

HIGH VOLTAGE ENGINEERING

UNIT II-BREAKDOWN IN GASES, LIQUIDS AND SOLIDS

Gaseous breakdown in uniform and non-uniform fields – Corona discharge – Vacuum breakdown – Conduction and breakdown in pure and commercial liquids – Breakdown mechanisms in solid and composite dielectrics.

PART-A

1. What are the different gases that are used as insulating medium?

Air, Nitrogen, Carbon dioxide, Freon and Sulphur hexafluoride.

2. What are the various phenomena that occur in gaseous dielectric?

When the applied voltage is low, small currents flow between the electrodes and the insulation retains its electrical properties. On the other hand, if the applied voltages are large, the current flowing through the insulation increases very sharply and an electrical breakdown occurs.

3. What is break down voltage?

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

4. Give the types of electrical discharge in gases.

- i. Non sustaining discharges
- ii. Self sustaining discharges

5. Define spark breakdown and ionization.

The break down in a gas, called spark breakdown is the transition of a non-sustaining discharge into self sustaining discharge.

The build-up of high currents in a breakdown is due to the process known as ionization in which electrons and ions are created from neutral atoms or molecules and their migration to the anode and cathode respectively leads to high currents.

6. Give the theories that explain the mechanism for breakdown.

- i. Townsend theory
- ii. Streamer theory

7. What are the conditions in the gases that govern the ionization process?

- (i) Pressure
- (ii) Temperature
- (iii) Electrode field configuration
- (iv) Nature of electrode surfaces
- (v) Availability of initial conducting particles

8. Define statistical time lag and formative time lag.

Statistical Time Lag: The time which lapse between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag of the gap.

Formative Time Lag: The time required for the ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag (t_f).

9. What are electronegative gases? Give example.

Electronegative gases are the gases that have affinity towards electrons. When electron comes into contact with these gas molecules, the gas molecule attracts the electrons and becomes negative ion.

Examples:

- Carbondioxide
- Oxygen
- SF6

10. Name the different secondary ionization process.

- a. Electron Emission due to Positive Ion Impact
- b. Electron Emission due to Photons
- c. Electron Emission due to Metastable and Neutral Atoms

11. Name the three properties of composite dielectrics that are important to their performance.

- a. Effect of Multiple Layers
- b. Effect of Layer Thickness
- c. Effect of Interfaces

12. What are pure liquids dielectrics?

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 are n- hexane (C_6H_{14}), n-heptane (C_7H_{16}) and other paraffin hydrocarbons.

13. What is breakdown voltage?

The maximum voltage that can be applied on the insulation at the moment of breakdown is called as breakdown voltage.

14. Define Townsend's first ionization co-efficient.

Townsend's Primary ionization coefficient α is defined as the average number of ionizing collision made by the free electron per centimeter travel in the direction of applied electric field.

15. Define Townsend's second ionization co-efficient.

The Townsend's secondary ionization coefficient γ is defined as the net number of secondary electrons produced per incident positive ion, photon, excited particle or metastable particle.

16. What are the limitations of Townsend's theory?

Townsend's mechanism failed to explain the following:

- According to the Townsend theory, current growth occurs as a result of ionization processes only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap.
- Mechanism predicts time lags of the order of 10^{-5} S, while in actual practice breakdown was observed to occur at very short times of the order of 10^{-8} S.
- Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular.

17. Name the various mechanism of breakdown in solid dielectrics.

Breakdown mechanisms in solid dielectrics can be classified as follows:

- (a) Intrinsic or ionic breakdown,
- (b) Electromechanical breakdown,
- (c) Failure due to treeing and tracking,
- (d) Thermal breakdown,
- (e) Electrochemical breakdown, and

(f) Breakdown due to internal discharges.

18. What is tracking and treeing?

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

19. What is tracking index?

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

20. What is called a composite dielectric?

Composite dielectrics are the different insulating materials in parallel or in series with each other, such as air or SF₆ gas in parallel with solid insulation.

21. Define time lag.

The time difference between the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself is called the time lag.

22. On what factors does time lag depend?

- (i) Statistical time lag- Pre ionization , size of the gap and quantity of radiation
- (ii) Formative time lag – Mechanism of the avalanche growth in the gap, transit time.

23. What is Paschen's Law?

The breakdown voltage of a uniform field gap is a unique function of the product of p, the gas pressure and d, the electrode gap, for a particular gas or for a given electrode material.

$$V=f(pd)$$

24. What are the effects of corona?

- (i) Loss of power
- (ii) Deterioration of insulation
- (iii) Rise to radio interference.

25. Define corona.

If the field is non-uniform an increase in voltage will first cause a discharge in the gas to appear at points with highest electric field intensity namely at sharp points or where the electrodes are curved or on transmission lines. This form of discharge is called a corona discharge.

