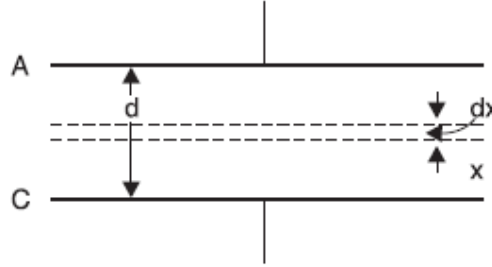# High Voltage Engineering & Power Apparatus

Breakdown Phenomena

Breakdown Phenomena

Breakdown of Gases

### 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 given figure.

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 was studied by **Townsend**. He found that the current at first increased proportionally as the voltage is increased and then remains constant, at I0 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 following figure.
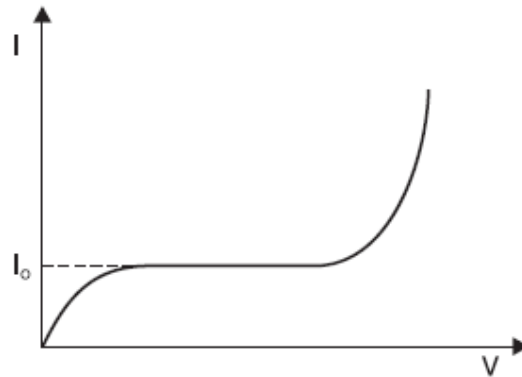
The exponential increase in current is due to *ionization of gas by electron collision*. As the voltage increases V/d increases and hence the electrons are accelerated more and more and between collisions these acquire higher kinetic energy and, therefore, knock out more and more electrons.

Townsend's first ionization coefficient

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

TOWNSEND SECOND IONISATION COEFFICIENT

From the equation

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

We have, taking log on both the sides.

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

This is a straight line equation.

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 v, known as Townsend second ionization coefficient 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 v effective electrons from the cathode then

or $$n_+ = v[n - (n_0 + n_+)]$$

or $$n_+ = vn - vn_0 - vn_+$$

or $$(1+v)n_+ = v(n - n_0)$$

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

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

$$n = \left[n_0 + \frac{v(n - n_0)}{1 + v} \right] e^{\alpha d} = \frac{(1+v)n_0 + vn - vn_0}{1 + v} e^{\alpha d} = \frac{n_0 + vn}{1 + v} e^{\alpha d}$$

or $$(n + vn) = n_0 e^{\alpha d} + vne^{\alpha d}$$

or $$n + vn - vne^{\alpha d}$$

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

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

In terms of current

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

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

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

Since normally

$$\nu e^{\alpha d} \gg 1$$

the current in the anode equals the current in the external circuit. 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.

$ve^{\alpha d} = 1$

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 release 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 $ve^{\alpha d} = 1$ defines the threshold sparking condition.

$ve^{\alpha d} > 1$

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

$ve^{\alpha d} < 1$

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

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 electric field E_0 due to the space charge field.

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 tr. 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

$$n_0 e^{\alpha x} \approx 10^8$$

or $\alpha x_c \approx 18$ to 20

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

Theory of streamer of Kanal mechanism for spark formation shows that 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 following figure.
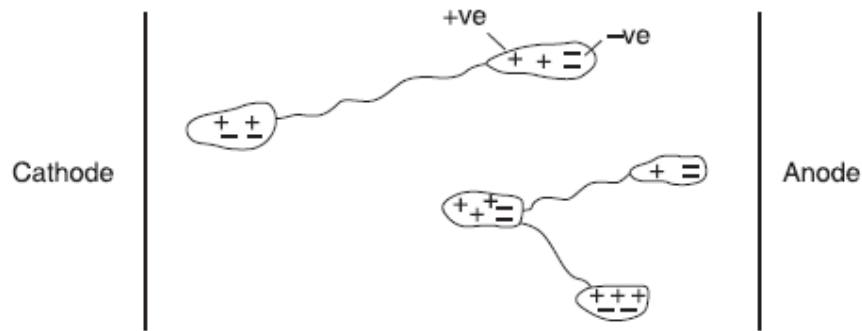
Since photons travel with velocity of light, the process leads to a rapid development of conduction channel across the gap.

Following equation is obtained for applied electric field

$$E = 5.3x10^{-7} . \frac{\alpha e^{\alpha d}}{(d/p)^{1/2}}$$

Taking log on both sides

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

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

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

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.

