2

Dielectric Breakdown

2.1. GASEOUS BREAKDOWN

Gases are the simplest and most commonly used dielectrics in the electrical apparatus.

Insulating Materials

- Air
- Nitrogen (N_2)
- Carbon-di-oxide (CO_2)
- Freon (CCl_2F_2 – dichloro-di-fluoro methane)
- Sulphur hexafluoride (SF_6)

Uses of Gas Insulators

Gas insulators are used in power transmission lines and power apparatus like generator, motor, *etc.*

Breakdown Voltage

The maximum voltage applied to the insulation at the moment of breakdown.

Types of discharges in gases

There are two types. They are:

- Non-sustaining discharges.
- Self-sustaining discharges.

Properties

The properties of gas insulators are:

- Large breakdown strength.
- Provide flexible and reliable medium for high voltage applications.
- Inertness.
- Chemically stable.
- Give smoothness to the electrode material.
- Arc quenching properties are high in SF_6 gas.

2.2. TOWNSEND'S FIRST IONISATION PROCESS

The process of emitting an electron from a gas molecule with the simultaneous production of a positive ion is called ionization. The arrangement for study of a Townsend's discharge is as shown in Fig.2.1.

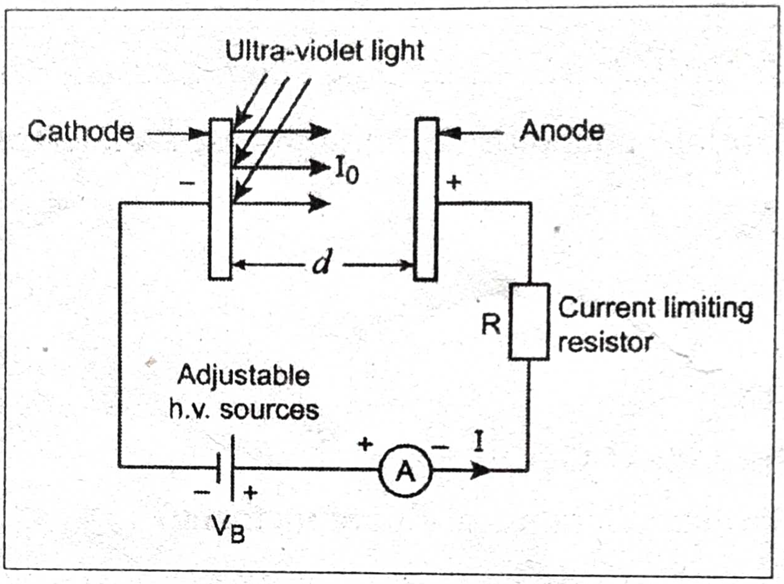


Fig. 2.1. Arrangement for study of a Townsend discharge

When an electric field is applied between anode and cathode, any electron from cathode collide with a neutral molecule and produces a positive ion and a new electron. This additional electrons again collide with a neutral molecule and this process repeats and ionizing collision takes place.

2.2.1. Townsend's First Ionization Coefficient (α)

The average number of ionizing collisions made by an electron per centimeter travel in the direction of the field is called Townsend's first ionization coefficient (α). α depends on $\frac{E}{P}$ and pressure P.

Let n_0 be the number of electrons leaving the cathode.

Let n_x be the number of electrons at a distance x from the cathode.

When n_x electrons travels a small distance dx, produces

$$dn_x = \alpha\, n_x\, dx \text{ electrons.}$$

$$dn_x = \alpha\, n_x\, dx \qquad \dots (2.1)$$

Separating the variables, in equation (2.1), we get,

$$\frac{dn_x}{n_x} = \alpha\, dx \qquad \dots (2.2)$$

Integrating equation (2.2) on both sides, we get

$$\int \frac{dn_x}{n_x} = \int \alpha\, dx$$

$$ln\ n_x = \alpha x + K \qquad \dots (2.3)$$

Find the value of K:

When the distance $x = 0$, $n_x = n_0$.

Substituting in equation (2.3), we get

$$ln\ n_0 = K \qquad \dots (2.4)$$

Substituting equation (2.4) in equation (2.3), we get

$$ln\ n_x = \alpha x + ln\ n_0$$

$$ln\ n_x - ln\ n_0 = \alpha x$$

$$ln\left[\frac{n_x}{n_0}\right] = \alpha x$$

$$\frac{n_x}{n_0} = e^{\alpha x}$$

$$\Rightarrow\ n_x = n_0\, e^{\alpha x} \qquad \dots (2.5)$$

Let n_d be the number of electrons reaching the anode at $x = d$.

$$\therefore\ n_d = n_0\ e^{\alpha d} \qquad \dots (2.6)$$

Average current in the gap, $I = I_0\, e^{\alpha d}$ ... (2.7)

where, I_0 = Initial current at the cathode.

Typical current growth curve is as shown in Fig.2.2.

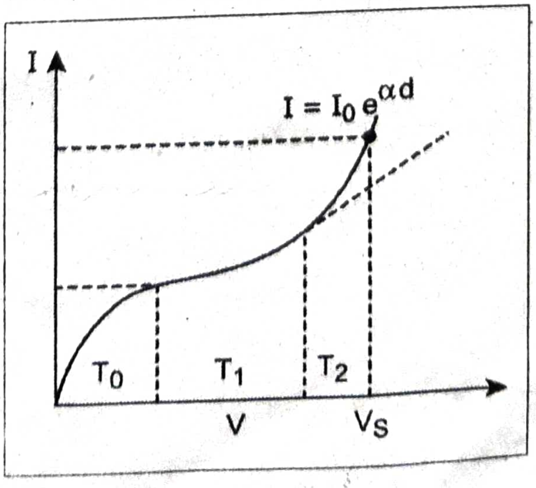


Fig. 2.2. Typical current growth curve

2.2.2. Townsends' Second Ionization

Mechanisms for Producing Additional Electrons to Create Avalanches

The mechanisms are:

- The positive ions produced may have sufficient energy to cause production of electrons from the cathode when they impinge on it.
- The excited atoms in avalanches may emit photons. Due to photo emission process, emission of electrons takes place.
- The excited particle or metastable particles may diffuse back, causing electron emission.

Townsend's Second Ionization Coefficient (γ)

The net number of secondary electrons produced per incident positive ions, photon, excited particle or meta stable particle and the total value of all is called Townsend's second ionization coefficient (γ).

Let n_0' be the number of secondary electrons produced due to secondary ionization process.

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

$$\therefore\ n_0'' = n_0 + n_0'$$

Let n be the total number of electrons reaching the anode.

$$n = n_0''\, e^{\alpha d} = (n_0 + n_0')\, e^{\alpha d} \qquad \ldots (2.8)$$

Number of electrons released from the gas,

$$n_0' = n - (n_0 + n_0')$$

$$n_0' = n\gamma - n_0\gamma - n_0'\gamma$$

$$n_0'[1 + \gamma] = \gamma[n - n_0]$$

$$n_0' = \frac{\gamma}{1+\gamma}[n - n_0] \qquad \ldots (2.9)$$

To eliminate n_0',

Substituting equation (2.9) in equation (2.8), we get

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

$$\begin{aligned} n(1+\gamma) &= \{(1+\gamma)\,n_0 + \gamma\,(n-n_0)\}\,e^{\alpha d} \\ n + n\gamma &= [n_0 + \gamma\, n_0 + \gamma\, n - \gamma\, n_0]\; e^{\alpha d} \\ &= n_0\, e^{\alpha d} - \gamma\, n\, e^{\alpha d} \\ n\,[1+\gamma-\gamma\, e^{\alpha d}] &= n_0\, e^{\alpha d} \\ n &= \frac{n_0\, e^{\alpha d}}{1+\gamma-\gamma\, e^{\alpha d}} = \frac{n_0\, e^{\alpha d}}{1-\gamma\,(e^{\alpha d}-1)} \end{aligned}$$

$$\left.\begin{array}{r}\text{Total average current in the gap}\\ \text{before breakdown}\end{array}\right\} \mathrm{I} = \frac{\mathrm{I}_0\, e^{\alpha d}}{1-\gamma\,(e^{\alpha d}-1)} \qquad \ldots (2.10)$$

2.2.3. Townsend's Criterion

At critical distance $d = d_s$ (sparking distance), the denominator of equation (2.10) becomes zero.

$$\therefore\ \mathrm{I} \rightarrow \infty$$

i.e., $\quad 1-\gamma\,(e^{\alpha d_s}-1) = 0,\ \text{(or)}\ \gamma\,(e^{\alpha d_s}-1) = 1$

Now $e^{\alpha d_s}$ is a large value. ∴ γ term can be neglected.

$$\therefore\ \gamma\, e^{\alpha d_s} = 1 \qquad \ldots (2.11)$$

This is the criterion for Townsend's breakdown.

Breakdown in electronegative gases: The electron attachment with neutral atom or molecules remove free electrons in certain gases which leads to current growth and breakdown at low voltage. They are called electronegative gases and have high breakdown stress.

Time Lag in the Breakdown of Dielectric

There is a time difference between the application of voltage sufficient to cause breakdown and the occurrence of breakdown in the dielectric. This time difference is called as time lag.

Fig.2.3 shows breakdown with a step function voltage pulse.

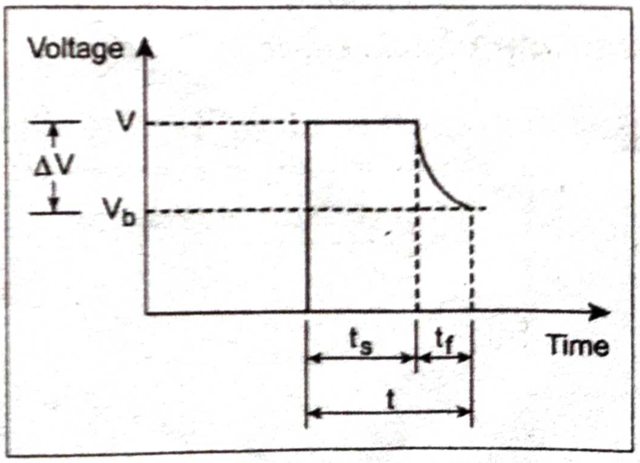


Fig. 2.3. Breakdown with a step function voltage pulse

Total time, $t = t_S + t_f$

t_f = Formative time lag.

t_S = Statistical time lag.

Example 2.1 *In an experiment of gas, it was found that at a steady current of 5.5 × 10^{-8} A with 0.4 cm separation between the plates. For constant field, if the separation reduces to 0.1 cm results in a current of 5.5 × 10^{-9} A. Find Townsend's primary ionization coefficient.*

☺ ***Solution:***

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

When
$$I_1 = 5.5 \times 10^{-8} \text{ A}$$
$$d_1 = 0.4 \text{ cm}$$
$$I_2 = 5.5 \times 10^{-9} \text{ A}$$
$$d_2 = 0.1 \text{ cm}$$
$$\frac{I_1}{I_2} = e^{\alpha(d_1 - d_2)}$$
$$10 = e^{\alpha \times 0.3}$$
$$0.3\,\alpha = ln\, 10 = 2.303$$
$$\alpha = 7.676 \text{ per cm-torr}$$

2.3. STREAMER MECHANISM (BREAKDOWN IN UNIFORM FIELD)

When the field is uniform and space charge due to ions lesser than electric field E, the charges present in between the electrodes increase by a factor $e^{\alpha d}$,

where, d = Gap distance.

α = Townsend's coefficient.

Observation by Raether

Raether observed the following condition.

Charge Concentration	Growth of Avalanche
$10^6 - 10^8$	Weak
$> 10^8$	Steep rise in the avalanche current leading to breakdown of gap.

The weakening of the avalanche at lower concentration and rapid growth of avalanche at higher concentration gives the modification of the electric field E due to the space charge field.

The field distortion in a gap due to space charge is as shown in Fig.2.4.