(Or)

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

26. What are the properties of good gaseous dielectric for the HV application?

- (i) High dielectric strength
- (ii) Thermal stability and chemical inactivity towards materials of construction.
- (iii) Non-flammability and physiological inertness and environmentally non- hazardous.
- (iv) Low temperature of condensation
- (v) Good heat transfer
- (vi) Ready availability at moderate cost.

27. What is vacuum?

A vacuum system which is used to create vacuum is a system in which the pressure is maintained at a value much below the atmospheric pressure.

28. Define vacuum discharge.

Electrons get multiplied due to the various ionization processes and an electron avalanche is formed. In high vacuum, even if the electrodes are separated by a few centimeters, an electron crosses the gap without encountering any collisions.

29. What are the different mechanisms of breakdown in vacuum?

- (i) Particle exchange mechanism
- (ii) Field emission mechanism
- (iii) Clump theory

30. On what factors does liquid dielectric is selected?

- (i) Chemical stability
- (ii) Space
- (iii) Cost
- (iv) Previous usage
- (v) Susceptibility to the environmental influences.

31. Give different properties of liquid electric.

- (a) Electrical properties
 - (i) Its capacitance per unit volume or its relative permittivity
 - (ii) Its resistivity
 - (iii) Its loss tangent or its power factor
 - (iv) Its ability to with stand high electric stresses.
- (b) Heat transfer characteristics
- (c) Chemical stability.

32. What are the factors that influence conduction in pure liquid dielectric and in commercial liquid dielectric?

- (i) The nature and condition of the electrodes
- (ii) The physical properties of the liquid
- (iii) The impurities and gases present in the liquid

33. What are the various theories that explain breakdown in commercial liquid dielectric?

- (i) Suspended particle mechanism
- (ii) Cavitation and bubble mechanism
- (iii) Stressed oil volume mechanism

34. What are the properties of good solid dielectric?

- (i) Low dielectric loss
- (ii) High mechanical strength
- (iii) Should be free from gaseous inclusions and moisture
- (iv) Resistant to thermal and chemical deterioration

35. Give different solid dielectric material.

- (i) Organic material:
 - (a) Paper
 - (b) Wood
 - (c) rubber
- (ii) Inorganic material
 - (a) Perspex

- (b) PVC
- (c) Epoxy resins
- (d) Mica
- (e) Glass
- (f) Porcelain

36. Give different breakdown mechanism in solid dielectrics.

- (i) Intrinsic or ionic breakdown
- (ii) Electromechanical breakdown
- (iii) Failure due to treeing and tracking
- (iv) Thermal breakdown
- (v) Electrochemical breakdown
- (vi) Breakdown due to internal charges.

37. What are the different breakdown mechanisms in composite dielectric?

- (i) Short term breakdown
- (ii) Long term breakdown

PART-B

1. State the criteria for sparking potential and hence obtain the relation between sparking potential and (pd) values (Paschen's law). Discuss on the nature of variations of sparking potential with (pd) values.

The breakdown criterion $1 - \gamma(e^{\alpha d} - 1) = 0$ (2.1) where α and γ are functions of E/p , i.e.

$$\alpha/p = f_1(E/p) \text{ and } \gamma = f_2(E/p). \text{ Also } E = V/d.$$

Substituting for E in the expressions α and γ and rewriting equation (2.1) we have

$$f_2(V/pd) \left[e^{pd f_1(V/pd)} - 1 \right] = 1. \text{ This equation shows a relationship between } V \text{ and } pd, \text{ and implies that}$$

the breakdown voltage varies as the product pd varies. Knowing the nature of functions f_1 and f_2 we can write the equation $V = f(pd)$ known as Paschen's law and has been experimentally established for many gases. Paschen's law is a very important law in high voltage engineering.

The relationship between V and pd is not linear and has a minimum value for any gas. The minimum breakdown voltages for various gases are as follow;

<u>Gas</u>	<u>V_s min(V)</u>	<u>pd at V_s min(torr-cm)</u>
Air	327	0.567
H_2	273	1.15
CO_2	420	0.51
O_2	450	0.7
SO_2	457	0.33
Helium	156	4.0

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

For values $pd > (pd)_{\min}$ electrons crossing the gap make more frequent collisions with gas molecules than $(pd)_{\min}$, but the energy gained between collisions is lower. Hence to maintain the desired ionization more voltage has to be applied.

For $pd < (pd)_{\min}$ electron may cross the gap without even making a collision or making only less number of collisions. Hence more voltage has to be applied for breakdown to occur.