THE SPARKING POTENTIAL - PASCHEN'S LAW

Townsend's Criterion

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

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

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

Taking in both the sides, we have

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

For uniform field

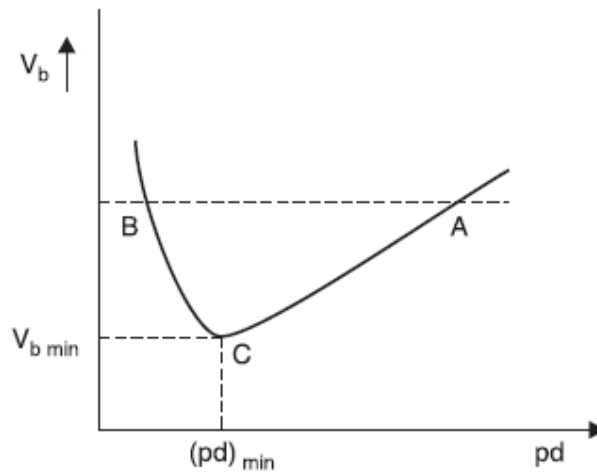$$E = \frac{V_b}{d}$$

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 is shown below.

Paschen's curve

Analytical expression for the minimum sparking potential

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

$$\frac{\alpha}{p} = Ae^{Bp/E}$$

or $$\alpha = pAe^{-Bpd/V_d}$$

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

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

or
$$d.\frac{1}{\alpha d} = \frac{e^{Bpd/V_b}}{pA}$$

We know that

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

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

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

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 log on both sides, we have

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

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

Differentiating V_b with respect to pd and equating the derivative to zero

$$\frac{dV_b}{d(pd)} = \frac{\ln\frac{Apd}{K}.B - Bpd.\frac{A}{K}}{\left(\ln\frac{Apd}{K}\right)^2} = \frac{B\ln\frac{Apd}{K}}{\left(\ln\frac{Apd}{K}\right)^2} - \frac{B}{\left(\ln\frac{Apd}{K}\right)^2} = 0$$

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

or
$$\ln\frac{Apd}{K} = 1$$

or
$$\ln\frac{Apd}{K} = e$$

or $\qquad (pd)_{\min} = \dfrac{e}{A} K$

or $\qquad V_{b,\min} = \dfrac{Be^{K/A}}{1} = \dfrac{B}{A}.eK$

or $\qquad V_{b,\min} = 2.718 \dfrac{B}{A} \ln\left(1 + \dfrac{1}{v}\right)$

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**.

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.

Disadvantages. 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.

Effect of polarity

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.

Following figure gives comparison between the positive and negative point-plane gap breakdown characteristics measured in air as a function of gas pressure.
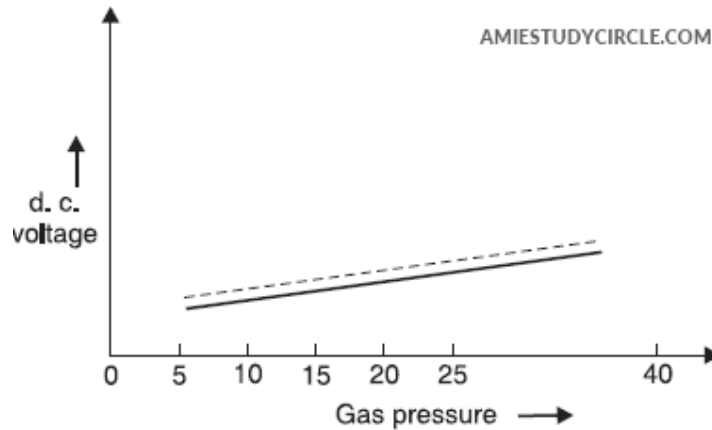

Point-plane breakdown for +ve and –ve polarities

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 breakdown 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.

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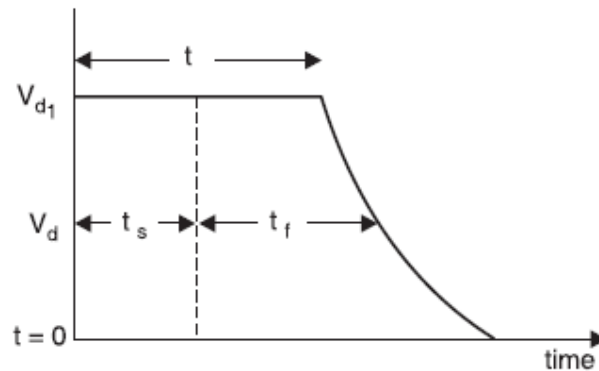
Let the same gap be subjected to a step voltage of peak value $V_{d1} > V_d$ and of a duration such that the gap breaks down in time t. If the breakdown were purely a function of voltage

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 figure, *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.

BREAKDOWN IN ELECTRONEGATIVE GASES

It has been recognised that one process that gives high breakdown strength to a gas is the electron attachment in which free electrons get attached to neutral atoms or molecules to form negative ions. Since negative ions like positive ions are too massive to produce ionization due to collisions, attachment presents an effective way of removing electrons which otherwise would have led to current growth and breakdown at low-voltage. The gases in which attachment plays an active role are called **electronegative gases**.

