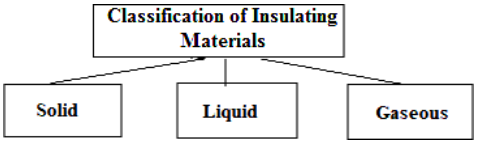
UNIT-I
BREAKDOWN IN GASES, LIQUID AND SOLID INSULATION

Classification of Insulating Materials:

- **The insulating materials can be classified in the following two ways:**
  1. Classification according to substances and materials.
  2. Classification according to temperature.

1. Classification According to Substances and Materials:



(i) Solids (Inorganic and Organic):

- Mica, wood, slate, glass, porcelain, rubber, cotton, silk, rayon, terylene, paper and cellulose materials etc.

(ii) Liquids (Oils and Varnishes):

- Linseed oil, refined hydrocarbon mineral oils, spirit and synthetic varnishes etc.

(iii) Gases:

- Dry air, carbon dioxide, argon, nitrogen etc.

2. Classification According to Temperature:

Class	Insulating materials included	Assigned limiting insulating temperature
Y (Formerly O)	Cotton, silk, paper, cellulose, wood, etc., neither impregnated nor immersed in oil. Materals of Y class are unsuitable for electrical machines and apparatus as they deteriorate rapidly and are extremely hygroscopic.	90°C
A	Materials of class Y impregnated with natural resin, cellulose esters, insulating oils etc. Also included in this list are laminated wool, varnished paper.	105°C
E	Synthetic resin enamels, cotton and paper laminates with formaldehyde bonding etc.	120°C
B	Mica, glass fibres, asbestos with suitable bonding substance, built up mica, glass fibre and asbestos laminates.	130°C
F	Materials of class B with bonding materials of higher thermal stability.	155°C
H	Glass fibre and asbestos materials, and built up mica, with silicon resins.	180°C
C	Mica, ceramics, glass, quartz without binders or with silicon resins of higher thermal stablity.	above 180°C

Characteristics of a Good Insulating Material:

1. Large insulating resistance.
2. High dialectic strength.
3. Uniform viscosity—it gives uniform electrical and thermal properties.
4. Should be uniform throughout—it keeps the electric losses as low as possible and electric stresses uniform under high voltage difference.
5. Least thermal expansion.
6. When exposed to arcing should be non-ignitable.
7. Should be resistance to oils or liquids, gas fumes, acids and alkalies.
8. Should have no deteriorating effect on the material, in contact with it.
9. Low dissipation factor (loss tangent).
10. High mechanical strength.
11. High thermal conductivity.
12. Low permittivity.
13. High thermal strength.
14. Free from gaseous insulation to avoid discharges (for solids and gases).
15. Should be homogeneous to avoid local stress concentration.
16. Should be resistant to thermal and chemical deterioration.

Dielectric material:

- Dielectric material is a non-conducting substance that holds electrical charges.
- Dielectric materials are used to store energy. These materials exist in solid, liquid and gaseous forms. Some examples of dielectric materials are:
    1. Solid Dielectrics – Ceramic, Plastic, Mica, and Glass.
    2. Dielectric Liquid – Distilled Water.
    3. Dielectric Gas – Dry Air, vacuum, nitrogen and helium.

Properties of Dielectric Material:

- The energy gap in the dielectric materials is very large.
- The temperature coefficient of resistance is negative and the insulation resistance is high.
- The dielectric materials have high resistivity.
- The attraction between the electrons and the parent nucleus is very strong.
- The electrical conductivity of these materials is very low as there are no free electrons to carry current.

Difference between Dielectric and Insulators:

Dielectrics	Insulators
Material that can develop an electric field with minimal loss of energy is known as a dielectric.	A substance that has low conductivity and that which obstructs the flow of current is known as an insulator.
Weakly bonded as compared to insulators.	Covalently bonded.
Store charges.	Obstructs charges.
Their application lies in power cables, capacitors and more.	They are used in high voltage systems and conducting wires.