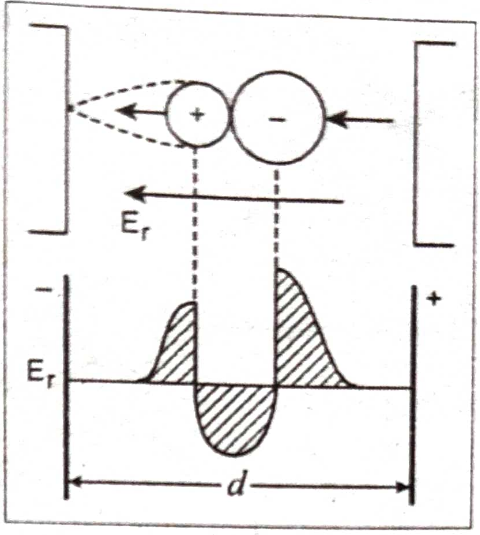


Fig. 2.4. Field distortion in a gap due to space charge

The space charge at the head of the avalanche is assumed to have a sphere containing negative charge at its top. Due to field lines from the anode, the field gets enhanced at the top of avalanche. At the bottom of the avalanche, the field between electrodes opposes the applied field, thereby reduces the applied field (E). Still further decreasing the field between cathode and positive ions gets enhanced. Thus field distortion takes place.

At the charge density in the avalanche is $n = 10^8$, streamer breakdown occurs.

$$\text{Now, space charge field} = \text{Applied electric field}$$

Thus space charge field plays an important role in the growth of avalanche in corona and non-uniform field gaps.

Transformation of avalanche to streamer occurs when

$$n_0 e^{\alpha x_c} = 10^8$$

$$\alpha x_c = 18 \text{ to } 20$$

where, x_c = Length of the avalanche in which the secondary electrons are produced by photo ionization.

2.3.1. Formation of Secondary Avalanche

At the critical condition, the applied field and the space charge field cause intense ionization and accelerate the gap particles in front of the avalanche. Positive ions and electrons recombine and produces photons. These photons produces secondary electrons by photoionization. These electrons develop into secondary avalanches when the electric field is applied. Formation of secondary avalanches due to photoionization is as shown in Fig.2.5.

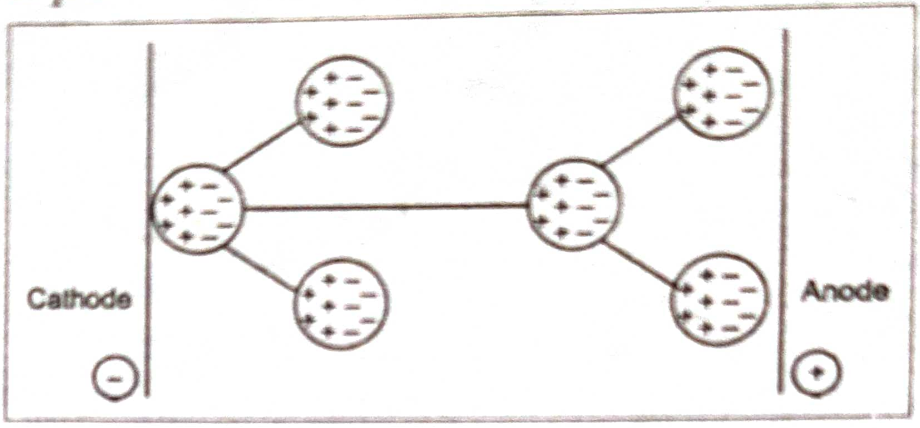


Fig. 2.5. Formation of secondary avalanches due to photoionization

Expression for streamer spark criterion is,

$$\alpha x_c = 17.7 + ln\, x_c + ln\left[\frac{E_r}{E}\right] \quad \dots (2.12)$$

where, E_r = Space charge field.

E = Applied electric field.

Condition for transition from avalanche to streamer is,

$$E_r = E$$

∴ Breakdown criterion becomes, $\alpha x_c = 17.7 + ln\, x_c$

Minimum breakdown value occurs when $x_c = d$

where, d = Gap length

∴ Breakdown criterion is $\alpha d = 17.7 + ln\, d \quad \dots (2.13)$

2.3.2. Meek's Expression

Space charge field, $E_r = 5.27 \times 10^{-7} \dfrac{\alpha e^{\alpha x}}{\left(\frac{x}{P}\right)^{\frac{1}{2}}}$ V/cm $\quad \dots (2.14)$

where, α = Townsend's ionization coefficient.

p = Gas pressure in torr.

To determine minimum breakdown voltage,

Substitute $E_r = E$ and $x = d$ in equation (2.14), we get

$$E = 5.27 \times 10^{-7} \alpha \frac{e^{\alpha d}}{\left(\frac{d}{p}\right)^{\frac{1}{2}}} \qquad \text{... (2.15)}$$

Taking ln on both sides, we get

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

Subtracting $ln\, p$ on both sides, we get

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

$$ln\left(\frac{E}{p}\right) = -14.5 + ln\left(\frac{\alpha}{p}\right) + \alpha d - \frac{1}{2}\, ln\left(\frac{d}{p}\right) \qquad \text{... (2.16)}$$

Experimental values of $\frac{\alpha}{p}$ and the corresponding $\frac{E}{p}$ values are used to solve this equation using trial and error method. Values of $\frac{\alpha}{p}$ and $\frac{E}{p}$ are chosen until the equation is satisfied.

2.4. PASCHEN'S LAW

Townsend's breakdown criterion for gases is,

$$\gamma\, (e^{\alpha d} - 1) = 1 \qquad \text{... (2.17)}$$

where, α, γ are the Townsend's ionization coefficients and are functions of $\left(\frac{E}{p}\right)$

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right) \Rightarrow \alpha = p \cdot f_1\left(\frac{E}{p}\right) \qquad \text{... (2.18)}$$

$$\gamma = f_2\left(\frac{E}{p}\right) \qquad \text{... (2.19)}$$

Substituting equations (2.18), (2.19) in (2.17), we get

$$f_2\left(\frac{E}{p}\right)\left[e^{p \cdot f_1\left(\frac{E}{p}\right) d} - 1\right] = 1 \qquad \text{... (2.20)}$$

We know $E = \frac{V}{d}$.

∴ Equation (2.20) becomes

$$f_2\left(\frac{V}{p\,d}\right)\left[e^{p\,d\,f_1\left(\frac{V}{p\,d}\right)} - 1\right] = 1 \qquad \ldots (2.21)$$

The equation (2.21) shows a relationship between V and $p\,d$.

i.e., The breakdown voltage varies as the product $p\,d$ varies.

Knowing the nature of functions f_1 and f_2, we can rewrite equation (2.21) as

$$V = f(p\,d)$$

The breakdown voltage of a uniform field gap is a unique function of the product of gas pressure p and gap length d for a particular gas and electrode material. This relation is known as Paschen's law.

The Paschen's curve is as shown in Fig.2.6.

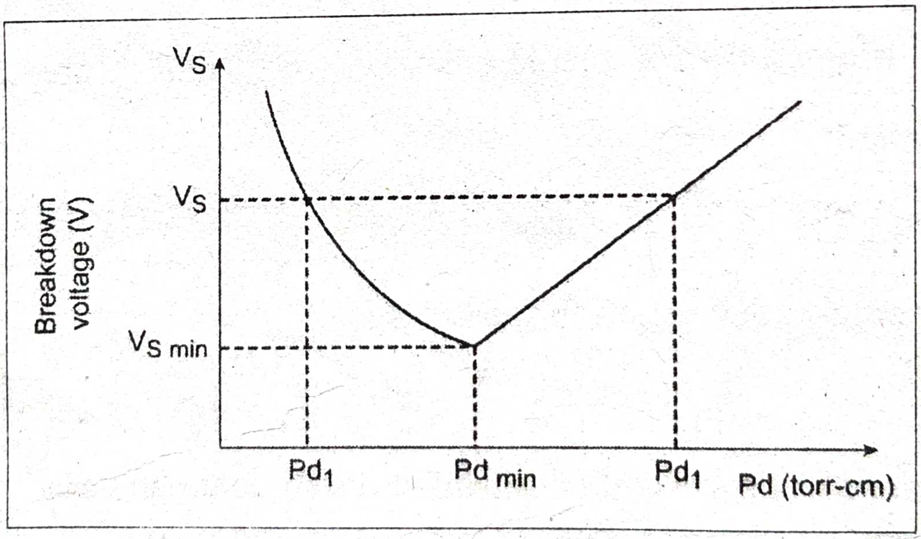


Fig. 2.6. Paschen's curve

Paschen's curve shows that the V_S value decreases initially as *Pd* increases and reaches minimum value at $V_{S\,min}$ and then increases linearly.

To account the effect of temperature, Paschen's law becomes

$$V = f(N\,d) \qquad \ldots (2.22)$$

where, N = Density of air molecules.

From gas law pv = NRT

$$\Rightarrow N = \frac{pv}{RT} \qquad \ldots (2.23)$$

where, v = Volume of the gas.

R = Constant.

T = Temperature.

From experimental results,

$$\text{Breakdown potential, } V = 24.33\left[\frac{293\,pd}{760\,T}\right] + 6.08\left[\frac{293\,pd}{760\,T}\right]^{\frac{1}{2}} \qquad \ldots (2.24)$$

At 760 torr pressure and 293 K temperature,

$$V = 24.33\left[\frac{293 \times 760\,d}{760 \times 293}\right] + 6.08\left[\frac{293 \times 760\,d}{760 \times 293}\right]^{\frac{1}{2}}$$

$$E = \frac{V}{d} = 24.33 + \frac{6.08}{\sqrt{d}} \text{ kV/cm} \qquad \ldots (2.25)$$

Value of E = 24 kV/cm for long gap.

Value of E = 30 kV/cm for air at room temperature and at atmospheric pressure

2.5. BREAKDOWN IN NON-UNIFORM FIELDS AND CORONA DISCHARGES

2.5.1. Corona Discharges

The phenomenon of faint violet glow, hissing noise and ozone gas produced in the transmission lines during rainy seasons is called as corona.

If the field is uniform, voltage across the gap increases and ionization process takes place and breakdown of gap in the form of a spark occurs.

Example: Sphere gap at different gap spacing.

If the field is non-uniform, voltage across the gap increases and causes a discharge in the gap at sharp points where the electrode is curved is known as corona discharge.

Corona influences,

- Power loss in high voltage transmission.
- Deterioration of insulation due to bombardment of ions or chemical action.
- Radio interference.

2.5.1.1. Corona Inception Field

The voltage gradient required to produce visual a.c. corona in air at a conductor surface.

Let 'r' be the radius of wire.

Let δ be the density correction factor.

$$\delta = \frac{0.392\, b}{273 + t} \quad \text{... (2.26)}$$

where, b = Atmospheric pressure in torr.

t = Temperature in °C.

Electric field intensity (for two parallel wires)

$$E = 30\, m\, \delta \left[1 + \frac{0.301}{\sqrt{r\, \delta}} \right] \text{ kV/cm} \quad \text{... (2.27)}$$

Electric field intensity for coaxial wires,

$$E_C = 31\, m\, \delta \left[1 + \frac{0.308}{\sqrt{\delta\, r}} \right] \text{ kV/cm} \quad \text{... (2.28)}$$

where, m = Surface irregularity factor.

m = 1 for polished smooth wires.

In high voltage transmission lines, appearance of corona differs when positive and negative polarities of applied voltage. When positive polarities are applied, corona appears as bluish white sheath over the entire surface of the line. When negative polarities are applied, corona appears as reddish glowing spots distributed along the lines.