For the effect of temperature, the Paschen's law is generally stated as $V = f(Nd)$ where N is the density of the gas molecules. This is necessary since the pressure of the gas changes with temperature according to the gas law $pv = NRT$. The breakdown potential of air is expressed due to the experimental results as;

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

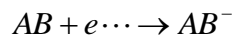
At 760 torr and 293°K,

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

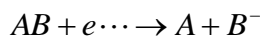
This equation yields a limiting value for E of $24 kV/cm$ for long gaps and a value of $30 kV/cm$ for $\left[\frac{293pd}{760T} \right] = 1$, which means a pressure of 760 torr at 20°C with 1 cm gap. This the breakdown strength of air at room temperature and at atmospheric pressure.

2. a. Explain why electronegative gases have high breakdown strength.

- One process that gives high breakdown strength to a gas is the electron attachment in which free electrons get attached to a neutral atoms or molecules to form negative ions.
- Since negative ions like positive ions are too massive to produce ionization due to collisions, attachment represents an effective way of removing electrons which otherwise would have led to current growth and breakdown at low voltages. The gases in which attachment plays an active role are called electronegative gases. Two types of attachment are encountered in gases as;
 - a) Direct attachment: An electron directly attaches to form a negative ion.



b) Dissociative attachment: The gas molecules split into their constituent atoms and the electronegative atom forms a negative ion.



- A simple gas for this type is the oxygen and others are sulphur hexafluoride, Freon, carbon dioxide and fluorocarbons. In these gases, 'A' is usually sulphur or carbon atom and 'B' is oxygen atom or one of the halogen atoms or molecules.
- The Townsend current growth equation is modified to include ionization and attachment with such gases. The current reaching the anode, can be written as,

$$I = I_0 \frac{\left[\frac{\alpha}{\alpha - \eta} e^{(\alpha - \eta)d} \right] - \left[\frac{\eta}{\alpha - \eta} \right]}{1 - \left[\gamma \frac{\alpha}{\alpha - \eta} e^{(\alpha - \eta)d} - 1 \right]} \quad (2.2)$$

where η is the number of attaching collisions made by one electron drifting one centimeter in the direction of the field

- The Townsend breakdown criterion for attaching gases can also be deduced from the denominator as, $1 - \left[\gamma \frac{\alpha}{\alpha - \eta} e^{(\alpha - \eta)d} - 1 \right] = 0$. When $\alpha > \eta$, breakdown is always possible irrespective of the values of α, η and γ . If $\alpha < \eta$ then an asymptotic form is approached with increasing value of d , $\gamma \frac{\alpha}{\alpha - \eta} = 1$ or $\alpha = \frac{\eta}{1 - \gamma}$.
- Normally γ is very small ($\leq 10^{-4}$) and the above equation can be written $\alpha = \eta$. This condition puts a limit for E/p below which no breakdown is possible irrespective of the value of d , and the limit value is called the critical E/p . For SF_6 it is $117 \text{ Vcm}^{-1}\text{torr}^{-1}$, for CCl_2F_2 $121 \text{ Vcm}^{-1}\text{torr}^{-1}$ both at 20°C . η values can also experimentally determined.

2.b. Discuss Meek's theory of breakdown in gases under non-uniform fields.

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

where, α - Townsend's Ionization coefficient
 P - Gas pressure in torr.

To determine minimum breakdown voltage,
 Substitute $E_r = E$ and $x = d$ in the above equation, we get

$$E_r = 5.27 \times 10^{-7} \alpha \frac{e^{\alpha x}}{\left(\frac{d}{P} \right)^{\frac{1}{2}}} \text{ V/cm}$$

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

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

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

Experimental values of (α/p) and corresponding E/p values are used to solve this equation using trial and error method. Value of (α/p) and (E/p) are chosen until the equation is satisfied.

3. Explain streamer theory of breakdown in air at atmospheric pressure.

- Townsend's Mechanism is not consistent with non-uniform field gaps.
- It was difficult to envisage how the Townsend mechanism would apply for long gaps where the sparks are observed to branch and to have an irregular character of growth.
- Streamer theory was proposed by,
 - Loeb (1955) and Meek for the positive streamer, and
 - Raether for the negative streamer
- In both versions, spark discharge develops directly from a single avalanche which the space charge transforms into a plasma streamer.
- Principal features of both versions are the photo-ionization of gas molecules in the space ahead of the streamer and the local enhancement of the electric field by the space charge at its tip.

