcing. It has been observed that for a vacuum of 10^{-6} torr, some of the metals like silver, bismuth-copper etc. attain their maximum breakdown strength when the gap is slightly less than 3 mm. This property of vacuum switches permits the use of short gaps for fast operation.

Electric Discharge in Vacuum

The electric discharge in vacuum results from the neutral atoms, ions and electrons emitted from the electrodes themselves. Cathode spots are formed depending upon the current flowing. For low currents a highly mobile cathode spot is formed and for large currents a multiple number of cathode spots are formed. These spots constitute the main source of vapour in the arc. The processes involved in drawing the discharge will be due to high electric field between the contacts or resistive heating produced at the point of operation or a combination of the two. The cathode surfaces, normally, are not perfectly smooth but have many micro projections. Due to their small area of cross-section, the projections will suffer explosive evaporation by resistive heating and supply sufficient quantity of vapour for the arc formation. Since in case of vacuum, the emission occurs only at the cathode spots and not from the entire surface of the cathode, the vacuum discharge is also known as *cold cathode discharge*. In cold cathode the emission of electrons could be due to any of the combinations of the following mechanisms: (*i*) Field emission; (*ii*) Thermionic emission; (*iii*) Field and Thermionic emission; (*iv*) Secondary emission by positive ion bombardment; (*v*) Secondary emission by photons; and (*vi*) Pinch effect.

The stability of discharge in vacuum depends upon: (*i*) the contact material and its vapour pressure, and (*ii*) circuit parameters such as voltage, current, inductance and capacitance. It has been observed that higher the vapour pressure at low temperature the better is the stability of the discharge. There are certain metals like Zn, Bi which show these characteristics and are better electrode materials for vacuum breakers. Besides the vapour pressure, the thermal conductivity of the metal also affects the current chopping level. A good heat conducting metal will cool its surface faster and hence its electrode surface temperature will fall which will result into reduction in evaporation rate and arc will be chopped because of insufficient vapour. On the other hand, a bad heat conductor will maintain its temperature and vaporization for a longer time and the arc will be more stable.

The process of multiplication of charged particles by the process of collision is very small in the space between the electrode in vacuum, electron avalanche is not possible. If somehow a gas cloud could be formed in vacuum, the usual kind of breakdown process can take place. This is the line of action adopted by the researchers to study mechanism of breakdown in vacuum. By finding the way, gas cloud could be created in a vacuum.

1.15.1 Non-metallic Electron Emission Mechanism

The pre-breakdown conduction current in vacuum normally originates from a nonmetallic electrode surface. These are present in the form of insulating/semiconducting oxide layer on the surfaces or as impurities in the electrode material. These microinclusions present in the electrode surface can produce strong electron emission and significantly reduce the break down strength of the gap.

Even when a vacuum system is completely sealed off, the electrode surfaces may still get contaminated. It has been observed that when glass is heated to ‘its’ working temperature for sealing the electrodes into a closed container, fluxes are vaporised from the glass which get deposited in the cool inner surfaces in the form of spherical particles upto a μm diameter . Therefore, the surface of a sealed electrode may have on its surface contaminates *e.g.,* sodium, potassium, boron aluminium and silicon. When an electric field is applied across such electrodes the oxides adsorbates and dust particles, then undergo chemical changes *e.g.,* oxides and adsorbates undergo chemical reactions which are initiated by photons, electrons and ions and thus these contaminants limit the maximum field intensity for the following reasons:

(*i*) The adsorbates and dust enhance the field emission of electrons.

(*ii*) The oxides adsorbates and dust particles enhance the secondary electron emission.

(*iii*) The oxides adsorbates and dust particles exhibit stimulated desorption of molecules and ions under the impact of electrons, protons or ions.

Due to these mechanism, there is increase in electron emission process and therefore, more electric field energy is converted into kinetic energy of electron and ions which leads to an increase in surface energy of the metal. Thus, the electric strength of the gap may reduce to a level as low as 10 kV/cm as compared to 10^4 kV/cm which is required for the field emission process.

1.15.2 Clump Mechanism

The vacuum breakdown mechanism based on this theory makes following assumption:

(*i*) A loosely bound particle known as *clump* exists on one of the electrode surfaces.

(*ii*) When a high voltage is applied between the two electrodes, this clump gets charged and subsequently gets detached from the mother electrode and is attracted by the other electrode.

(*iii*) The breakdown occurs due to a discharge in the vapour or gas released by the impact to the particle at the opposite electrode.

It has been observed that for a certain vacuum gap if frequent recurrent electric breakdowns are carried out, the withstand voltage of the gap increases and after certain number of breakdown, it reaches an optimum maximum value. This is known as *conditioning* of electrodes and is of paramount importance from practical reasons. In this electrode conditioning, the microemission sites are supposed to have been destroyed.

Various methods for conditioning the electrodes have been suggested. Some of these are

(*i*) To treat the electrodes by means of hydrogen glow discharge. This method gives more consistent results.