2.5.1.2. Negative Point-Plane Corona

When point is negative, the corona current flows in very irregular pulses called as Trichel pulses, whose repetition frequency increases with current. This frequency is independent of the gap length but increases with the point sharpness. For studying corona, the point-plane gap with the point is connected to high voltage source. The plate is connected to earth through resistance and voltage drop can be measured using CRO. A decrease in pressure, decreases the frequency of the Trichel pulses.

Formation of Negative Corona

A random positive ion impact at the cathode and an electron is produced. The electrons collide with neutral particle and produces a positive ion (photon) and an electron. The photons collide with cathode and produces new avalanches. This process repeats and the current increases due to ionization. The positive ions liberated may have sufficient energy to cause liberation of electrons when impinge on the cathode and increases the field strength. The last few ions are being driven into the point, the field strength again increases to accelerate one of them to trigger an electron and this process repeats. Thus negative corona is formed.

The voltage of different negative coronas as a function of gap length is as shown in Fig.2.7.

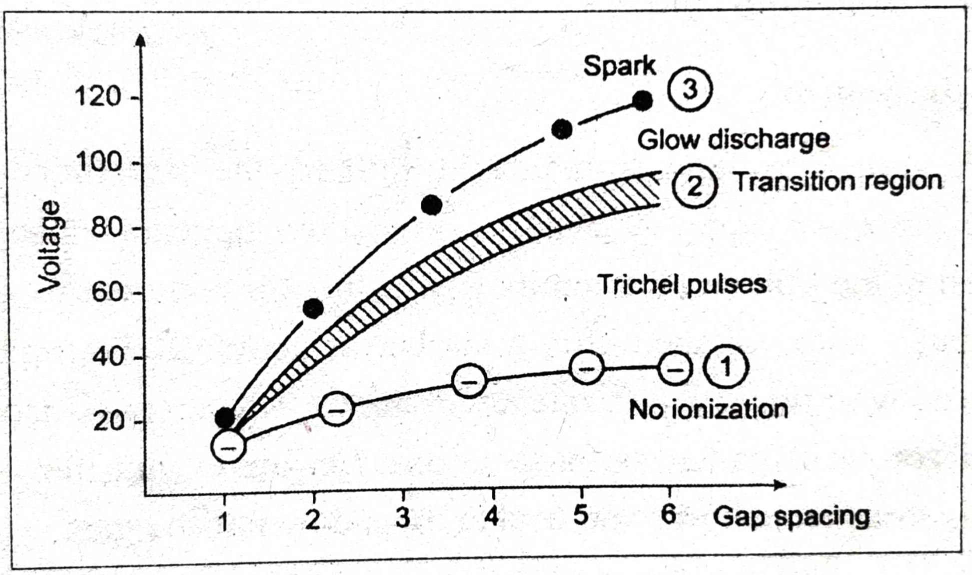


Fig. 2.7. Negative corona's in rod-plane breakdown for different gap length

Below the curve (1), no ionization takes place. Between curve (1) & (2) ionization takes place and trichel pulses are formed but no corona formed. When applied voltage is increased further, transition region occurs. At the end of this region, corona discharge can be seen upto breakdown occurs. At curve (3) breakdown occurs and spark is formed.

Breakdown under negative polarity needs higher voltage than that under positive polarity. Therefore, breakdown of non-uniform field gap occurs during the positive half cycle of the voltage wave.

2.5.1.3. Positive Plane Corona

When point is positive, a large portion of the work is concerned with the study of the nature of streamers. They are common to the mechanism of positive point corona and breakdown mechanism in non-uniform fields.

Formation of Streamer

When a positive voltage pulse is applied to a point electrode, a filamentary branch is formed by ionization. This discharge is called as streamer. As the impulse voltage is increased, the streamer grows into number of branches, but does not cross each other as shown in Fig.2.8.

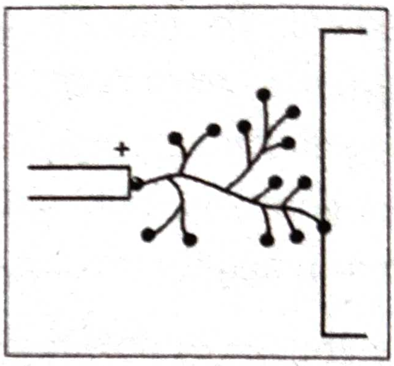


Fig. 2.8. Streamer due to positive voltage pulse

Breakdown Mechanism

When the applied voltage is increased further, the streamers become more frequent upto transient state. A steady corona flow appears close to the anode. Again increasing the voltage, the luminosity of the glow increases. Corona current increases steadily with voltage. After a current of about 10^{-7} Ampere, the current becomes pulsed with repetition frequency of about 1 kHz, consists of small bursts. This form of corona is called as burst corona. On increasing the voltage further, more rigorous streamers appear and lead to breakdown of the gap.

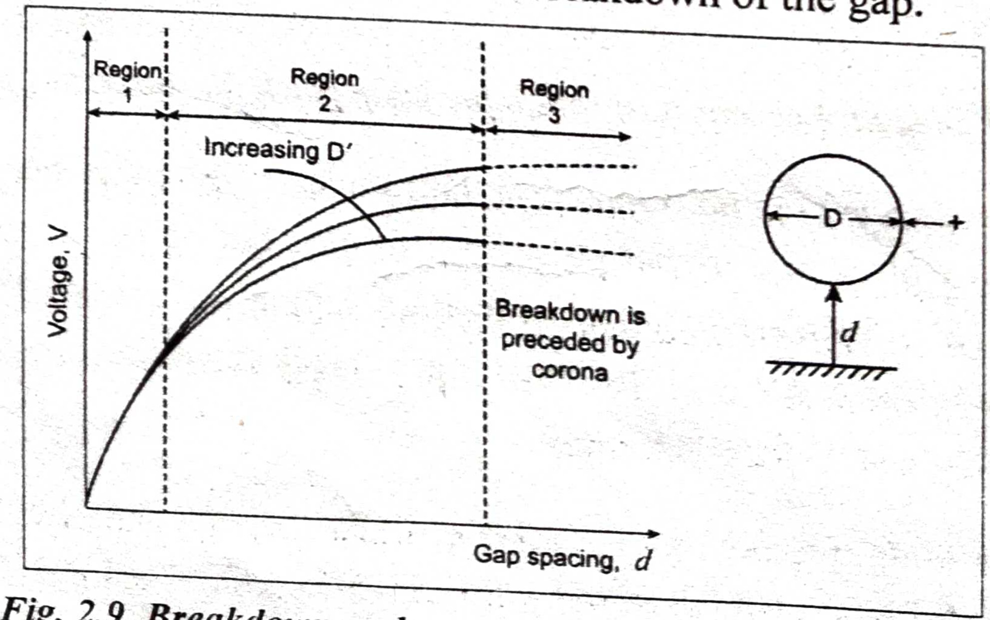


Fig. 2.9. Breakdown and corona inception characteristics for sphere-plane gap at different gap spacing

Breakdown and corona inception characteristics for sphere-plane gap at different gap spacing is as shown in Fig.2.9.

From the above figure, the following observations are noted.

Region	**Spacing**	**Field**	**Dependence of Breakdown voltage**
Region 1	Small	Uniform	Depends on gap spacing
Region 2	Fairly large	Non-uniform	Depends on gap spacing and sphere diameter
Region 3	Large	Non-uniform	Depends on sphere diameter and gap spacing. Breakdown is preceded by corona.

2.5.2. Breakdown in Non-Uniform Fields

In non-uniform fields, such as coaxial cylinders, point-plane and sphere plane gaps, the applied field varies across the gap.

Similarly, Townsend's first ionization coefficient (α) also varies with the gap. Hence, αd in Townsend's criterion is written by replacing αd by $\int_0^d \alpha\, dx$.

Townsend's criterion is, $\gamma \left(\exp(\alpha d) - 1\right\} = 1$

The new criterion for breakdown is,

$$\gamma\left\{\exp\left(\int_0^d \alpha\, dx\right) - 1\right\} = 1 \qquad \dots (2.29)$$

Meek and Raether also discussed the non-uniform field breakdown process as applied to the streamer theory, and the Meek's equation for the radial field at the head of an avalanche when it has crossed a distance x is modified as, From the curves it can be seen that the breakdown voltages are higher for negative polarity. The breakdown voltages depend on humidity in air.

In case of rod gaps the field is non-uniform, while in the case of sphere gaps field is uniform, if the gap is small compared with diameter.

In case of sphere gaps, the breakdown voltages do not depend on humidity and also independent of the voltage waveform. The formative time lag is quite small (~ 0.5 μs) even with 5% over voltage.

Hence sphere gaps are used for breakdown voltage (peak value) measurements.

2.6. VACUUM BREAKDOWN

Properties of Perfect Vacuum

The properties of perfect vacuum should be

- no conduction.
- act as a perfect insulating medium.

Classification of Vacuum

The vacuum may be classified as:

High vacuum = 1×10^{-3} to 1×10^{-6} torr
Very high vacuum = 1×10^{-6} to 1×10^{-8} torr
Ultra high vacuum = 1×10^{-8} torr and below
1 standard atmosphere = 760 millimeters of mercury at 0° temperature
1 torr = 1 mm of mercury

Applications of Vacuum Insulators

The applications of vacuum insulators in devices are:

- Interrupters and contactors.
- High frequency capacitors.
- Relays and circuit breakers.
- Electrostatic generators.
- Microwave tubes.

Uses of Vacuum Insulators

Vacuum insulators are used in:

- Particle accelerators.
- X-ray tubes.
- Field emission tubes.
- Electron microscopes.
- Capacitors.
- Circuit breakers.

Breakdown Process

When the electrodes are separated by a distance in a high vacuum, an electron crosses the gap without encountering any collisions. Therefore, growth of current before breakdown cannot be due to the formation of electron avalanches. But a gas is liberated in vacuum and breakdown occurs due to Townsend phenomenon.

Classification of Breakdown Mechanism in Vacuum

Vacuum breakdown mechanism may be divided into:

- Particle exchange mechanism.
- Field emission.
- Clump mechanism.

2.6.1. Particle Exchange Mechanism

A charged particle is emitted from one electrode (cathode) when high electric field is applied. This charged particle impinges on the other electrode (anode), it liberates oppositely charged particles due to ionization of absorbed gases. These particles accelerate and impinge on the first electrode when voltage is applied and produces more number of original type of particles. A chain reaction takes place when this process repeats and leads to breakdown of gases.

Assuming an electron emitted from cathode is accelerated towards the anode and releases positive ions (A) and photons (C). These positive ions and photons are accelerated towards the cathode and produce electrons (B) due to positive ion, electrons (D) due to photons. The breakdown process is as shown in Fig.2.13.

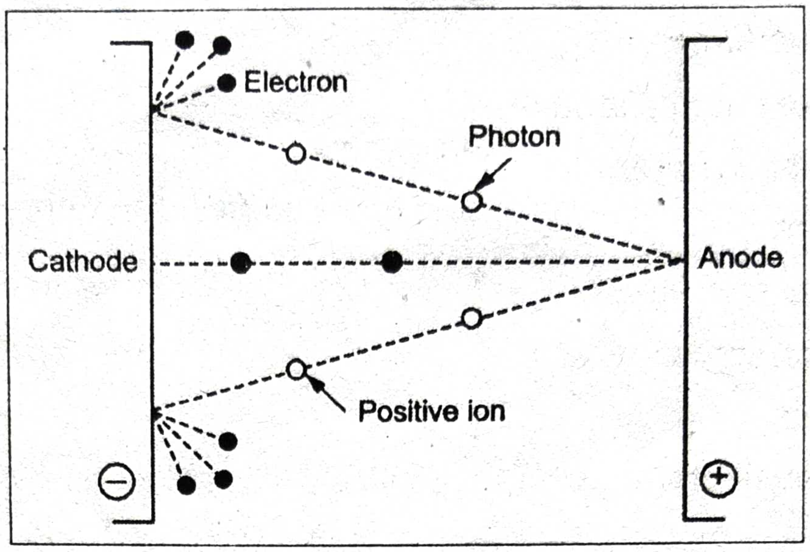


Fig. 2.13. Particle exchange mechanism of vacuum breakdown

Condition for breakdown: (AB + CD) > 1

where, A = Number of positive ions produced due to the accelerated electrons.