The most common attachment processes encountered in gases are (a) the **direct attachment** in which an electron directly attaches to form a negative ion, and (b) the **dissociative attachment** in which the gas molecules split into their constituent atoms and the electronegative atom forms a negative ion.

SF_6, has excellent insulating strength because of its affinity for electrons (electro negativity) 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:

$$SF_6 + e \rightarrow SF_6^-$$

$$SF_6 + e \rightarrow SF_5^- + F$$
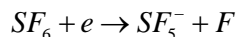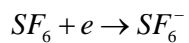
The negative ions formed are relatively heavier as compared to free electrons and, therefore, under a given electric field the ions do not attain sufficient energy to lead cumulative ionization in the gas. Thus, these processes represent an effective way of removing electrons from the space which otherwise 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 liquefied at moderate pressure and stored in steel cylinders. Even though SF_6 has better insulating and arc quenching 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 liquefaction.

Example (AMIE S14, 19, 7 marks)

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

$$600 = I_0 e^{0.5\alpha}$$

and $$60 = I_0 e^{0.1\alpha}$$

or $$I_0 = e^{0.4\alpha}$$

or $$0.4\alpha = \ln(10)$$

or $$\alpha = 5.75 \text{ ionising collisions/cm}$$

Problem

In an experiment in a certain gas it was found that the steady state current is 5.5 x 10^{-8} A at 8 kV at a distance of 0.4 cm between the plane electrodes. Keeping the field constant and reducing the distance to 0.1 cm results in a current of 5.5 x 10^{-9} A. Calculate Townsend's primary ionization coefficient aα. (ii) (ii) if the breakdown occurred when the gap distance was increased to 0.9 cm, what is the value of γ?

Answer: 7.676/cm torr

Breakdown occurs when $\gamma e^{\alpha d} = 1$

∴ $\gamma = 9.993 \times 10^{-4}$

Example

State and explain Paschen's law. Derive expression for (pd)$_{min}$ and $V_{b,min}$. Assume A = 12, B = 365 and γ = 0.02 for air. (i) determine (pd)$_{min}$ and $V_{b,min}$

Determination of $(pd)_{min}$

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

$$(pd)_{min} = \frac{2.718}{12}\ln(1+1/0.02) = 0.89$$

Determination of $V_{b,min}$

Now $V_{b,min} = \frac{B}{A}eK = \frac{365}{12}(2.718\ln 51) = 325\ Volts$

Problem

What will be the breakdown voltage of a spark gap in a gas at pr = 760 torr at 25°C if A = 15/cm, B = 360/crn, d = 1 mm and γ = 1.5 x 10⁻⁴? What is the minimum spark over voltage of the above gap if γ = 10⁻⁴ with all other parameters remaining the same.

Solution

Breakdown voltage

$$V = \frac{(Bpd)}{\ln\left(1+\dfrac{1}{\gamma}\right)}$$

Here pd = 760 x 0.1 = 76 torr cm

∴ $V = \dfrac{(360 \times 76)}{\ln\left(1+\dfrac{1}{1.5}x10^4\right)} = 4885V$

Determination of $V_{b,min}$

$$V_{b,min} = \frac{Be}{A}\ln\left(1+\frac{1}{\gamma}\right) = \frac{360}{15}x2.178\ x\ln\left[1+\frac{1}{1.5}x10^4\right] = 574V$$

Breakdown of Liquid

Liquid dielectrics, because of their inherent properties, appear as though they would be more useful as insulating materials than either solids or gases. This is because both liquids and solids are usually 10^3 times denser than gases and hence, from Paschen's law it should follow that they possess much higher dielectric strength of the order of 10^7 V/cm. Also, liquids, like gases, fill the complete volume to be insulated and simultaneously will dissipate heat by convection. Oil is about 10 times more efficient than air or nitrogen in its heat transfer capability when used in transformers. Although liquids are expected to give very high dielectric strength of the order of 10 MV/cm, in actual practice the strengths obtained are only of the order of 100 kV/cm.

Liquid dielectrics are used mainly as impregnates in high-voltage cables and capacitors, and for filling up of transformers, circuit breakers, etc. Liquid dielectrics also act as heat transfer agents in transformers, and as arc-quenching media in circuit breakers. Petroleum oils (Transformer oil) are the most commonly used liquid dielectrics.

Liquid dielectrics normally are mixtures of hydrocarbons and are weakly polarised. When used for electrical insulation purposes they should be free from moisture, products of oxidation and other contaminants. The most important factor that affects the electrical strength of an insulating oil is the presence of water in the form of fine droplets suspended in the oil. The presence of even 0.01% water in transformer oil reduces its electrical strength to 20% of the dry oil value.

TRANSFORMER OIL (MINERAL OIL)

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

CHARACTERISTICS OF LIQUID DIELECTRICS

Essentially, a liquid dielectric should possess good dielectric properties, excellent heat transfer characteristics and must be chemically stable under the range of conditions under which the equipment operates.