(*ii*) Allowing the pre-breakdown currents in the gap to flow for some time or to heat the electrodes in vacuum to high temperature.

(*iii*) Treating the electrodes with repeated spark breakdown. This method is however quite time consuming.

The area of electrodes for breakdown of gases, liquids, solids or vacuum plays an important role. It has been observed that if the area of electrodes is increased for the same gap distance in uniform field, the breakdown voltages are reduced.

1.15.3 Effect of Pressure on Breakdown Voltage

It has been observed that in case of very small gaps of less than a mm and the gas pressure between the gap lies in the range 10^{-9} to 10^{-2} Torr, there is no change in the breakdown voltage *i.e.*, if the gap length is small a variation of gas pressure in the range given above doesn't affect the breakdown voltage. However, if the gap length is large say about 20 cm, the variation of gas pressure between the gap adversely affects the withstand voltage and the withstand voltage lowers drastically.

EXAMPLES

Example 1.1 *A steady current of 600 μA flows through the plane electrode separated by a distance of 0.5 cm when a voltage of 10 kV is applied. Determine the Townsend's first ionization coefficient if a current of 60 μA flows when the distance of separation is reduced to 0.1 cm and the field is kept constant at the previous value.*

Solution: Since the field is kept constant (*i.e.,* if distance of separation is reduced, the voltage is also reduced by the same ratio so that V/d is kept constant).

$$I = I_0 \, e^{\alpha x}$$

Substituting two different sets of values,

we have $600 = I_0 \, e^{0.5\alpha}$ and $60 = I_0 \, e^{0.1\alpha}$

or $10 = e^{0.4\alpha}$ or $0.4\,\alpha = 1n\ 10$

$$0.4\,\alpha = 2.3026$$

$\alpha = 5.75$ ionizing collisions/cm.

Example 1.2. *The following table gives two sets of experimental results for studying Townsend's mechanism. The field is kept constant in each set:*

I set 30 kV/cm *Gap distance (mm)*	*II set kV/cm* *Observed current A*	
	I set	*II set*
0.5	1.5×10^{-13}	6.5×10^{-14}
1.0	5×10^{-13}	2.0×10^{-13}
1.5	8.5×10^{-13}	4×10^{-13}
2.0	1.5×10^{-12}	8×10^{-13}
2.5	5.6×10^{-12}	1.2×10^{-12}
3.0	1.4×10^{-10}	6.5×10^{-12}
3.5	1.4×10^{-10}	6.5×10^{-11}
4.0	1.5×10^{-9}	4.0×10^{-10}
5.0	7.0×10^{-7}	1.2×10^{-8}

The manimum current observed is 6×10^{-14} A. Determine the values of Townsend's first and second ionization coefficients.

Solution: 1st Set. Since there is gradual increase in current upto gap distance of 3 mm, slope between any two points

$$\left(\frac{1\text{n } I/I_0}{x}\right)$$

will give us the value of α.

Let us take gap distances of 2 and 2.5 mm.

The respective 1n I/I_0 are

$$1\text{n}\left(\frac{1.5\times10^{-12}}{6\times10^{-14}}\right) = 3.2188$$

and

$$1\text{n}\left(\frac{1.5\times10^{-12}}{6\times10^{-14}}\right) = 4.5362$$

$\therefore$ The slope $= \dfrac{4.5362-3.2188}{0.05} = 26.34$

Since there is sudden rise in current at the last observation, this is used to evaluate γ.

We know that

or

$$I = \frac{I_0 e^{\alpha x}}{1-\gamma\,(e^{\alpha x}-1)}$$

or

$$\frac{I}{I_0} = \frac{7}{6}\times10^7 = \frac{e^{26.34\times0.5}}{1-\gamma(e^{13.17}-1)}$$

$$= \frac{5.24\times10^5}{1-5.24\times10^5\,\gamma}$$

or

$$\frac{7}{6}\times10^7\;\frac{1}{5.24\times10^5} = \frac{1}{1-5.24\times10^5\,\gamma}$$

or $\quad 0.0449 = 1 - 5.24\times10^5\,\gamma$

or $\quad 0.9551 = 5.24\times10^5\,\gamma$

or $\quad \gamma = 0.182\times10^{-5}$ /cm.