C = Number of photons produced due to accelerated electrons.

B = Number of electrons produced due to the accelerated positive ions.

D = Number of electrons produced due to the photons

This theory was modified by Trump and Vande-Graff because the constants A, B, C, D values are too small.

Criterion for breakdown becomes,

$$(AB + EF) > 1$$

where, A = Number of positive ions produced due to the accelerated electrons.

B = Number of electrons produced due to the accelerated positive ions.

E = Number of electrons liberated by positive ions.

F = Number of electrons liberated by photons.

2.6.2. Field Emission Theory

When the gap voltage increases and nearer to the breakdown voltage, sharp points on the cathode surface are responsible for the existence of the pre-breakdown current. This process is called as field emission process. There are two mechanisms.

(a) Anode Heating Mechanism

Small projections on the cathode produce electrons due to field emission mechanism. These electrons accelerate and bombard the anode and increases temperature and releases gases in the gap. These electrons ionize the atoms of the gas and produce positive ions. These positive ions accelerate toward cathode and increases the number of electrons emitted due to space change formation. This process continues until breakdown of vacuum occurs as in Townsend breakdown. This mechanism is explained in Fig.2.14.

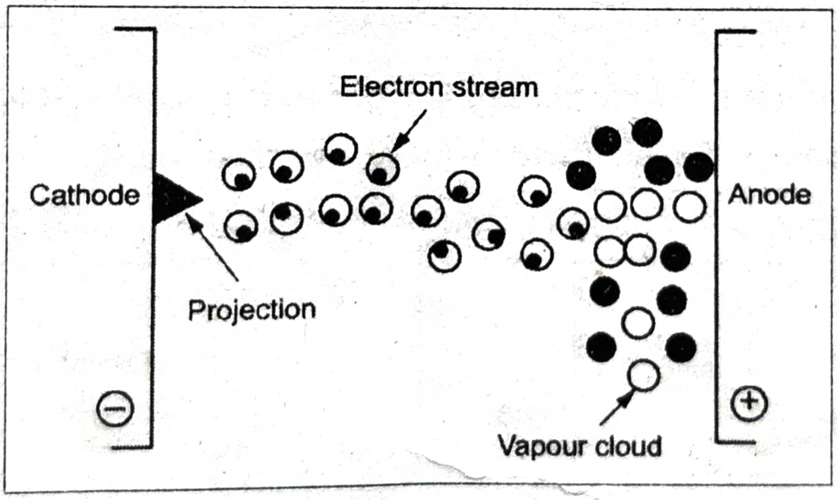


Fig. 2.14. Anode heating mechanism

(b) Cathode Heating Mechanism

The pre breakdown current causes resistive heating at the projections in the cathode. The tip melts due to heating and explodes and initiates vacuum discharge. This is called as cathode heating mechanism. The initiation of breakdown depends on the conditions and properties of cathode surface. The cathode heating mechanisms is as shown in Fig.2.15.

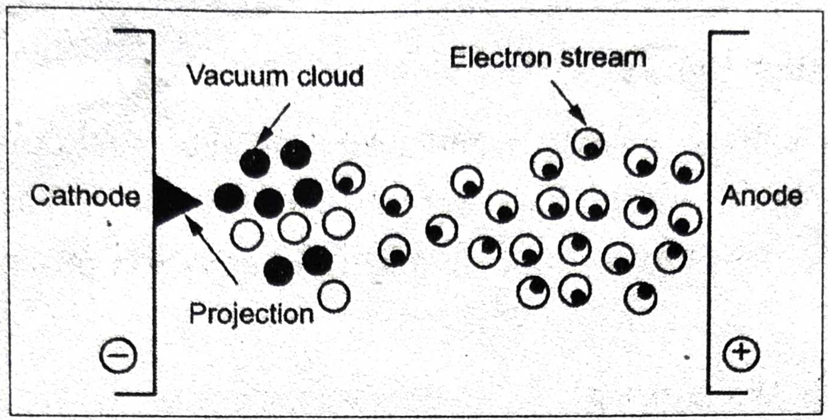


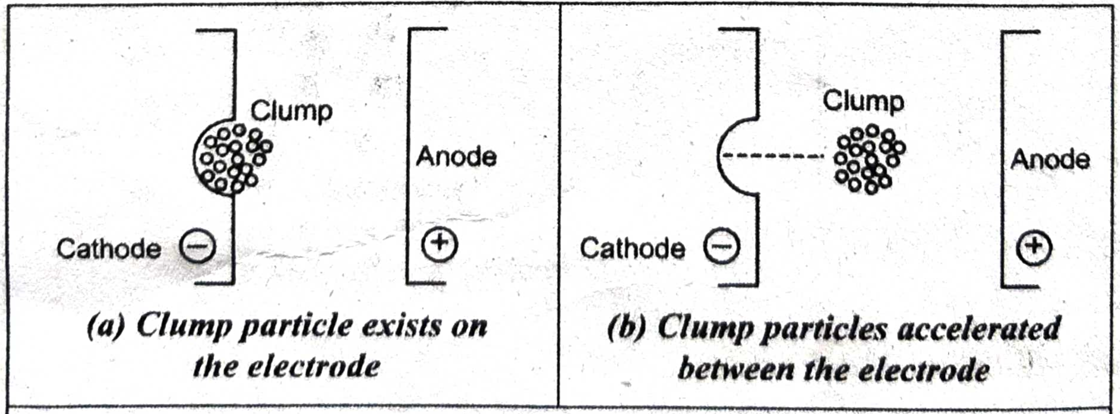
Fig. 2.15. Cathode heating mechanism

2.6.3. Clump Mechanism

The assumptions on the clump mechanisms are:

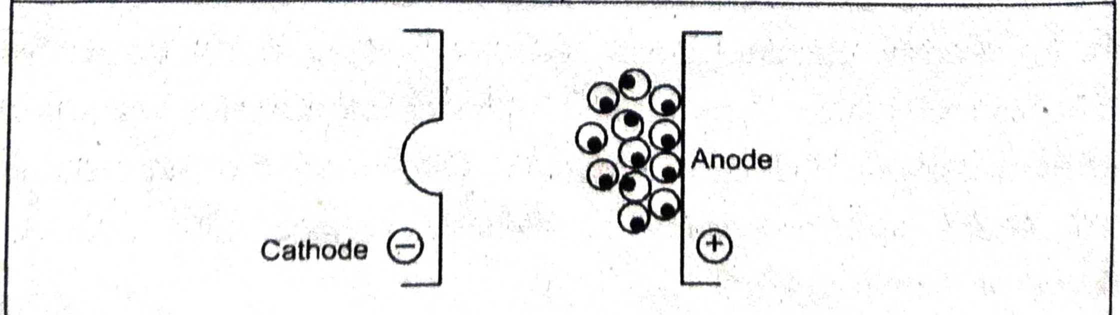
- A clump particle (loosely bound) exists on one of the electrode.
- Clump particle gets charged, accelerated in the gap when high voltage is applied.
- This particle reaches the other electrode and discharges vapour and breakdown occurs.
- Breakdown occurs when the energy per unit area W exceeds a constant C′ which depends on the characteristics of two electrodes.

Clump mechanism is explained as shown in Fig.2.16.



(a) Clump particle exists on the electrode

(b) Clump particles accelerated between the electrode



(c) Formation of vapour

Fig. 2.16. Clump mechanism

$$\therefore W = \text{Gap voltage} \times \text{Charge density}$$

$$\text{Charge density} \propto E \text{ (electric field at the electrode)}$$

$$\therefore W = V \times E = C' \quad \ldots (2.31)$$

This is the criterion for breakdown.

For parallel plane electrodes, $$E = \frac{V}{d} \quad \ldots (2.32)$$

where, d = Distance between the electrodes.

Substituting equation (2.32) in equation (2.31), we get

$$V \times \frac{V}{d} = C'$$

$$V^2 = C' d$$

$$V = \sqrt{C' d} \quad \ldots (2.33)$$

This is the generalized criterion for breakdown.

2.7. CONDUCTION AND BREAKDOWN IN LIQUID DIELECTRICS

Liquid dielectrics are more useful than solid and gaseous dielectrics.

Uses of Liquid Dielectrics

Liquid dielectrics are used in:

- high voltage cables.
- high voltage capacitors.
- transformers.
- circuit breakers.

Commonly used Liquid Dielectrics

The commonly used liquid dielectric is:

- Petroleum oil (transformer oil).

Other Liquid Dielectrics

The liquid dielectrics are:

- Synthetic hydrocarbons.
- Halogenated hydrocarbons.
- Silicone oils.
- Fluorinated Hydrocarbons.
- Esters.

Characteristics of Liquid Dielectric

It should possess:

- Good dielectric.
- Excellent heat transfer characteristics.
- Chemical stability.

2.7.1. Electrical Properties to Determine Dielectric Performance

The electrical properties of liquid dielectrics are:

- Capacitance per unit volume or its relative permittivity.
- Resistivity.
- Loss tangent (tan δ) or power factor.
- Ability to withstand high electric stresses.

Permittivity

For non-polar liquids – Permittivity is independent of frequency.

For polar liquids (water) – Permittivity changes with frequency.

Resistivity

In high voltage applications, resistivity of liquid dielectric should be more than 10^{16} Ω-m.

Example: Pure liquid.

Power Factor

Power factor is a measure of power loss. In transformer, dielectric loss is negligible, because power factor is high. In cable and capacitor, power factor is high and the efficiency increases.

Dielectric Strength

Dielectric strength varies with the atomic and molecular properties of the liquid. In practical case, dielectric strength depends on:

- Material of the electrodes.
- Temperature.
- Type of voltage applied.
- Gas content present in the liquid.

2.7.2. Conduction and breakdown in Pure Liquids

Pure liquids are chemically pure and do not contain any other impurities even in traces of 1 in 10^9, and has simple structure.

Examples: *n*-Hexane, *n*-Heptane, Other Paraffin hydrocarbons

When low electric field < 1 kV/cm, conductivities of 10^{-18} to 10^{-20} mho/cm are obtained. Probably, these are due to the impurities present after purification.

When electric fields > 100 kV/cm, currents increases rapidly and violent fluctuations occur. The fluctuations reduces and die out after some time. This is the condition for breakdown of pure liquids.

Conduction current versus electric field characteristics in hexane at high fields is as shown in Fig.2.17.

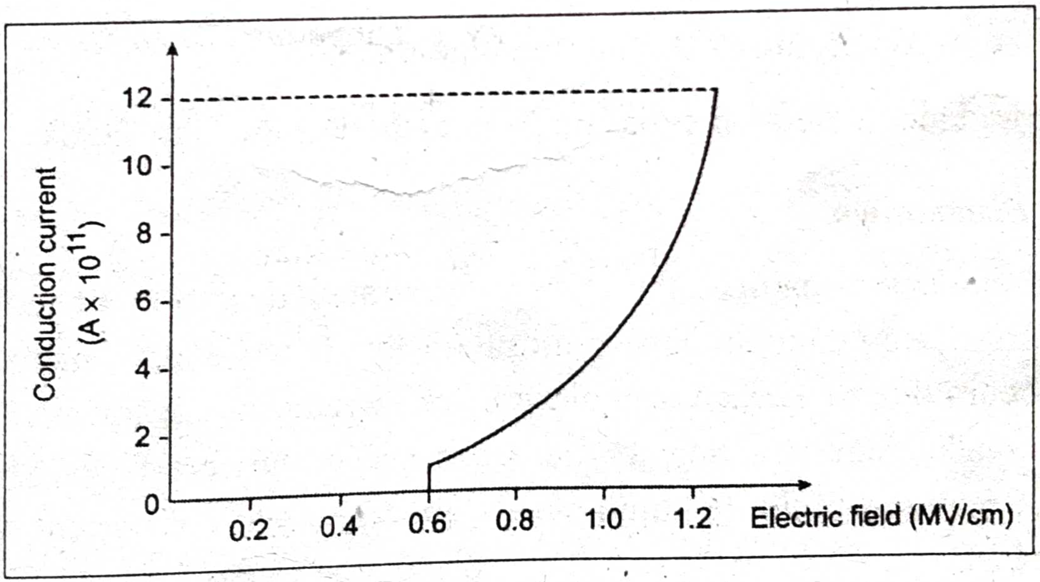


Fig. 2.17. Conduction current Vs Electric field in hexane

Conduction current Vs Electric field in a hydrocarbon liquid is as shown in Fig.2.18.