Version by Loeb and Meek:

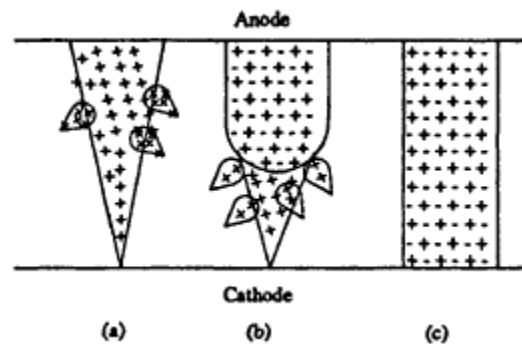


Figure 2.1: Cathode-directed streamer as envisaged by Meek and Loeb: (a) First Avalanche Crossing the Gap; (b) Streamer Extending from the Anode; (c) Streamer Crossing the Gap.

- When the avalanche has crossed the gap, the electrons are swept into the anode, the positive ions remaining in a cone shaped volume extending across the gap.
- A highly localized space-charge field is produced near the anode, but elsewhere in the gap the ion density is low.
- Photoelectrons are produced by photons emitted from the densely ionized gas constituting the avalanche stem
- These photoelectrons initiate auxiliary avalanches, which are directed by both the space-charge field and the externally applied field
- The greatest multiplication in these auxiliary avalanches will occur along the axis of the main avalanche.
- Positive ions left behind by these avalanches effectively branch, lengthen, and intensify the space charge of the main avalanche toward the cathode. The process thus develops a self propagating streamer, which effectively extends the anode toward the cathode.
- Ultimately, a conducting filament of highly ionized gas bridges the whole gap between the electrodes

- An electron avalanche changes into a streamer when the radial field E_r produced by the positive ions at the head of the avalanche is of the order of the externally applied field E , that is,

$$E_r = \kappa E \quad \text{where } \kappa \approx 1$$

$$E_r = \frac{5.27 \times 10^{-7} \alpha e^{\alpha x}}{(13,500x/p)^{1/2}} \text{ V/m}$$

Raether's Version:

- Slightly different criterion was proposed independently by Raether for negative anode-directed streamers.
- He postulated that streamers would develop when the initial avalanche produces a sufficient number of electrons ($e^{\alpha x}$) such that its space-charge field E_r is comparable to the applied field E .
- The total field, thus enhanced, would promote secondary anode-directed avalanches ahead of the initial one, forming a negative streamer. These secondary avalanches are initiated by photoelectrons in the space ahead of the streamer.
- At higher pd values, the streamer mechanism plays the dominant role in explaining breakdown phenomena.
- Streamer mechanism has been widely used to explain breakdown in non-uniform fields, such as in point-plane or point-point gaps.
- In long gaps, if the voltage gradient at the stressed electrode exceeds the corona onset level, the ionization activity in the gap increases. As a result, a highly ionized and luminous filamentary channel, called the leader channel, develops at the electrode and propagates toward the other electrode.

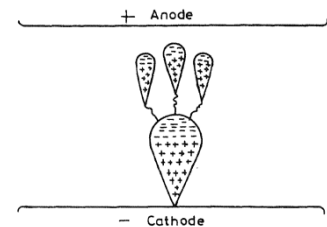


Figure 2.2: Anode-directed streamer as envisaged by Raether

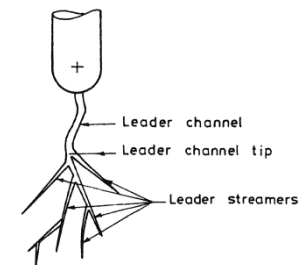


Figure 2.3: Leader channel and leader streamers.

B). Explain about time lag in gas breakdown.

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

The Townsend criterion for breakdown is satisfied only if at least one electron is present in the gap between the electrodes as in the case of applied d.c. or slowly varying (50 Hz a.c.) voltages. With rapidly varying voltages of short duration ($\approx 10^{-6}$ s), the initiatory electron may not be present in the gap that the breakdown can not occur.

Statistical Time Lag: The time which lapse between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag of the gap.

Formative Time Lag: The time required for the ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag (t_f).

4. Discuss in details, about the breakdown of vacuum medium.

Applications:

- Vacuum contractors, interrupters
- High frequency Capacitors and Relays,
- Electrostatic Generators,
- Microwave tubes.

Vacuum pressures:

- 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^{-9} Torr and Below.

Unlike gaseous breakdown, electron crosses the gap without encountering any collisions

- Classifications
- Particle Exchange Mechanism
- Field Emission Mechanism
- Clump Theory

Particle Exchange Mechanism

- Charged particle emission, impinges on other electrode, liberation of opposite charges takes place.
- Involves electrons, positive ions, photons, absorbed gases
- Anode releases positive ions and photons
- Photons and Positive ions liberates the electrons called secondary electrons
- Break down criterion $(AB+CD) > 1$
- Modifications $(AB+EF) > 1$, where A-no of positive ions, C-no of photons, B-No of electrons liberated by positive ions, D- B-No of electrons liberated by positive ions photons. E-No of electrons liberated by negative ions, F-No of electrons liberation by +v ions
- Product Ef closer to unity for copper, aluminium, and stainless electrodes.