Electrical Properties

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

- capacitance per unit volume or its relative permittivity

- resistivity

- loss tangent (tan δ) or its power factor which is an indication of the power loss under ac voltage application

- its ability to withstand high electric stresses.

Permittivities of most of the petroleum oils vary from 2.0 to 2.6 while those of silicone oils from 2.0 to 73.

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

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

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

Heat Transfer Characteristics

In equipments filled with a liquid dielectric (transformer, cable, circuit breaker, etc.), heat is transferred mainly by convection. Under natural atmospheric cooling conditions convection (AO is given by

$$N = f[K^3 AC/v]^n$$

where K = thermal conductivity, A = coefficient of expansion, C = specific heat per unit volume, v = kinematic viscosity, and n = 0.25 ~ 0.33.

Chemical Stability

In service, insulating liquids are subjected to thermal and electrical stresses in the presence of materials like O_2, water, fibres and decomposition products of solid insulation. These, either singly or in combination, cause degradation of the liquid with the result that soluble solid and gaseous products are found, which can result in corrosion, impairment of heat transfer, deterioration of electrical properties, increased dielectric losses, discharges and arcing. In the absence of any remedial action, this cycle continues and produces an ever-worsening liquid purity and equipment condition.

PURE LIQUIDS AND COMMERCIAL LIQUIDS

Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 10^9, and are structurally simple. Examples of such simple pure liquids are n-

hexane (C_6H_{14}), n-heptane (C_7H_{16}) and other paraffin hydrocarbons. By using simple and pure liquids, it is easier to separate out the various factors that influence conduction and breakdown in them.

On the other hand, the **commercial liquid** oils which are not chemically pure, normally consist of mixtures of complex organic molecules which cannot be easily specified or reproduced in a series of experiments.

Purification

The main impurities in liquid dielectrics are dust, moisture, dissolved gases and ionic impurities. Various methods employed for purification are filtration (through mechanical filters, spray filters, and electrostatic filters), centrifuging, degassing and distillation, and chemical treatment (adding ion exchange materials such as alumina, fuller's earth, etc. and filtering). Dust particles when present become charged and reduce the breakdown strength of the liquid dielectrics, and they can be removed by careful filtration. Liquid will normally contain moisture and dissolve gases in small quantities. Gases like oxygen and carbon dioxide significantly affect the breakdown strength of the liquids, and hence it is necessary to control the amount of gas present. This is done by distillation and degassing. Ionic impurity in liquids, like water vapour which easily dissociates, leads to very high conductivity and heating of the liquid depending on the applied electric field. Water is removed using drying agents or by vacuum drying. Sometimes, liquids are shaken with concentrated sulphuric acid to remove wax and residue and washed with caustic soda and distilled water.

A commonly used closed-cycle liquid purification system to prepare liquids as per the above requirements is shown in following figure.
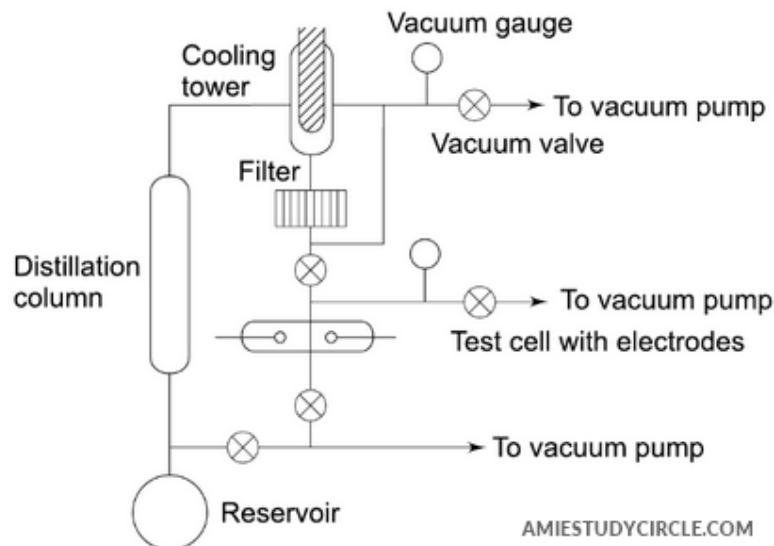
This system provides for cycling the liquid. The liquid from the reservoir flows through the distillation column where ionic impurities are removed. Water is removed by drying agents or frozen out in the low-temperature bath. The gases dissolved in the liquid are removed by passing them through the cooling tower and/or pumped out by the vacuum pumps. The liquid

then passes through the filter where dust particles are removed. The liquid thus purified is then used in the test cell. The used liquid then flows back into the reservoir. The vacuum system thus helps to remove the moisture and other gaseous impurities.