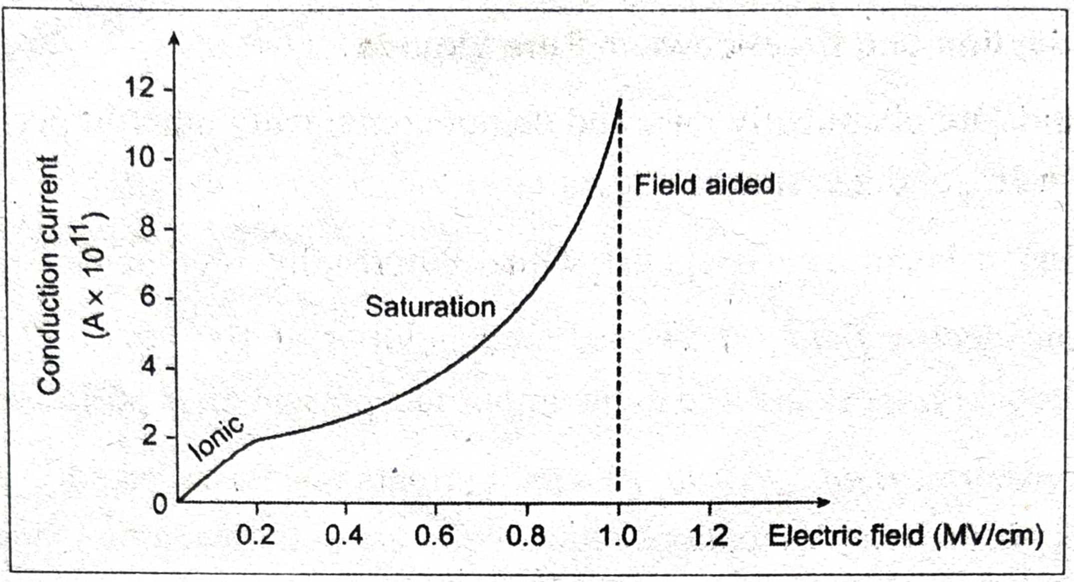


Fig. 2.18. Conduction current Vs Electric field in hydrocarbon

The graph has three regions. They are:

- Ionic region – At low fields.
- Saturation region – At intermediate fields
- Field aided electron emission from cathode – At high fields.

Electronic Breakdown

At high fields are applied, the current generated due to field aided electron emission from the cathode gets multiplied by Townsend's mechanism. The emission occurs due to surface irregularities or interfaces of impurities and liquid. The current also generates due to the electrons at the interfaces of liquid and impurities. Breakdown of pure liquid occurs due to increase of current by repetition of this process.

Breakdown Mechanism

The electrons are generated from the cathode by field emission of electrons. These electrons are injected into the liquid, it gains energy from the applied field. Some electrons get more energy from the field and collides with neutral molecules and produces positive ions and electrons. These positive ions reaching the cathode generate secondary electrons. So, avalanche is formed. This will lead to breakdown. This process is similar to Townsend's ionization process.

Condition for the formation of electron avalanche is,

$$e E \lambda = C h \nu \quad \dots (2.34)$$

where, E = Applied field.
λ = electron mean free path (average distance between collisions)
$h\nu$ = Quantum of energy lost in ionization of electrons
C = Constant

Breakdown voltage depends on:

- Field gap separation.
- Cathode work-function.
- Temperature of the cathode.
- Viscosity of liquid.
- Liquid temperature.
- Density of liquid.
- Molecular structure of the liquid.
- Hydrostatic pressure.

2.7.3. Conduction and Breakdown in Commercial Liquids

Commercial liquids are insulating liquids like oils which are not chemically pure, consists of mixtures of complex organic molecules and impurities like gas bubbles, suspended particles, *etc.*

Breakdown mechanism in commercial liquid depends on:

- Nature and condition of the electrodes.
- Physical properties of liquids.
- Impurities present in the liquids.
- Gases present in the liquid.

Breakdown mechanism in commercial liquids may be classified as:

- Suspended particle mechanism.
- Cavitation and bubble mechanism.
- Stressed oil volume mechanism.

2.7.3.1. Suspended Particle Mechanism

Consider spherical particles of radius 'r' of permittivity ε_2 to be suspended in a dielectric of permittivity ε_1. The particles will become polarized when electric field E is applied. Then the particles experience a force F,

$$F = \frac{1}{2r^3}\left(\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}\right) \text{grad } E^2 \qquad \ldots (2.35)$$

In commercial liquids, solid impurities like fibre, paper or dispersed solid particles are present.

If $\varepsilon_2 > \varepsilon_1$, Force F is directed the impurities towards the area of maximum stress.

If $\varepsilon_2 < \varepsilon_1$, Force F is directed the impurities towards the area of lower stress when gas bubbles are present.

Breakdown Mechanism

When electric fields is applied, the particles become aligned head-to-tail to form a bridge across the gap and breakdown occurs between the electrodes. The movement of particles due to electric field is opposed by the viscous drag and by diffusion.

If single conducting particle present between the electrodes, local field enhancement takes place.

If Applied field > Breakdown strength of liquid,

- Local breakdown occurs.
- Gas bubbles are formed.
- Gas bubbles lead to breakdown of liquid.
- Breakdown strength of liquid with solid impurities < Breakdown strength of pure liquids.

2.7.3.2. Cavitation and Bubble Mechanism

Formation of vapour bubbles occur due to the following:

- Gas pockets on the surface of the electrodes.
- Changes in temperature and pressure.

- Dissociation of products by electron collisions giving rise to gaseous products.
- Liquid vapourization by corona-type discharges from points and irregularities on the electrodes.

Breakdown Mechanism

When a gas bubble is formed, it will elongate in the direction of electric field. The volume of the elongated bubble remains constant.

Breakdown occurs when,

$$\left.\begin{array}{r}\text{Voltage drop along the}\\ \text{length fo the bubble}\end{array}\right\} = \left\{\begin{array}{l}\text{Minimum value of Paschen's}\\ \text{curve i.e., } (Pd)_{min} \text{ corresponding to } (V_S)_{min}\end{array}\right.$$

The breakdown strength depends on:

- Initial size of the bubble.
- Hydrostatic pressure.
- Temperature.

Electric field in a gas bubble immersed in a liquid of permittivity ε_1 is given by,

$$E_{gas\ bubble} = \frac{3\,E_0}{\varepsilon_1 + 2} \qquad \ldots (2.36)$$

$$\left.\begin{array}{r}\text{Breakdown}\\ \text{field}\end{array}\right\} E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma\,(2\varepsilon_1 + \varepsilon_2)}{r}\left(\frac{\pi}{4}\sqrt{\frac{V_b}{2rE_0}} - 1\right)\right]^{\frac{1}{2}} \qquad \ldots (2.37)$$

where, σ = Surface tension of liquid.

ε_1 = Permittivity of liquid.

ε_2 = Permittivity of gas bubble.

V_b = Voltage drop in the bubble (or) $(V_S)_{min}$ in Paschen's curve.

Thermal Mechanism of Breakdown

High current pulses are produced at the cathode surfaces when microscopic projections are present in the cathode. The high density current pulses leads to local heating of oil. This will lead to the formation of vapour bubble. These vapour bubble elongates between the electrodes and bridges the gap between the electrodes and gives rise to spark.

Breakdown strength depends on:

- Pressure.
- Temperature.
- Molecular structure of the liquid.

2.7.3.3. Stressed Oil Volume Mechanism

In commercial liquids, minute particles of impurities present. The impurities reduce the breakdown strength of oil and weakens the oil region. *i.e.*, the region is stressed to the maximum and by the volume of oil in that region. According to stressed oil volume theory, the breakdown strength is inversely proportional to the stressed oil volume.

Breakdown voltage depends on:

- Gas content in the oil.
- Viscosity of the oil.
- Impurities present in the oil.

The variation of breakdown stress with the stressed oil volume is as shown in Fig.2.19.

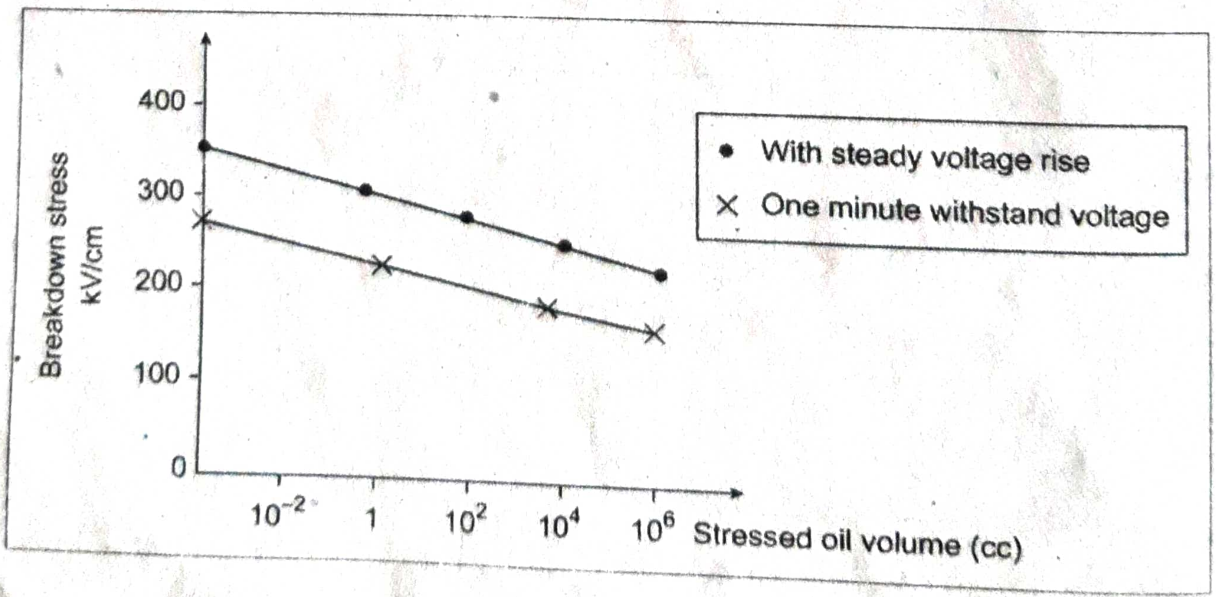


Fig. 2.19. Breakdown stress Vs stressed oil volume

2.7.4. Maintenance of Oil Quality

Transformer oil is a mineral oil. Oil acts as good insulating medium and a cooling agent. It allows transfer and absorption of water, air and residues created by the ageing of the solid insulation. So, oil is to be maintained to attain high degree of purity.

The impurities in liquid dielectrics are dust, moisture, dissolved gases and ionic impurities. These will decrease the dielectric strength of oil.

Example: Oil with water accelerates the process of ageing and reduce insulation quality. Air dissolved in oil produces bubble and reduces dielectric strength of oil.