Field Emission Theory

Anode Heating Mechanism

- Field emission bombard, anode temperature rise-gases and vapors released
- Ionise the atoms into +ve
- Secondary electrons formed due to positive ions in cathode

Cathode Heating Mechanism

- Pre-breakdown current
- Resistive heating
- Vacuum discharge
- Breakdown strength- 10^6 to 10^7 V/cm

Clump Mechanism

- A loosely bound particle (Clump) exist on one of the electrode
- On high voltage, particles gets charged, detached from mother electrode, accelerated across the gap
- Breakdown occurs due to a discharge in vapour or gas released by impact of particle at target electrode.

5. What is electrical avalanche? How do avalanche give rise to an electrical breakdown in case of Townsend's type of discharge.

Assuming n_0 electrons are emitted from the cathode and when one electron collides with a neutral particle, a positive atom and electron formed. This is called an ionization collision. Let α be the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field where it depends on gas pressure p and E/p , and is called the Townsend's first ionization coefficient. At any distance x from the cathode when the number of electrons, n_x , travel a distance of dx they give rise to $(\alpha n_x dx)$ electrons. Then, the number of electrons reaching the anode at $x=d$, n_d will be $n_d = n_x \Big|_{x=0}$

$$\frac{dn_x}{dx} = \alpha n_x \text{ or } n_x = n_0 e^{\alpha x} \text{ and}$$

$$n_d = n_0 e^{\alpha d} \text{ at } x=d.$$

The number of new electrons created, on the average, by each electron is $e^{\alpha d} - 1 = \frac{n_d - n_0}{n_0}$.

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

$$I = I_0 e^{\alpha d} \text{ (eqn. 2.6) where } I_0 \text{ is the initial current at the cathode.}$$

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

When low electric fields less than 1 kV/cm are applied, conductivities of 10^{-18} - 10^{-20} mho/cm are obtained. These are probably due to the impurities remaining after purification. However, when the fields are high (>100kV/cm) the currents not only increase rapidly, but also undergo violent fluctuations which will die down after some time. A typical mean value of the conduction current in hexane is shown in Fig. 2.4. This is the condition nearer to breakdown.

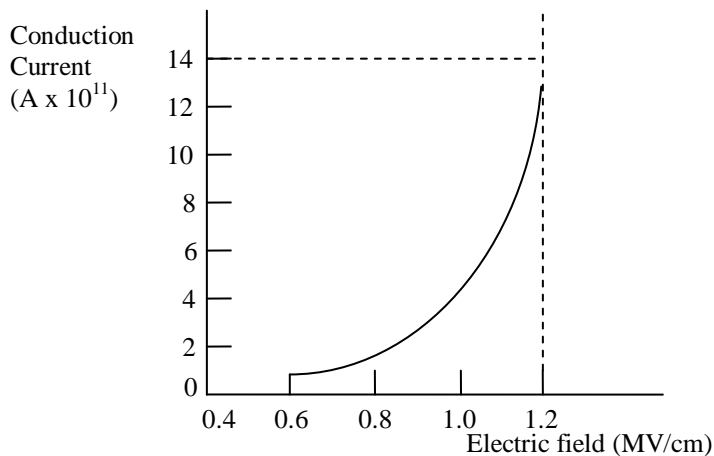


Fig.2.4 Conduction current-electric field characteristics in hexane at high fields

However, if this figure is redrawn starting from very small currents, a current-electric field characteristics as shown in Fig. 2.5, can be obtained. This curve will have three distinct regions as shown. At very low fields the current is due to the dissociation of ions. With intermediate fields the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from

the cathode gets multiplied in the liquid medium by a Townsend type of mechanism. The current multiplication also occurs from the electrons generated at the interfaces of liquid and impurities. The increase in current by these processes continues till breakdown occurs.

The exact mechanism of current growth is not known; however, it appears that the electrons are generated from the cathode by field emission of electrons.