Breakdown Tests

Breakdown tests are normally conducted using test cells. For testing pure liquids, the test cells used are small so that less quantity of liquid is used during testing. Also, test cells are usually an integral part of the purification system as shown in previous figure. The electrodes used for breakdown voltage measurements are usually spheres of 0.5 to 1 cm in diameter with gap spacings of about 100-200 nm (i.e. 0.1 mm).

The gap is accurately controlled by using a micrometer. Electrode separation is very critical in measurements with liquids, and also the electrode surface smoothness and the presence of oxide films have a marked influence on the breakdown strength.

The test voltages required for these tests are usually low, of the order of 50-100 kV, because of small electrode spacings. The breakdown strengths and dc conductivities obtained in pure liquids are very high, of the order of 1 MV/cm and 10^{-18} - 10^{-20} mho/cm respectively, the conductivity being measured at electric fields of the order of 1 kV/cm.

BREAKDOWN THEORIES

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.

Breakdown in liquids on a model which is an extension of gaseous breakdown

It is based on the avalanche ionization of the atoms caused by electron collision 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. 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 linearly 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. (a) shows the variation of current as a function of electric field for hexane.

(a)   (b)
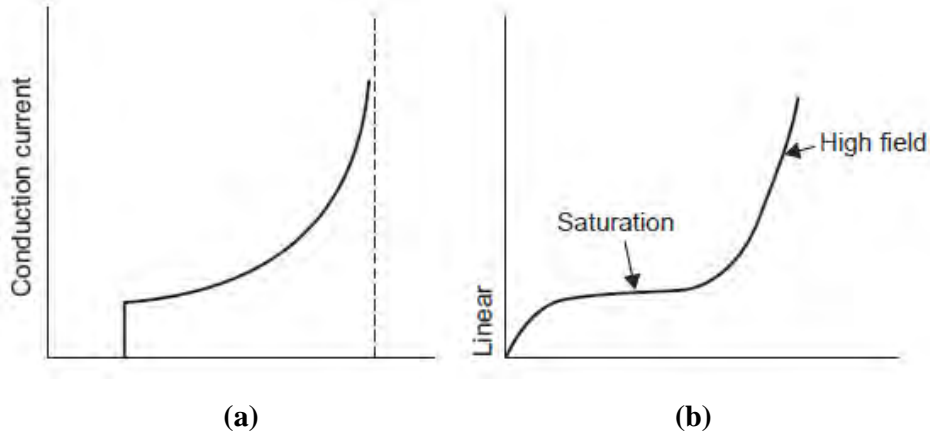
This is the condition nearer to breakdown. However, if the figure is redrawn starting with low fields, a current-electric field characteristic as shown in Fig. (b) will be obtained. This curve has three distinct regions as discussed above.

Bubble Theory

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 polarisable 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

$$e \lambda E = Chv$$

where λ is the mean free path, hv is the energy of ionization and C is a constant.

Suspended Solid Particle Mechanism

Commercial liquids will always contain solid impurities either as fibres or as dispersed solid particles. The permittivity of these solids (ε_1) will always be different from that of the liquid

(ε_2). Let us assume these particles to be sphere of radius r. These particles get polarized in an electric field E and experience a force which is given as

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

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.

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

Let $\varepsilon_1 \to \infty$

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

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 → 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, breakdown 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.

Cavity Breakdown

It has been observed experimentally that the dielectric strength of liquid depends 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:

- Gas pockets on the surface of electrodes.

- Due to irregular surface of electrodes, point charge concentration may lead to corona discharge, thus vaporising the liquid.

- Changes in temperature and pressure.

- 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.

Stressed Oil Volume Theory

In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the 'largest possible impurity' or 'weak link'. On a statistical basis, it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region.

In non-uniform fields, the **stressed oil volume** is taken as the volume which is contained between the maximum stress (E_{max}) contour and $0.9E_{max}$ contour. *According to this theory, the breakdown strength is inversely proportional to the stressed oil volume.*

The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage.

The variation of the breakdown voltage stress with the stressed oil volume is shown in following figure.