Oxidization means acid in the oil when it comes in contact with oxygen. This acid will form sludge and settles on the windings of transformer and produces heat. This acid content and increased heat reduces dielectric strength of oil.

Air Absorption

The process of air absorption can be compared to a diffusing phenomenon in which a gaseous substance is in contact with oil.

When the viscosity of liquid is low, due to convection, a uniform concentration is achieved (*i.e.,*) air or water content of top and bottom of tank is same.

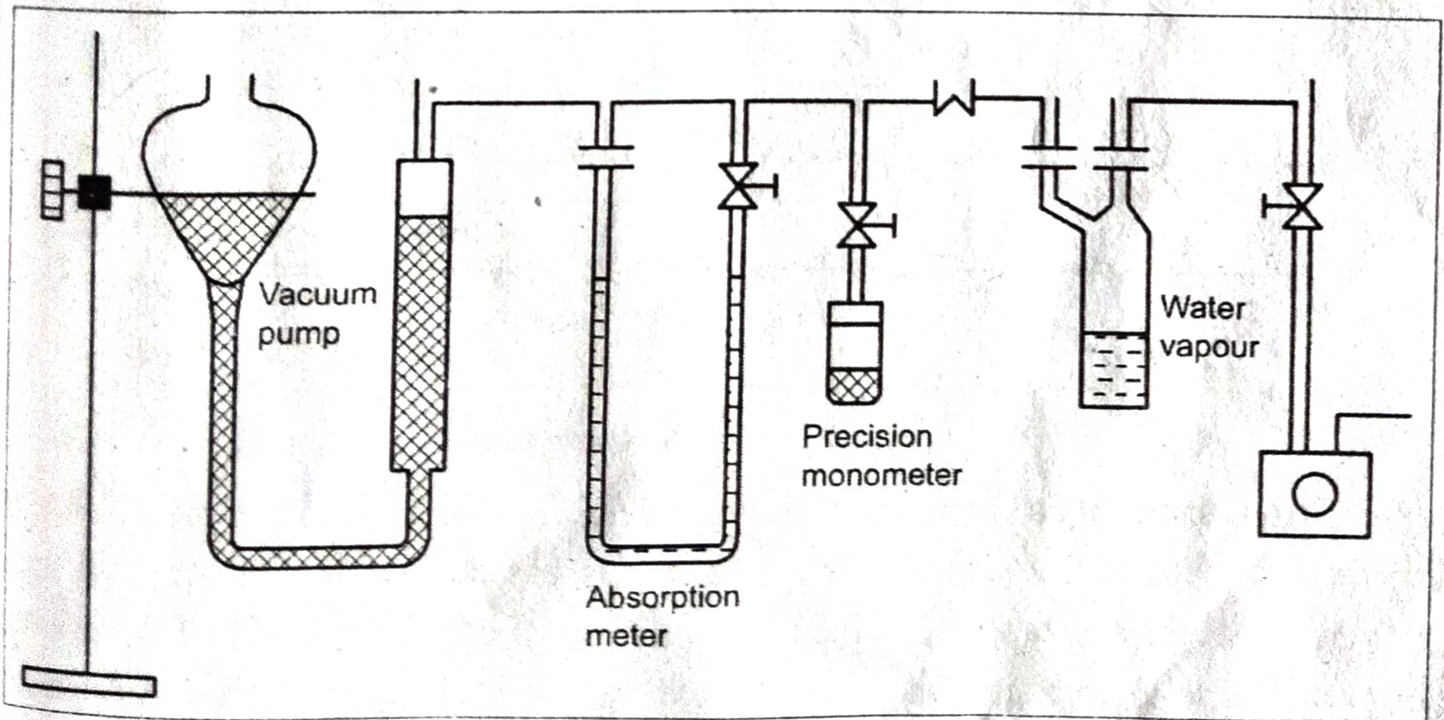


Fig. 2.20. Measurement of oil absorption

Air absorption is measured as shown in Fig.2.20. The oil is degassed and dried in the vacuum pump. A part of air is absorbed by oil and reduce the volume in absorption meter to maintain constant pressure. Now air content of oil by volume is measured. Precision manometer is used to calibrate absorption meter. Phosphorus pentoxide trap removes the remaining water vapour.

Filtration and Treatment under Vacuum

Filter press with soft and hard filter paper is used for insulating oil. Oil is predried before filtering to remove water. So, this oil cannot be used for high voltage insulation. Again, the oil is dried under vacuum. Then oil is distributed over a large surface (Rasching-Ring) is for degassing.

Transformer oil purity can be achieved by selection of the rate of flow of oil, degassing, vacuum pump, *etc.*

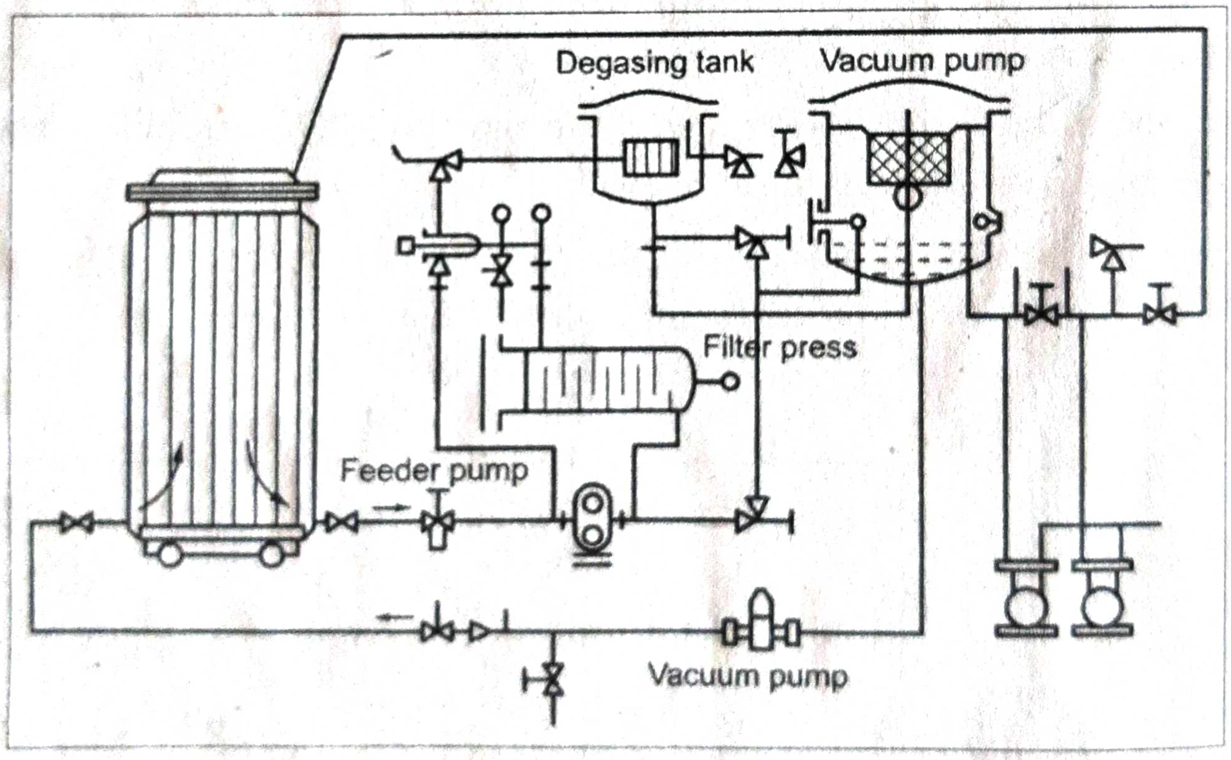


Fig. 2.21. Oil treatment plant

Oil treatment plant is as shown in Fig.2.21. Oil from ***storage tank*** is prefiltered. The oil is heated in the tank and is passed into filter press and then flows into degassing tank. The dielectric strength of oil reduces with the presence of water. The degasifier tank is evacuated by using vacuum pump. In vacuum pump, the oil is dried under vacuum. This filtration process should be done at suitable temperature.

Centrifugal Method

To extract solid impurities and water by this method, the centrifugal device is kept in a tank under vacuum to remove impurities.

Electrostatic Filters

The oil is passed between two electrodes which are placed in a container. The electrostatic field is applied between the electrodes. This electrostatic field charges the impurities and traces of water and attracted by the electrodes. If the water content is less than 2 ppm, this method of filtration is economical. The oil flow is slow if efficient filtering is required. In industries, large volume of oil to be filtered, so number of filers are connected in parallel which is uneconomical.

2.8. BREAKDOWN IN SOLID DIELECTRICS

Solid dielectrics are mostly used in all electrical apparatus for the purpose of electrical isolation.

2.8.1. Properties of Solid Dielectrics

Solid dielectrics should have the following properties.

- Low dielectric loss.
- Free from gaseous particles and moisture.
- High mechanical strength.
- Resistant to thermal and chemical deterioration.
- High breakdown strength than liquid and solid breakdown strength.

Materials used for Solid Dielectrics

The materials used are:

- Organic materials
  - Paper
  - Wood
  - Rubber
- Inorganic materials
  - Perspex
  - PVC
  - Epoxy resin, *etc.*

2.8.2. Classification of Breakdown Mechanism in Solid Dielectric

The breakdown mechanism in solid dielectrics are classified as:

- Intrinsic or ionic breakdown.
- Electromechanical breakdown.
- Thermal breakdown.
- Electrochemical breakdown.
- Failure due to treeing and tracking.
- Breakdown due to internal discharges.

The mechanism of failure of a solid dielectric changes as the time of voltage application increases as shown in Fig.2.22.

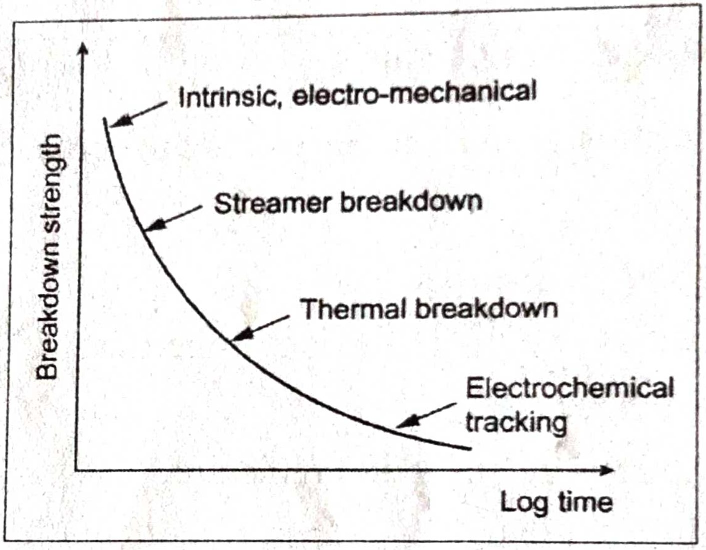


Fig. 2.22. Variation of breakdown strength with log time

2.8.2.1. Intrinsic Breakdown (or) Ionic Breakdown

When voltages are applied for very short time of the order of 10^{-8} sec, the electric strength of a solid material increases rapidly to an upper limit. This is called as Intrinsic electric strength.

Dielectric strength of solid dielectric increases when the extraneous influences (structural imperfections and impurities) are isolate. This dielectric strength depends on:

- Structure of the material.
- Temperature.

Maximum dielectric strength = 5 MV/cm to 10 MV/cm

Breakdown Mechanism

Free electrons present in the solid dielectric are capable of migration in the lattice of the dielectric. These electron conduction takes place due to structural imperfections and impurities present in the solid dielectric. Due to the applied electric field and temperature, these impurities act as conduction electrons. When increase of electric field, more electrons are released and conduction takes place *i.e.*, breakdown occurs.

There are two types of intrinsic breakdown.

- Electronic breakdown.
- Avalanche or streamer breakdown.