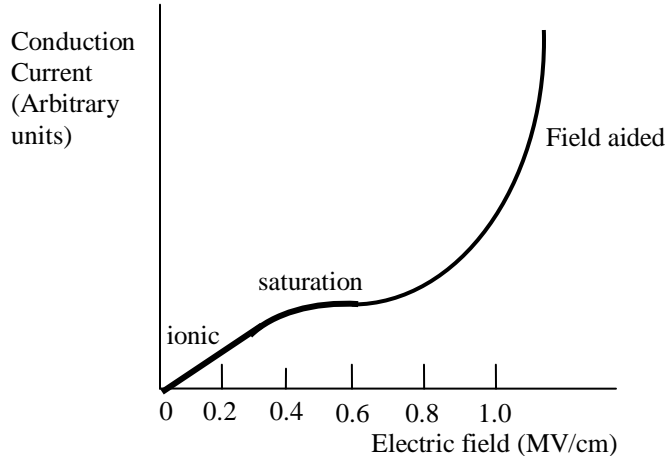


Fig.2.5 Conduction current-electric field characteristics in hydrocarbon liquid

The electrons so liberated get multiple by a process similar to Townsend's primary and secondary ionization in gases. As the breakdown field is approached, the current increases rapidly due to process similar to the primary ionization process and also the positive ions reaching the cathode generate secondary electrons, leading to breakdown. The breakdown voltage depends on the field, gap separation, cathode work-function, and the temperature of the cathode. In addition, the liquid viscosity, the liquid temperature, the

density, and the molecular structure of the liquid also influence the breakdown strength of the liquid.

7. Deduce the Townsend's breakdown criteria. Also define the Townsend's primary and secondary ionization co-efficient.

Assuming n_0 electrons are emitted from the cathode and when one electron collides with a neutral particle, a positive atom and electron formed. This is called an ionization collision. Let α be the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field where it depends on gas pressure p and E/p , and is called the Townsend's first ionization coefficient. At any distance x from the cathode when the number of electrons, n_x , travel a distance of dx they give rise to $(\alpha n_x dx)$ electrons. Then, the number of electrons reaching the anode at $x=d$, n_d will be $n_d = n_x \Big|_{x=0}$

$$\frac{dn_x}{dx} = \alpha n_x \text{ or } n_x = n_0 e^{\alpha x} \text{ and}$$

$$n_d = n_0 e^{\alpha d} \text{ at } x=d.$$

The number of new electrons created, on the average, by each electron is $e^{\alpha d} - 1 = \frac{n_d - n_0}{n_0}$.

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

$$I = I_0 e^{\alpha d} \text{ where } I_0 \text{ is the initial current at the cathode.}$$

Secondary Process:

When the initial set of electrons reaches the anode the single avalanche process is completed. Since the amplification of electrons $e^{\alpha d}$ is occurring in the field, the probability of additional new electrons being liberated by other mechanisms increases, and created further avalanches and are called as secondary electrons. The other mechanisms are

- i) The positive ions liberated may have sufficient energy to cause liberation of electrons from the cathode when they impinge on it.
- ii) The excited atoms or molecules in avalanches may emit photons, and this will lead to the emission of electrons due to photo-emission.
- iii) the metastable particles may diffuse back causing electron emission.

Defining the Townsend's secondary ionization coefficient γ in the same way as α , then the net number of secondary electrons produced per incident positive ion, photon, excited particle or metastable particle and the total value of γ due to the three different processes is $\gamma = \gamma_1 + \gamma_2 + \gamma_3$ and is function of gas pressure p and E/p .

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

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

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

Then $n_0'' = n_0 + n_0'$

the total number of electrons n reaching to the anode becomes,

$$n = n_0'' e^{\alpha d} = (n_0 + n_0') e^{\alpha d} \text{ and } n_0' = \gamma [n - (n_0 + n_0')]$$

$$\text{Eliminating } n_0', \quad n = \frac{n_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \text{ or } I = \frac{I_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$

Townsend's Criterion for Breakdown

The above equation gives the total average current in a gap before the occurrence of breakdown. As the distance between the electrodes d is increased the denominator of equation tend to zero and at some critical distance $d=d_s$

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

For values of $d < d_s$, I is approximately equal to I_0 and if the external source for the supply of I_0 is removed, I becomes zero. If $d = d_s$, $I \Rightarrow \infty$ and the current will be limited only by the resistance of power supply and the external circuit. This condition is called Townsend's Breakdown Criterion and can be written as $\gamma(e^{\alpha d} - 1) = 1$.

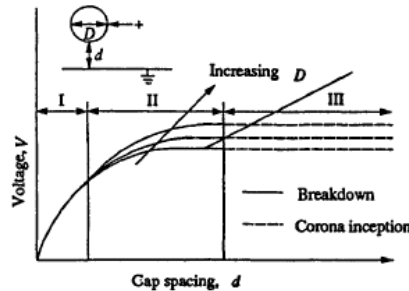
Normally, $e^{\alpha d}$ is very large, and hence the above equation reduces to

$$\gamma e^{\alpha d} = 1$$

For a given gap spacing and at a given pressure the value of voltage V which gives the values of α and γ satisfying the breakdown criterion is called the spark breakdown voltage V , and the corresponding distance d is called the sparking distance.