TESTING OF TRANSFORMER OIL
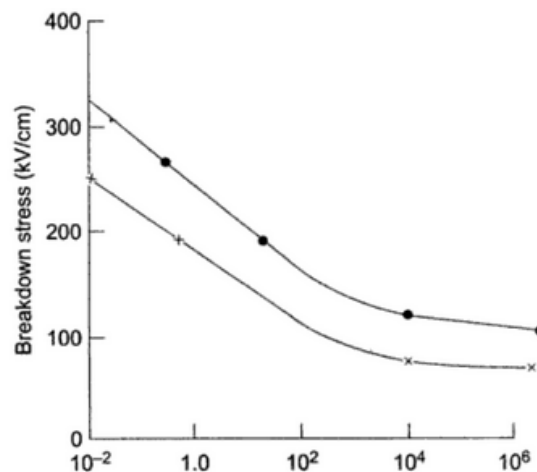
The oil is poured in a container known as test-cell which has internal dimensions of 55 mm × 90 mm × 100 mm high. The electrodes are polished spheres of 12.7 to 13 mm diameter, preferably of brass, arranged horizontally with their axis not less than 40 mm above the bottom of the cell. For the test, the 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. Following figure 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.
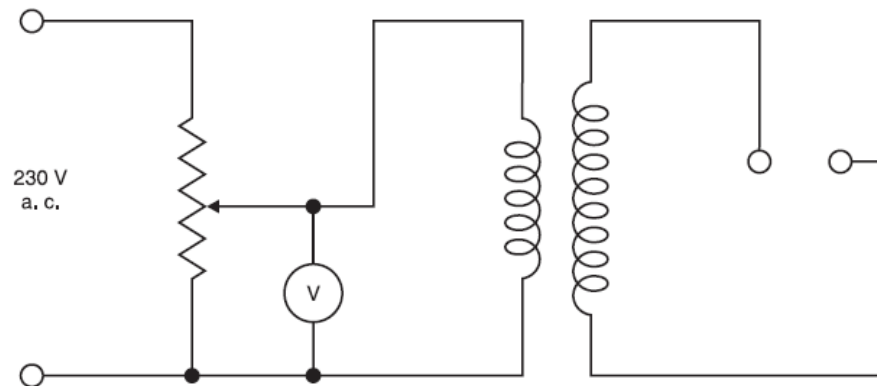
The gap between the spheres is adjusted to 4 mm with the help of a gauge and the spheres are immersed in oil to a depth as mentioned earlier. The voltage is increased gradually and continuously till a flash over of the gap is seen or the MCB operates. Note down this voltage. This voltage is known as *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 every time 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.

Example (AMIE Summer 2014, 12 marks)

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

$$88 = K(4)^n$$

$$165 = K(8)^n$$

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

$$1.875 -= 2^n$$

or taking log and solving

$$0.6286 = n \times 0.693$$

or $\qquad$ n = 0.9068

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

Similarly taking 2nd and 4th observation, we find

$$K = 27.9$$

Therefore, average value of n ≈ 0.89 and that of K ≈ 26.46

$$\therefore \qquad V = 26.46d^{0.89}$$

Example (AMIE Winter 2016, 6 marks)

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

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

*Answer: n = 0.947 and K = 24.5 Hence relation is $V = 24.5d^{0.947}$*

Breakdown of Solid Dielectrics

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

Solid insulating materials, which are generally used in practice, are of two types, namely, the organic materials, such as paper, wood and rubber, and the inorganic materials, such as mica, glass and porcelain, and synthetic polymers, such as Perspex, PVC, epoxy resins, etc.

The various breakdown mechanisms can be classified as follows:

- intrinsic or ionic breakdown,

- electromechanical breakdown,

- failure due to treeing and tracking,

- thermal breakdown,

- electrochemical breakdown, and

- breakdown due to internal discharges.
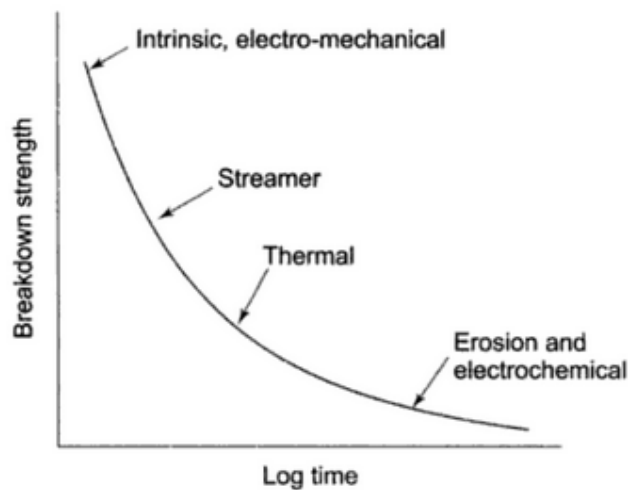
Variation of breakdown strength with time after application of voltage

INTRINSIC BREAKDOWN

When voltages are applied only for short durations of the order of 10^{-8} s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. The maximum electrical strength recorded is 15 MV/cm for polyvinyl-alcohol at -196°C. The maximum strength usually obtainable ranges from 5 MV/cm to 10 MV/cm.

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

AVALANCHE OR STREAMER BREAKDOWN

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

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

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

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 specimen 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 highest apparent strength is

$$\frac{V}{d_0} = E_a = 0.6 \left[\frac{\gamma}{\varepsilon_0 \varepsilon_r} \right]^{1/2}$$

where ε_r is the relative permittivity of the specimen and γ is the Young's modulus.