#Over voltages in power systems

- Protection of transmission lines and Power apparatus from the chief causes of over voltages is necessary
    - Lightning over voltages
    - Switching over voltages

1. Lightning over voltages – Natural Phenomenon of charging and Discharging of clouds

- Magnitude of Lightning over voltages not depends on Line design and Operating Voltages

Causes of Lightning:

- Lightning phenomenon- peak discharge in which charge accumulated in the cloud into neighbouring cloud or to the ground
- Electrode separation – cloud to cloud or cloud to ground is about 10 km or more

Charge formation of cloud:

- Positive and negative charges become separated by heavy air current with ice crystals in theupper part and rain in the lower region.
- Charge separation depends on height of cloud (200 – 10,000m).
- Charge centers at a distance about 300 – 2km
- Charge inside the cloud – 1 to 100 C
- Cloud potential – 10^7 to 10^8 V

2. Switching over voltages – connection and disconnection of circuit breakers due to interruption of faults like short duration over voltage and temporary over voltages

- Magnitude of Switching over voltages proportional to line design and Operating Voltages
- From 300 kV to 765 kV, both operating voltages to be considered and above 700 kV, Switching operating voltages be the chief condition for design purpose.

Characteristics of switching surges

- De-energizing of transmission lines, cables, shunt capacitor, banks, etc.
- Disconnection of unloaded transformers, reactors, etc.
- Energization or reclosing of lines and reactive loads.
- Sudden switching off of loads.
- Short circuit and fault clearances.
- Resonance phenomenon like ferro-resonance, arcing grounds, etc.

Control of over voltages due to switching:

- Energization of transmission lines in one or more steps by inserting resistances and withdrawingthem afterwards.
- Phase controlled closing of circuit breakers.
- Drainage of trapped charges before reclosing
- Use of shunt reactors.
- Limiting switching surges by suitable surge diverters.

Protection against over voltages:

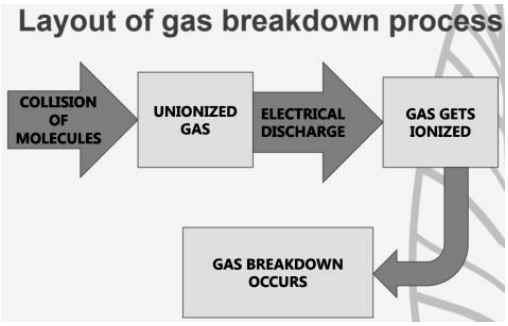
- Minimizing the lightning over voltages are done by suitable line designs,
- Providing guard and ground wires,
- Using surge diverters.
- Shielding the overhead lines by using ground wires above the phase wires,
- Using ground rods and counter-poise wires,
- Including protective devices like explosion gaps, protector tubes on the lines, and surge diverters at the line terminations and substations.

What are the applications of high voltage?

- High voltage power transmission
- Insulation testing
- Measurement of insulation resistance
- Breakdown voltage measurements
- Measurement of electric stress on different materials
- Testing of power transmission equipments
- Lightning simulation
- Study of high voltages transients/surges on transmission line.

Electrical Breakdown Types:

- Breakdown occurs within gas when dielectric strength of gas failures.
- The electrical breakdown of a gas is brought about by various process of ionization.
- These are good processes involving the collision of electrons, ions and photons with gas molecules and electrode processes.



1. Electrical Breakdown:

- During an Electric Breakdown: the insulating gas between the electrodes is bridged by a conducting discharge canal (channel).
- In small gap distance the charge carriers required in order to build this discharge canal are not only produced within the gaseous dielectric across the gap (*primary or α- process*), but are alsoreleased from the electrode surfaces (*secondary or γ - process*).

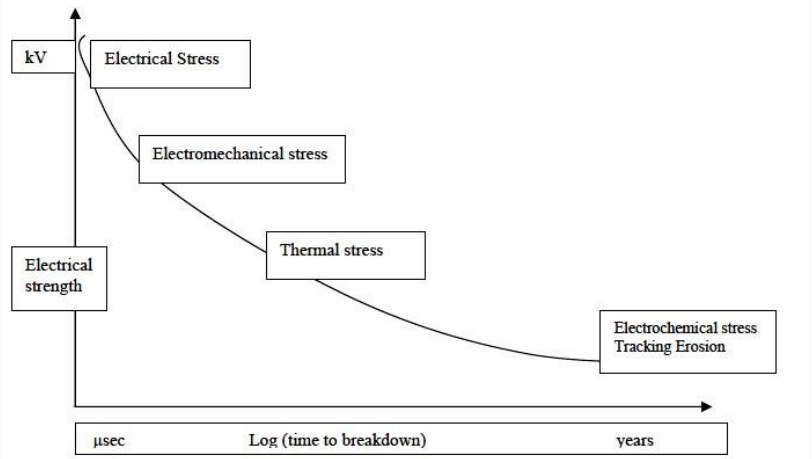


Fig: The relation between the breakdown strength of a solid insulator with respect to time

- All insulating materials undergo breakdown when the electric field caused by an applied voltage exceeds the material's dielectric strength.
- The voltage at which a given insulating object becomes conductive is called its breakdown voltage and depends on its size and shape.