Townsend Mechanism explains the phenomena of breakdown only at low pressures, corresponding to $p \times d$ values of 1000 torr-cm and below.

8. Explain clearly breakdown in non-uniform fields and corona discharges.



If the field is non-uniform, an increase in voltage will first cause a discharge in the gas to appear at points with highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission lines. This form of discharge is called a corona discharge and can be observed as a bluish luminiscence.

This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone. Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges. Corona also gives rise to radio interference.

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

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

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

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

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

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

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

9. Explain various theories of breakdown mechanism of the commercial liquid dielectrics.

The breakdown mechanism in commercial liquids is dependent on several factors, such as, the nature and condition of the electrodes, the physical properties of the liquid, and the impurities and gases present in the liquid. Several theories have been proposed to explain the breakdown in liquids, and they are classified as follows:

- a) Suspended Particle Mechanism
- b) Cavitation and Bubble Mechanism

c) Stressed Oil Volume Mechanism

a. Suspended Particle Theory

In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres or as dispersed solid particles. The permittivity of these particles (ϵ_2) will be different from the permittivity of the liquid (ϵ_1). If we consider these impurities to be spherical particles of radius r , and if the applied field is E , then the particles experience of force F , where

$$F = \frac{1}{2} r^3 \frac{(\epsilon_2 - \epsilon_1)}{2_{\epsilon_1 + \epsilon_2}} \text{grad } E_2 \quad (3.1)$$

This force is directed towards areas of maximum stress, if $\epsilon_2 > \epsilon_1$, for example, in the case of the presence of solid particles like paper in the liquid. On the other hand, if only gas bubbles are present in the liquid, i.e. $\epsilon_2 < \epsilon_1$, the force will be in the direction of areas of lower stress. If the voltage is continuously applied (d.c) or the duration of the voltage is long (a.c), then this force drives the particles towards the area of maximum stress. If the number of particles is large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

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

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

b. Cavitation and the Bubble Theory

It was experimentally observed that in many liquids, the breakdown strength depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of vapor bubble formed is responsible for breakdown. The following processes have been suggested to be responsible for the formation of the vapor bubbles:

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

Once a bubble is formed it will elongated (long and thin) in the direction of the electric field under the influence of electrostatic forces. The volume of the bubble remains constant during elongation. Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the minimum value on the Paschen's curve for the gas in the bubble. The breakdown field is given as

$$E_0 = \frac{1}{(\epsilon_1 - \epsilon_2)} \left[\frac{2\pi\sigma(2_{\epsilon_1 + \epsilon_2})}{r} \left\{ \sqrt{\frac{V_b}{(2rE_0)}} - 1 \right\} \right]^{\frac{1}{2}} \quad (3.2)$$

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

the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid. But this theory does not take into account the production of the initial bubble and hence the results given by this theory do not agree well with the experimental results.

Later this theory was modified, and it was suggested that only incompressible bubbles like water globules can elongate at constant volume, according to the simple gas law

$pV = nRT$. Under the influence of the applied electric field the shape of the globule is assumed to be approximately a spheroid. These incompressible bubbles reach the condition of instability when β , the ratio of the longer to the shorter diameter of the spheroid is about 1.85, and the critical field producing the instability will be:

$$E_0 = 600 \sqrt{\frac{\pi\sigma}{\varepsilon_1 R}} \left[\frac{\varepsilon_1}{\varepsilon_1 - \varepsilon_2} - G \right] H \quad (3.3) \text{ where } \sigma = \text{surface tension, } R = \text{initial radius of bubble, } \varepsilon_1 =$$

permittivity of the liquid dielectric, $\varepsilon_1 =$ permittivity of the globule,

$$G = \frac{1}{\beta^2 - 1} \left[\frac{\beta \cosh^{-1} \beta}{(\beta^2 - 1)^{\frac{1}{2}}} - 1 \right] \text{ and } H^2 = 2\beta^{\frac{1}{3}} \left(2\beta - 1 - \frac{1}{\beta^2} \right)$$

For a water globule having $R=1 \mu\text{m}$ with $\sigma = 43 \text{ dyne/cm}$ and $\varepsilon_1 = 2.0$ (transformer oil), the above equation gives a critical field $E_c = 226 \text{ Kv/cm}$ which is approximately the maximum strength obtained for commercial oils.