Electronic Breakdown

When electric field is applied across the solid dielectric, the density of free electrons is more and collision occurs between electrons. These electrons gain energy from the electric field and cross the forbidden energy gap from the valency band to the conduction band. This process is repeated, more electrons are produced and breakdown of dielectric occurs due to the conduction of electrons.

Avalanche or Streamer Breakdown

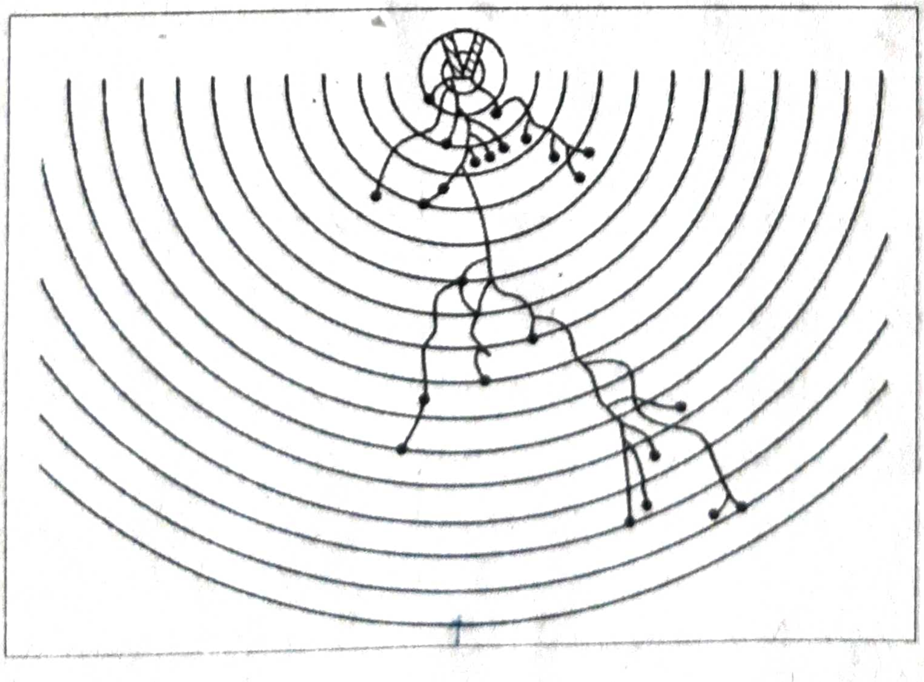


Fig. 2.23. Streamer breakdown

When electric field is applied, an electron in the dielectric moves from the cathode to the anode and gains energy from the field and loses energy during collision with other electrons. Due to collision, additional electrons will be produced. This process repeats and electron avalanche is formed and this avalanche bridges the gap and breakdown of dielectric occurs.

Breakdown occurs due to many avalanches and leads to streamer as shown in Fig.2.23.

2.8.2.2. Electromechanical Breakdown

When high electric field is applied across the solid dielectric, deformation occurs when the electrostatic compressive forces exceed its mechanical compressive strength. The compressive forces arise due to attraction between surface charges.

Let d_0 be the thickness of the specimen.

Let d be the compressed thickness when electric field is applied.

Let Y be the Young's modulus.

Let ε_0 be the permittivity of free space.

Let ε_r be the relative permittivity.

Let V be the applied voltage.

The electrically developed compressive stress is in equilibrium if,

$$\varepsilon_0 \, \varepsilon_r \, \frac{V^2}{2\,d^2} = Y \, ln\left[\frac{d_0}{d}\right] \qquad \dots (2.38)$$

$$V^2 = \frac{2\,Y}{\varepsilon_0 \, \varepsilon_r} \cdot d^2 \; ln\left[\frac{d_0}{d}\right] \qquad \dots (2.39)$$

To determine maximum electric strength,

Differentiating equation (2.39) with respect to d, we get

$$0 = \frac{2Y}{\varepsilon_0 \, \varepsilon_r}\left[ln\left[\frac{d_0}{d}\right] \cdot 2\,d + d^2 \cdot \frac{1}{\left(\frac{d_0}{d}\right)} \left(\frac{-d_0}{d^2}\right) \right]$$

$$2\,d \; ln\left[\frac{d_0}{d}\right] = d^2 \times \frac{d}{d_0}\left(\frac{+d_0}{d^2}\right)$$

$$ln\left[\frac{d_0}{d}\right] = \frac{1}{2} \qquad \dots (2.40)$$

Taking exponential on both sides, we get

$$\frac{d_0}{d} = e^{\frac{1}{2}} = 1.649, \quad \text{(or)} \quad \frac{d}{d_0} = 0.6 \qquad \dots (2.41)$$

Substituting $V = V_{max}$ and $\frac{d}{d_0} = 0.6$ in equation (2.39), we get

$$V_{max}^2 = \frac{2\,Y}{\varepsilon_0\,\varepsilon_r} d^2 \ln 0.6$$

$$V_{max}^2 = \frac{2\,Y}{\varepsilon_0\,\varepsilon_r} d^2 \times 0.5 = \frac{2\,Y}{\varepsilon_0\,\varepsilon_r} \times \frac{d^2}{d_0^2} \times d_0^2 \times 0.5$$

$$V_{max}^2 = \frac{Y}{\varepsilon_0\,\varepsilon_r} d_0^2 \times 0.6^2$$

$$V_{max} = 0.6 \times d_0 \times \sqrt{\frac{Y}{\varepsilon_0\,\varepsilon_r}}$$

$$\frac{V_{max}}{d_0} = 0.6 \sqrt{\frac{Y}{\varepsilon_0\,\varepsilon_r}} = E_{max} \qquad \dots (2.42)$$

- Value of Y depends on mechanical stress, therefore equation (2.42) is approximate.
- Instability occurs in lower average field due to stress concentration at irregularities.
- Cracks propagate through dielectric material releases electrostatic energy and electromechanical energy when field is applied.

2.8.2.3. Thermal Breakdown

When a field is applied to a solid dielectric at room temperature, a small conduction current flows and its value increases and heats up the dielectric and the lattice temperature increases. The heat generated by the current is conducted to the surrounding and is absorbed to increase lattice temperature.

Condition for instability or thermal breakdown,

Heat generation > Heat conduction

$$\therefore \left.\begin{matrix}\text{Heat input to}\\ \text{the element}\end{matrix}\right\} = \left\{\begin{matrix}\text{Heat}\\ \text{conducted}\end{matrix}\right\} + \left\{\begin{matrix}\text{Heat used to}\\ \text{increase lattice}\\ \text{temperature}\end{matrix}\right\}$$

$$W_T = c_v \frac{dT}{dt} + \text{div}\,(K\ \text{grad}\ T) \qquad \dots (2.43)$$

where, c_v = Specific heat of the specimen.

T = Temperature of the specimen.

K = Thermal conductivity of the specimen.

t = Time over which the heat is dissipated.

$$\left.\begin{matrix}\text{Heat generated under}\\ \text{D.C. stress}\end{matrix}\right\} W_{D.C} = E^2 \sigma \quad W/cm^3 \qquad \dots (2.44)$$

where, σ = D.C. conductivity of the specimen.

$$\left.\begin{matrix}\text{Heat generated under}\\ \text{A.C. stress}\end{matrix}\right\} W_{A.C} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \quad W/cm^3 \qquad \dots (2.45)$$

where, E = rms value.

δ = Loss angle of the dielectric.

$W_T = W_{D.C}$ or $W_{A.C}$

Thermal breakdown is more serious at high frequencies, because for a given loss angle δ and applied voltage V, heat generated $\propto$ frequency (f).

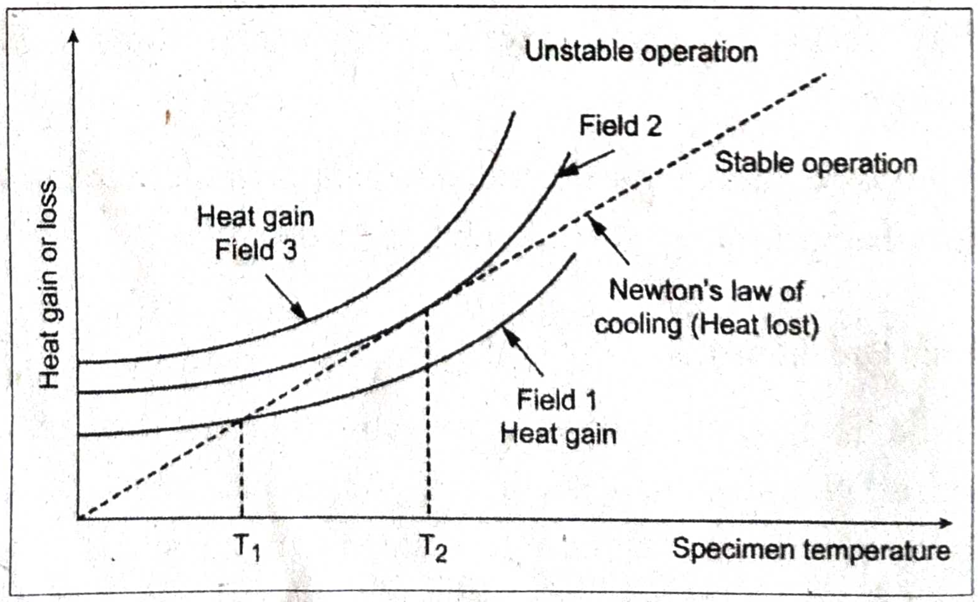


Fig. 2.24. Thermal stability or unstability under different applied field

Fig.2.24 explains the thermal stability and instability under different fields. Cooling of the specimen or heat cost is represented by a straight line and heating at different fields are represented by curves. Field 1 of curve cuts the heat lost curve at T_1. At this point a equilibrium occurs and after that the field 1 of curve is stable because heat generated is lesser than heat lost. Field 2 of curves is in equilibrium at T_2 and heat generated is greater than heat lost, so it is unstable. Field 3 of current does not reach equilibrium and it is unstable.

Thermal breakdown stresses are less in A.C than in D.C field

Thermal breakdown stresses are less in A.C compared to that of D.C fields, because:

- Power loss under A.C. field is high.
- Heat generated is high.

2.8.2.4. Electrochemical Breakdown

Electrochemical breakdown was caused by chemical transformations due to electrolysis, formation of ozone gas, *etc.*

When electric field is applied across the solid dielectric, instability or breakdown occurs due to oxidation, hydrolysis and chemical action. Due to this action, gas is formed in the cavities. When the gas breaks down, the electrons are produced. These electrons impinge on the anode and produces electrons. This process repeats and breaks the chemical bonds of insulation surface.

Important Chemical Reactions

- ***Oxidation:*** Cracks are formed due to oxidation in the presence of air or oxygen in the materials such as rubber, polyethylene.
- ***Hydrolysis:*** Electrical and mechanical properties of the solid dielectric like paper, cotton, cellulose materials lose due to the hydrolysis in the presence of water or moisture on the surface.
- ***Chemical Action***

Electrical and mechanical properties of solid dielectrics loses due to:

- Chemical instability at high temperature.
- Oxidation and formation of crack in the presence of air or oxygen.
- Hydrolysis due to moisture and water.

The chemical and electrochemical deterioration increases with temperature, chemical reaction occurs between materials reduces the electrical and mechanical properties and leading to failure of solid dielectrics.

2.8.2.5. Breakdown due to Treeing and Tracking

When a solid dielectric subjected to electrical stresses during a long time, breakdown takes place in the solid dielectric.

Breakdown occurs due to the following processes.

- Formation of conducting path across the surface of the insulation due to surface erosion.
- Formation of spark due to the leakage current passes through the conducting path.

Tracking

When voltage is applied, a formation of continuous conducting paths across the surface of the insulation due to surface erosion is called as tracking.