Set-II. For the same gap distance the slope will be α = 1n (12/8)/0.05 = 8.1 collisions/cm and therefore

$$\frac{I}{I_0} = 2\times10^5 = \frac{e^{8.1\times0.5}}{1-\gamma(e^{4.05}-1)}$$

$$2\times10^5 = \frac{57.39}{1-\gamma\,(56.39)}$$

or

$$\frac{200\times10^3}{57.39} = 3.4849\times10^3 = \frac{1}{1-56.39\gamma}$$

$$2.87\times10^{-4} = 1-56.39\,\gamma$$

$$56.39\gamma = 1.0$$

or $$\gamma = 1.7 \times 10^{-2} \text{ collisions/cm}$$

Example 1.3. *The following observations were made in an experiment for determination of dielectric strength of transformer oil. Determine the power law equation.*

Gap spacing	*4*	*6*	*8*	*10*
Breakdown Voltage (kV)	*88*	*135*	*165*	*212*

Solution: Let us assume that the relation between gap spacing and breakdown voltage be given as

$$V_b = Kd^n$$

Our objective is to find out values of K and n. Substituting values of two observations , we have

$$88 = K.4^n$$

$$165 = K.8^n$$

∴ $$\frac{165}{88} = \frac{8^n}{4^n} = 2^n$$

$$1.875 = 2^n$$

$$0.6286 = n \times 0.693$$

or $$n = 0.9068$$

and $$K = \frac{88}{4^{0.9068}} = 25.03$$

Similarly taking 2nd and 4th observation, we have

$$135 = K6^n$$

$$212 = K10^n$$

or $$\frac{212}{135} = 1.67^n$$

$$1.57 = 1.67^n$$

Taking 1n on both sides

$$0.4513 = 0.5128\, n$$

or $$n = 0.88$$

and $$K = \frac{135}{6^{0.88}} = 27.9$$

Therefore, average value of $n \approx 0.89$ and that of $K \approx 26.46$ Ans.

Example 1.4. *State and explain Paschen's law. Derive expression for* $(pd)_{min}$ *and* V_{bmin}. *Assume* $A = 12$, $B = 365$ *and* $\gamma = 0.02$ *for air. Determine* $(pd)_{min}$ *and* V_{bmin}.

Solution: We know that

$$(pd)_{\min} = \frac{ek}{A}$$

where $$K = \ln (1 + 1/\gamma)$$

Therefore, $(pd)_{\min} = \frac{e}{A} \ln (1 + 1/\gamma)$

Substituting the values, we have

$$(pd)_{\min} = \frac{2.718}{12} 1\text{n} (1 + 1/0.02) = 0.89 \qquad \text{Ans.}$$

Now $$V_{bmin} = \frac{B}{A} e K = \frac{365}{12} \times 2.718\, 1\text{n}\, 51 = 325 \text{ Volts} \qquad \text{Ans.}$$

PROBLEMS

1.1. Discuss various factors which affect breakdown of gases.

1.2. Define Townsend's first and second ionisation coefficients. Explain the Townsends criterion for a spark.

1.3. State and explain Paschen's law. How do you account for the minimum voltage for breakdown under a given *pd* condition?

1.4. Explain the mechanism of development of anode and cathode streamers and explain how these lead to breakdown.

1.5. What is time-lag? Discuss its components and the factors which affect these components.

1.6. Explain briefly various theories of breakdown in liquid dielectrics.

1.7. Explain clearly suspended particle mechanism of liquid breakdown.

1.8. State various process which lead to formation of bubbles in liquid dielectrics and explain clearly cavity breakdown mechanism in liquid dielectrics.

1.9. What is electroconvection? Explain liquid breakdown based on electroconvection.

1.10. Discuss various criteria suggested by researchers for transition from avalanche to streamer.

1.11. Explain Penning Effect when referred to gaseous discharges.

1.12. What is corona discharge? Explain clearly Anode and Cathode coronas.

1.13. Describe briefly various mechanism of breakdown in solids.

1.14. What are 'Treeing' and 'Tracking'? Explain clearly the two processes in solid dielectrics.

1.15. Derive an expression for maximum thermal voltage and show that the voltage is independent of thickness of specimen. State clearly the assumptions made.

1.16. Derive an expression for critical electric field and show that the field is independent of the critical temperature of the dielectric. State the assumptions made.

1.17. What do you mean by 'Intrinsic strength' of a solid dielectric? Explain electric breakdown of solid dielectrics.

1.18. Explain Thermal breakdown in solid dielectrics. How this mechanism is more significant than the other mechanisms?

1.19. Explain the process of breakdown in electronegative gases.

1.20. Explain the application of oil in power apparatus and discuss clearly its function with reference to a circuit breaker.

1.21. Describe the main requirements of solid insulating materials used for power apparatus and describe the dielectric characteristics of the following material:

(*i*) vulcanized rubber (*ii*) PVC (*iii*) cross-link polyethylene (*iv*) insulating press board (*v*) mica (*vi*) ceramics (*vii*) glass (*viii*) epoxy resins.

1.22. Describe the application of various insulating materials used in the following power apparatus:

(*i*) Power transformers	(*ii*) Circuit breakers
(*iii*) Rotating machines	(*iv*) Power cables
(*v*) Power capacitors	(*vi*) Capacitor bushings

1.23. Explain clearly various processes which explain electric breakdown in vacuum.

1.24. What is ‘‘conditioning of elecrodes’’? How does it affect breakdown in vacuum?

1.25. Discuss the effect of ‘‘Area of electrode’’ and ‘‘Effect of pressure’’ on the breakdown of vacuum.

1.26. Discuss the application of gases in electric power apparatus.

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