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 temperature and a condition of instability is reached when the heat generated exceeds the heat dissipated by the material and the material breaks down.

Basic equation for studying thermal breakdown is

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

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

which reduces to

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

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. 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.

Example (AMIE W17, 5 marks)

A solid specimen of dielectric has a dielectric constant of 4.2 and tan δ = 0.001 at a frequency of 50 Hz. If it is subjected to an alternating field of 50 kV (rms)/cm, calculate the heat generated in the specimen due to dielectric loss.

$$W_{ac} = \frac{E^2 f \varepsilon_r \tan \delta}{1.8x10^{12}} = \frac{(50x10^3)^2 (50)(4.2)(0.001)}{1.8x10^{12}} = 0.291 mW / cm^3$$

BREAKDOWN OF SOLID DIELECTRICS IN PRACTICE

There are certain types of breakdown which do not come under either intrinsic breakdown or thermal breakdown, but actually occur after prolonged operation. These are, for example, breakdown due to tracking in which dry conducting tracks are formed on the surface of the insulation. These tracks act as conducting paths on the insulator surfaces leading to gradual breakdown along the surface of the insulator.

Another type of breakdown in this category is the electrochemical breakdown caused by chemical transformations such as electrolysis, formation of ozone, etc. In addition, failure also occurs due to partial discharges which are brought about in the air pockets inside the insulation. This type of breakdown is very important in the impregnated paper insulation used in high-voltage cables and capacitors.

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 following figure, it is known as **breakdown due to treeing**.
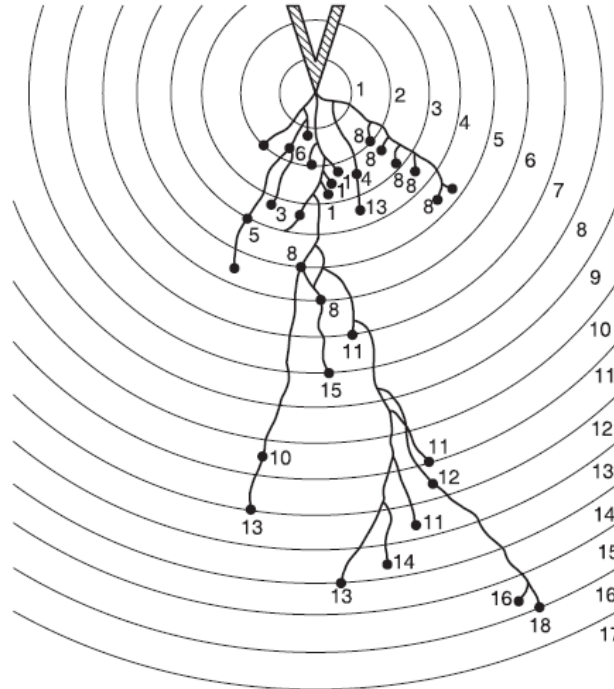
The treeing phenomenon can be readily demonstrated in a laboratory by applying an impulse voltage between point plane electrodes with the point embedded in a transparent solid dielectric such as Perspex. The treeing phenomenon can be observed in all dielectric wherever non-uniform fields prevail.

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

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

Tracking. 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 carbon tracks 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.

Breakdown due to Internal Discharges

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

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

All these effects will result in a gradual erosion of the material and consequent reduction in the thickness of insulation leading to breakdown. The life of the insulation with internal discharges depends upon the applied voltage and the number of discharges. Breakdown by this process may occur in a few days or may take a few years.

ASSIGNMENT

Q.1. (AMIE S14, 4 marks): Discuss briefly the mechanisms of charge multiplication.

Q.2. (AMIE S14, 19, W18, 8 marks): Define Townsend's first and second ionization coefficients. Discuss Townsend breakdown mechanism.

Q.3. (AMIE S15, 10 marks): Deduce the current expressions in terms of Townsend first and second ionization coefficients.

Q.4. (AMIE W17, 5 marks): Explain briefly the transition from a non-self-sustaining Townsend discharge to a self-sustaining discharge.

Q.5. (AMIE S14, 15, 17, 18, 19, W17, 8 marks): State and explain Paschen's law for the sparking potential. Determine an analytical expression for the minimum sparking potential. Derive expression for $(pd)_{min}$ and V_{min}.

Q.6. (AMIE W14, 16, S19, 5 marks): Discuss various factors which affect breakdown of gases.

Q.7. (AMIE W15, 16, S16, 10 marks): Explain clearly Streamer theory of breakdown of gases.

Q.8. (AMIE W18, S19, 5 marks): What are the anode and cathode streamers? Explain the mechanism of their formation and development leading to breakdown.

Q.9. (AMIE S17, 5 marks): Why uniform field theory is required to do the experiment for breakdown voltage in gases? Explain.