When voltage is applied across the dielectric, a conducting film is formed due to moisture. When the film starts conducting, heat is produced and the surface starts drying and sparks are produced to damage the dielectric. This leads to tracking.

Treeing

The spreading of spark channels during tracking, in the form of the branches of a tree is called treeing.

Treeing occurs due to the erosion of material at the tips of spark. Dirt and contaminations present at the tips of spark leads to conducting path bridging the electrode and breakdown or failure of dielectric occurs. Treeing phenomenon is present in cables and capacitors.

Consider a dielectric material is placed between two electrodes as shown in Fig.2.25.

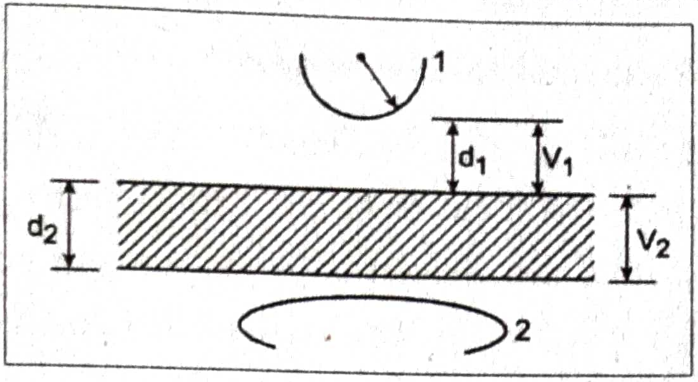


Fig. 2.25. Dielectric material is arranged between electrodes

The air acts as another dielectric media which is in series with the dielectric.

Let V_1 be the voltage across the airgap.

Let V_2 be the voltage across the dielectric.

Let ε_1 be the permittivity of air.

Let ε_2 be the permittivity of dielectric.

$$\text{Now } V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2} \qquad \dots (2.46)$$

where, V = Applied field.

Mostly $\varepsilon_2 > \varepsilon_1$, therefore voltage across d_1 is more. Charge accumulates on the surface of the insulator due to sparking. As time increases, the conducting paths increases and spreads through the insulator in an irregular tree like fashion. This forms treeing. This phenomenon of treeing is as shown in Fig.2.23.

Tracking Index

- Numerical value of voltage that initiates tracking is called as tracking index.
- It is used to qualify the surface condition of the material under test.

Prevention Methods for Treeing and Tracking

- Surface should be clean, dry.
- Surface must be undamaged.
- Materials used for surfaces should be resistant to tracking. (Moisture repellent greases are used).
- Increasing creepage distance to prevent tracking.

2.8.2.6. Breakdown Due to Internal Discharges

Solid dielectric materials contain void and cavities within the dielectric. These voids and cavities are filled with gas or liquid. The dielectric strength of this filling medium is less than that of the dielectric. When voltage is applied, electric field strength of the filling material may exceed its breakdown strength and produce internal discharges. Due to this breakdown may occur.

Consider a cross-section of an insulating slab containing a cavity in the form of a disc as shown in Fig.2.26.

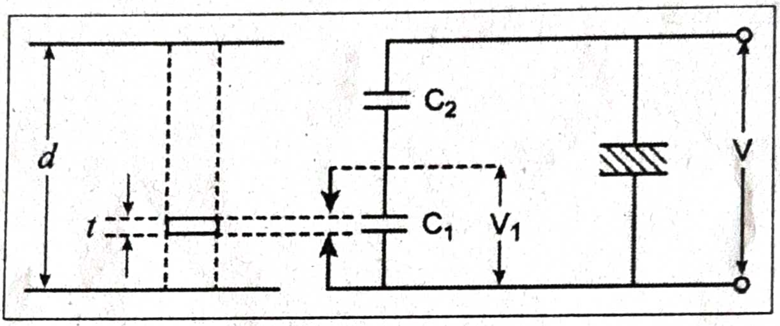


Fig. 2.26. Equivalent circuit for electrical discharging in cavities

Let d be the insulation thickness.

Let t be the thickness of cavity.

Let c_1 be the capacitance of the cavity which is discharged.

Let c_2 be the capacitance of the dielectric.

When the cavity is filled with gas, then

$$V_1 = V \cdot \varepsilon_r \left(\frac{t}{d}\right) \qquad \dots (2.47)$$

where, V = Applied voltage.

ε_r = Relative permittivity of dielectric.

Breakdown Mechanism

When voltage is applied, the discharge inception voltage V_1 reaches the breakdown strength of cavity and discharge takes place and voltage drop decreases and the gap extinguishes. The voltage across the cavity V_1 again increases and several discharges formed and resulting in breakdown.

During internal discharges, some electrons impinge on anode to break chemical bonds and produces electrons and positive ions. These positive ions hits the cathode producing heat and thermal instability occurs. Therefore, chemical degradation occurs due to carbonization of the surface of the voids which leads to breakdown of solid dielectric. Breakdown processes may occur in a few days or few years.

2.9. BREAKDOWN IN COMPOSITE DIELECTRICS

Different dielectric materials can be in parallel with each other (air or SF_6 gas in parallel with solid insulation) or in series with one another. Such insulating systems are called as composite dielectrics.

Breakdown Mechanism

Composite insulating materials contain voids and composed of different chemical substances. When voltage is applied to the solid dielectric, chemical reactions occur and heat is produced. Composite dielectrics undergo chemical deterioration and reduces the mechanical, electrical strength and breakdown occurs.

2.9.1. Properties of Composite Dielectrics

The properties of composite dielectrics which are important to their performance are listed below.

Effect of Multiple Layer

The effect of using multiple layers of dielectrics are:

- Different layers of dielectric have a higher dielectric strength than a single dielectric.
- Significant in having a wide variation of dielectric strength measured at different points on its surface.

Effect of Layer Thickness

Breakdown voltage increases with increase in layer thickness. Breakdown occurs at the interfaces and not at other layer in case of layered construction.

In case of insulating paper with layered construction, the thickness varies from point to point and the dielectric strength varies. Variation of thickness gives a rough surface which helps for better impregnation. Low thickness of paper causes breakdown.

Investigations on Composite Dielectrics

Discharge inception voltage depends on:

- Thickness of the solid dielectric.
- Dielectric constant of liquid and solid dielectric.

Differences in dielectric constant does not affect the rate of change of electric field with the change in thickness.

Effect of Interfaces

Interface between tow dielectric surfaces plays an important role in determining–

- Pre-breakdown.
- Breakdown strength.

Discharges occurs at the interface. When the surface conductivity increases, magnitude of the discharge increases and leads to breakdown of composite insulators.

2.9.2. Breakdown Mechanism in Composite Dielectrics

There are two types of breakdown mechanism in composite dielectric. They are:

- Short-term Breakdown.
- Long-term Breakdown.

2.9.2.1. Short-Term Breakdown

When the applied electric field is high, failure may occur in seconds or even faster without damaging the insulating surface prior to breakdown is called as short-term breakdown.

When the applied voltage is very close to the breakdown voltage, breakdown of composite dielectric occurs due to discharges. The discharges of given magnitude can enter the insulation from the surface and propagate rapidly into its volume under critical stress to cause breakdown.

Breakdown strength increases due to:

- The presence of more electrons (bombarding particles) than positive ions.
- Local field intensifications due to–
  - the presence of impurities.
  - variations in the thickness of solid insulation.

2.9.2.2. Long-Term Breakdown (Ageing of Insulation)

Long-term breakdown occurs due to ageing of insulation from thermal process and partial discharges. Long-term breakdown arise due to the following:

- Ageing and breakdown due to partial discharges.
- Ageing and breakdown due to accumulation of charges on insulator surfaces.

Ageing and Breakdown due to Partial Discharges

In composite dielectric, gas filled cavities will be present within the dielectric or adjacent to the interface between the conductor and the dielectrics. When voltage is applied to the dielectric, discharges takes place within the gas filled cavities. These discharges are called as partial discharges.

Failure of composite dielectric occurs depends on:

- Geometry of the cavity.
- Nature of the dielectric.

The degree of ageing depends on discharge inception voltage. The discharge inception voltage depends on:

- Permittivity of the dielectrics ε_r.
- Thickness of the cavity, g.

$$\therefore \; V_i = \left(\frac{E_g}{\varepsilon_r}\right)(t + \varepsilon_r g) \qquad \ldots (2.48)$$

where, E_g = Breakdown strength of the cavity.

t = Thickness of dielectric.

Assume $(g + t)$ is a constant, say C.

Adding and subtracting $\frac{E_g g}{\varepsilon_r}$ in equation (2.48), we get

$$V_i = \frac{E_g}{\varepsilon_r}(t + g + \varepsilon_r g - g) = \frac{E_g}{\varepsilon_r}[(\varepsilon_r - 1)g + C] \quad \text{... (2.49)}$$

Differentiating equation (2.49) with respect to g, we get

$$\frac{dV_i}{dg} = \frac{(\varepsilon_r - 1)}{\varepsilon_r} E_g + \frac{\varepsilon_r - 1}{\varepsilon_r} g \frac{dE}{dg} + \frac{C}{\varepsilon_r}\frac{dE}{dg}$$

$$= \frac{\varepsilon_r - 1}{\varepsilon_r}\left\{E_g + g\frac{dE}{dg} + \frac{C}{\varepsilon_r - 1}\frac{dE}{dg}\right\}$$

$$\frac{dV_i}{dg} = \frac{\varepsilon_r - 1}{\varepsilon_r}\left\{E_g + \frac{dE}{dg}\left(g + \frac{C}{\varepsilon_r - 1}\right)\right\} \quad \text{... (2.50)}$$

where, E_g = Positive, $\frac{dE}{dg}$ = Negative or zero.

Assumptions:

- ➢ $E_g = \varepsilon_r \cdot E$
- ➢ $\frac{E_{g\,(max)}}{E_g} = 1$

where, E = Applied electric field

Paschen's curve can be used to explain breakdown of the gas gap when these assumptions are valid. When the voltage is applied, the breakdown of gas in the cavity occurs, and discharge progresses. This discharge causes rise in temperature and pressure of gas. This causes decrease in the extinction voltage levels and erosion of cavity occurs.

Conclusions:

- ➢ V_i decreases as cavity depth increases and follows Paschen's curve.
- ➢ $E < 2\,V_i$, erosion of cavity occurs but breakdown will not takes place and the life of insulation is long.
- ➢ $E > 2\,V_i$, erosion and breakdown takes place due to ageing.

Ageing and Breakdown due to Accumulation of Charges on Insulator Surfaces

When electric field is applied to the composite dielectric, discharges occurs due to the charges (electrons or positive ions) gets deposited on the solid insulator surface. These charges stays for a long duration (days or weeks). This accumulation of charges increases the conductivity and increases the discharged magnitudes which causes damage to the dielectric surface. The discharge increases as the life of the insulation increases.

For clean surface, V_i value depends on:

- Nature of dielectric.
- Size of dielectric.
- Shape of dielectric.

Example 2.2 ***A steady state current of 5.5 × 10⁻⁸ A was noted during experiment in a certain gas at 8 kV at a distance of 0.4 cm between plane electrodes. Keeping the field constant and reducing the distance to 0.1 cm resulted in a current of 5.5 × 10⁻⁹ A. Calculate the Townsend's primary ionization coefficient, α.***

Given Data: $I_1 = 5.5 \times 10^{-8}$ A; $d_1 = 0.4$ cm

$I_2 = 5.5 \times 10^{-9}$ A; $d_2 = 0.1$ cm

To find: $\alpha = ?$

☺ ***Solution:***

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

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

$$\frac{5.5 \times 10^{-8}}{5.5 \times 10^{-9}} = e^{\alpha (0.4 - 0.1)}$$

$$10 = e^{\alpha (0.3)}$$

$$0.3\,\alpha = \ln 10$$

$$0.3\,\alpha = 2.303$$

$$\boxed{\alpha = 7.675 \text{ per cm-torr}}$$