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

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

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

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

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

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

$$P_c = P_{vp} = P_{es} + P_s + P_h, \quad (3.5) \quad \text{where, } P_c = \text{coulombic pressure,}$$

$$P_{vp} = \text{vapour pressure inside the cavity,}$$

$$P_{es} = \text{electrostatic pressure,}$$

$$P_s = \text{pressure due to surface tension, and}$$

$$P_h = \text{hydrostatic pressure.}$$

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

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

c. Stressed Oil Volume Theory

In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the “largest possible impurity” or “weak link”. On a statistical basis it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region. In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress (E_{max}) contour and 0.9 (E_{max}) contour. According to this theory the breakdown strength is inversely proportional to the stressed oil volume.

The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage. The variation of the breakdown voltage stress with the stressed oil volume is shown in Fig. 3.4.

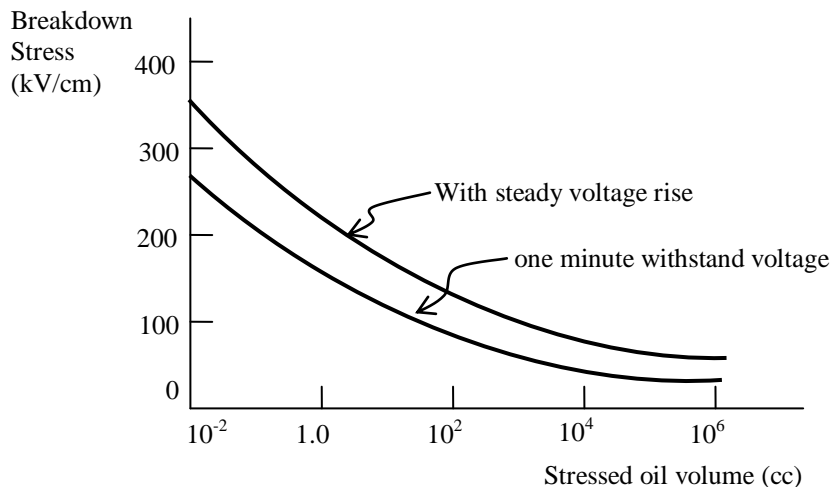


Fig 3.4 Power frequency (50 Hz) a.c breakdown stress as function of stressed oil volume

10. Explain the characteristics of liquid dielectrics.

Capacitance pu volume (Permittivity)

- Petroleum oils – 2-2.6
- Askerals – 4.5-5
- Silicone oils – 2-73

Resistivity

- In the order of 10^{16} Ohm metre

Loss Tangent or Power factor

- 10^{-4} at 200C and 10^{-3} at 900C Withstand ability of high electric stresses
- Depends atomic and molecular properties
- Material of electrodes, temperature, type of voltage, gas content of the liquid

11. Explain the different mechanisms by which the breakdown occurs in solid dielectrics.

The solid dielectrics contain the following properties:

- Low dielectric loss
- High mechanical strength
- Free from gaseous inclusions, and moisture resistant to thermal and chemical deterioration

Mechanisms

- Intrinsic or Ionic
- Electromechanical
- Failure due to treeing and tracking
- Thermal
- Electrochemical
- Internal discharges

Intrinsic or Ionic breakdown:

- Intrinsic electric strength (10^{-8} s)
 - 15 MV/cm polyvinyl alcohol at -1960C
- Free electrons presence
- Electronic breakdown:
 - Initial density of free electrons be large
 - They cross forbidden energy gap from valency to conduction band when voltage is applied.
- Cumulative ionization
- If electrons embedded in specimen, b.d will occur when an electron avalanche bridges the electrode gap
- Breakdown does not occur by the formation of single avalanche.

Electromechanical Breakdown:

- Electrostatic compressive forces exceeds mechanical compressive strength.
- At equilibrium,
 $\epsilon \epsilon_0 \epsilon_r V^2 / (2d^2) = Y \ln(d_0/d)$
- $Y \rightarrow$ Young Modulus
- $V^2 = d^2 (2Y / \epsilon_0 \epsilon_r) \ln(d_0/d)$
- Mechanical instability occurs when $d/d_0 = 0.6$ or 1.67
- $E_{max} = V/d_0 = 0.6 \cdot (Y / \epsilon_0 \epsilon_r)^{1/2}$

Thermal Breakdown:

- Equilibrium is reached when the heat used to raise the temperature of dielectric plus heat radiated out equals heat generated.

- Heat generated
 $W_{dc} = E^2 \sigma \text{ W/cm}^3$
 σ -dc conductivity of the specimen
 $W_{ac} = (E^2 f \epsilon_r \tan \delta) / (1.8 \times 10^{12}) \text{ W/cm}^3$
Where, f-frequency, δ – loss angle of dielectrics material, E rms value
 - Heat dissipated, $W_T = C_V dT/dt + \text{div} (K \text{ grad } T)$
Where, CV specific Heat, T-Temperature, K-Thermal Conductivity
 - Breakdown occurs W_{dc} or W_{ac} exceeds W_T
-