Q.10. (AMIE W18, 5 marks): What is time lag in context of gas breakdown? Discuss the components of time lag and the factors which affect them.

Q.11. (AMIE W16, 18, 5 marks): What are electronegative gases? Why is the break-down voltage of electronegative gas higher as compared to a normal gas? Give one example of an electronegative gas and the power apparatus where it is used.

Q.12. (AMIE S17, 18, 5 marks): Discuss the experimental investigation of discharge in long air gap.

Q.13. (AMIE W18, S19, 5 marks): Define corona. What are the effects of corona? Discuss effect of corona and write its advantages and disadvantages.

Q.14. (AMIE W14, S15, 10 marks): What is corona discharge? Explain clearly the effect of polarity of voltage on corona and breakdown process.

Q.15. (AMIE S17, 18, 5 marks): Discuss the practical methods of calculation of corona loss at A.C. voltage.

Q.16. (AMIE W16, 5 marks): What are the advantages and limitations of corona?

Q.17. (AMIE S17, 18, 5 marks): Discuss the effect of humidity of air on breakdown.

Q.18. (AMIE W18, 5 marks): How does the internal discharge phenomena lead to breakdown in solid dielectrics?

Q.19. (AMIE S14, 12 marks): Enumerate six mechanisms for the breakdown of solids explain three such mechanisms in detail.

Q.20. (AMIE W16, 5 marks): What do you understand by intrinsic breakdown in solids? Explain.

Q.21. (AMIE W14, 15, 18, S15, 16, 5 marks): What are "treeing" and "tracking"? Explain clearly two processes in solid dielectrics.

Q.22. (AMIE W18, 5 marks): What is the purpose of impregnating a solid solution? Give two practical examples, where impregnation is carried out.

Q.23. (AMIE S18, 5 marks): What are "dielectric constant" and "loss factor"? How can these be measured?

Q.24. (AMIE S15, 10 marks): Deduce the analytical expression for minimum sparking potential in solid dielectrics.

Q.25. (AMIE W17, S18, 5 marks): What do you understand by the term intrinsic strength of solid dielectrics? Is it possible to experimentally measure the intrinsic strength?

Q.26. (AMIE W16, 17, 5 marks): What is thermal breakdown in solid dielectrics? How is it practically more significant than other mechanisms?

Q.27. (AMIE S14, 8 marks): Explain the following breakdown mechanism in liquids: (i) cavitation theory (ii) suspended particle theory.

Q.28. (AMIE W14, S15, 10 marks): State various process which lead to formation of bubbles in liquid dielectrics. Explain clearly cavity breakdown mechanism in liquid dielectrics.

Q.29. (AMIE S17, 18, 5 marks): Explain the bubble theory for the breakdown of liquid and solid insulation.

Q.30. (AMIE S15, 16, W16, 5 marks): Explain suspended particle breakdown mechanism in liquid dielectrics.

Q.31. (AMIE W17, 18, S19, 5 marks): Explain the phenomena of electrical conduction in liquids. How does it differ from that in gases?

Q.32. (AMIE W18, 19, S19, 5 marks): Explain briefly the various theories of breakdown in commercial liquid dielectrics.

Q.33. (AMIE W 16, 17, S18, 5 marks): What are commercial liquid dielectrics and how are they different from pure liquid dielectrics? Name two commercial liquid dielectrics used in power apparatus.

Q.34. (AMIE W18, 5 marks): State the electrical properties which are essential for electrical performance of liquid dielectrics. Give example of one liquid dielectric that satisfies these properties.

Q.35. (AMIE W17, S18, 5 marks): What is stressed oil volume theory? How does it explain breakdown in large volume of commercial liquid dielectrics?

Q.36. (AMIE S17, 18, 5 marks): Discuss breakdown voltage test of transformer oil.

Q.37. (AMIE W17, S18, 5 marks): What are the difference between (i) Townsend discharges (ii) Streamer discharges (iii) Leader discharges? Describe briefly the main characteristics of each and the conditions under which each phenomenon occurs.

Q.38. (AMIE W11, 17, 5 marks): In an experiment in a certain gas, it was found that steady state current is 55 nA at 8 kV at a distance of 0.4 cm between the plane electrodes. Keeping the field constant and reducing the distance to 0.1 cm results in a current of 5.5 nA. Calculate Townsend's primary ionization coefficient α.

Answer: 7.676

Q.39. (AMIE W17, 5 marks): Assuming a power law relationship $V = Kd^n$ for the breakdown of transfer oil where V is breakdown voltage in kV, d is the gap distance in mm, K, a proportionality constant and n the power law index. Find the breakdown voltage at gap spacing of 4 mm, 6 mm, 10 mm and 12 mm. Given K = 24.5 and n = 0.947.

Answer: 91 kV; 133.68 kV; 216.85 V and 257.7 kV

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