- Under sufficient electrical potential, electrical breakdown can occur within solids, liquids, gases or vacuum.

2. Electromechanical Breakdown:

- When an electric field is applied to a dielectric (insulator) between two electrodes, a mechanical force will be exerted on the insulator due the force of attraction between the surface charges.
- Therefore as the voltage is increased, the thickness of the insulator will decrease.
- Consider plane electrodes with a solid insulator between them, **let (d_o)** is the initial thickness, then, from general electrostatic and mechanical strain theories, the field strength at breakdown (E_b) is given by:

$$E_b = V/d_o = 0.6\,[Y/ €_o€_r]^{1/2}$$

Where: **Y** is the Young's Modulus and $€_o€_r$ is the absolute permittivity

3. Electro thermal Breakdown:

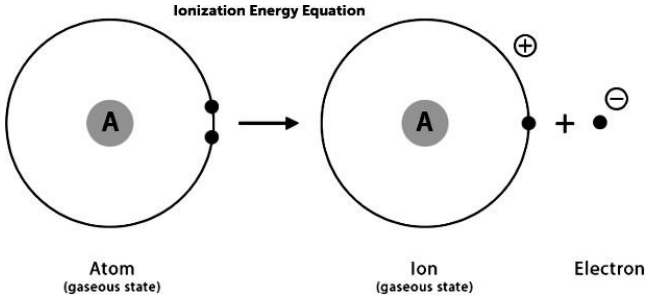
- A dielectric to which a voltage is applied liberates heat, the temperature of the dielectric rises and the losses are therefore increased still more.
- The process is intensified until the dielectric is heated so much that it gets damaged, and the breakdown of the dielectric occurs at so low voltage at which it would never develop at a low temperature and in an undamaged material.

4. Chemical breakdown:

- Insulation can degrade chemically even in the absence of an electric field due to one or more of the following causes:
  - ***i. Chemical instability***
    - The chemical structure of most insulators breaks down if subjected to excessive temperature.
    - This causes deterioration of insulating properties and loss of mechanical strength.
  - ***ii. Oxidation***
    - Some insulation oxidizes in the presence of air. This causes loss of mechanical strength and cracking the surface of the insulator. Materials which suffer oxidation include rubbers.

Ionization:

- Ionization is the process by which ions are formed by gain or loss of an electron from an atom or molecule. **(or) Ionization** in chemistry and physics, any process by which electrically neutral atoms or molecules are converted to electrically charged atoms or molecules (ions) through gaining or losing electrons.



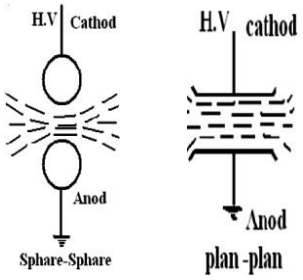
- If an atom or molecule gains an electron, it becomes negatively charged (an *anion*), and if it loses an electron, it becomes positively charged (a *cation*).
- Ionization is one of the principal ways that radiation, such as charged particles and X rays, transfers its energy to matter.
- Ionization by collision occurs in gases at low pressures when an electric current is passed through them.
- If the electrons constituting the current have sufficient energy , they force other electrons out of the neutral gas molecules, producing ion pairs that individually consist of the resultant positive ion and detached negative electron.
- Negative ions are also formed as some of the electrons attach themselves to neutral gas molecules. Gases may also be ionized by intermolecular collisions at high temperatures.
- Ionization, in general, occurs whenever sufficiently energetic charged particles or radiant energy travel through gases, liquids, or solids.
- Pulses of radiant energy, such as X-ray and gamma-ray photons, can eject electrons from atoms by the photoelectric effect to cause ionization.
- The energetic electrons resulting from the absorption of radiant energy and the passage of charged particles in turn may cause further ionization, called **secondary ionization.**

Gaseous Insulation:

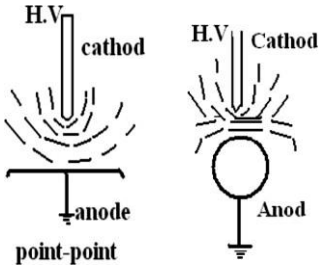
- The simplest and the most commonly found dielectrics are gases.
- Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as nitrogen (N2, carbon dioxide (CO2, freon (CCl2F2) and sulphur hexafluoride (SF6).
- When the applied voltage is low, small currents 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.
- A strongly conducting spark formed during breakdown practically produces a short circuit between the electrodes. The maximum voltage applied to the insulation at the moment of breakdown is called the **breakdown voltage.**

Electrical Discharges in Gases:

- The behavior of a gas under the application of electric field between two electrodes could in general be studied for the two following cases;
    1. Homogenous field (Uniform field) such field is normally established using the following electrodes; plane to plane or sphere to sphere electrodes.



2. Non- homogeneous fields (Non-Uniform field), such field is normally established using the following electrodes; plane – rod (point), sphere – rod (point), and rod – rod (point to point).



- 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.
- At present two types of theories, viz. (i) Townsend theory, and (U) Streamer theory are known which explain the mechanism for breakdown under different conditions.
- The various physical conditions of gases, namely, pressure, temperature, electrode field configuration, nature of electrode surfaces, and the availability of initial conducting particles are known to govern the ionization processes.

Ionization processes:

- A gas in its normal state is almost a perfect insulator. However, when a high voltage is applied between the two electrodes immersed in a gaseous medium, the gas becomes a conductor and an electrical breakdown occurs.
- The processes that are primarily responsible for the breakdown of a gas are
  (a) Ionization by collision,
  (b) photo-ionization, and
  (c) The secondary ionization processes.
- The first step which lead to breakdown is 'ionisation'
- Initial process of ionisation in gaseous dielectric, caused by electric field also known as 'electron avalanche'

(a) Ionization by collision

- The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionization.
- In the process of ionization by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion.
- If we consider a low pressure gas column in which an electric field *E* is applied across two plane parallel electrodes, as shown in fig below.
- Then, any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel towards the anode.
- If the energy($\mathfrak{E}$) gained during this travel between collisions exceeds the ionization potential, V_i ,which is the energy required to dislodge an electron from its atomic shell, then ionization takes place. This process can be represented as-

$$e^- + A \xrightarrow{\varepsilon > V_i} e^- + A^+ + e^-$$

A is the atom, A^+ is the positive ion and e^- is the electron.

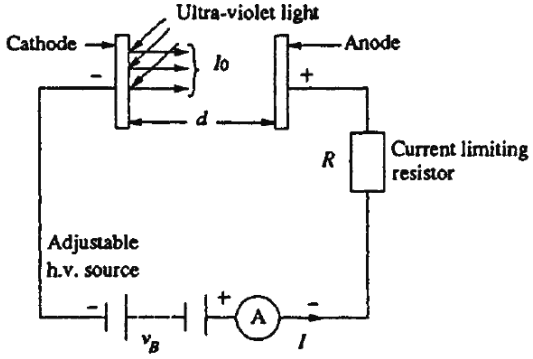


Fig — Arrangement for study of a Townsend discharge

- A few of the electrons produced at the cathode by some external means like ultra-violet light falling on the cathode, ionise neutral gas particles producing positive ions and additional electrons.
- The additional electrons, themselves make 'ionising collisions' and thus the process repeats itself. This represents an increase in the electron current, since the number of electrons reaching the anode per unit time is greater than those liberated at the cathode.
- In addition, the positive ions also reach the cathode and on bombardment on the cathode give rise to secondary electrons.

(b) Photo-ionization

- The phenomena associated with ionization by radiation, or photo-ionization, involves the interaction of radiation with matter.
- Photo-ionization occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionization potential.
- There are several processes by which radiation can be absorbed by atoms or molecules. They are
  i. Excitation of the atom to a higher energy state
  ii. Continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionization etc.
- Just as an excited atom emits radiation when the electron returns to the lower state or to the ground state, the reverse process takes place when an atom absorbs radiation. This reversible process can be expressed as –

$$h\nu + A \rightleftharpoons A^*$$

- Ionization occurs when -----

$$\lambda \leq c \cdot \frac{h.}{V_i}$$

Where, ***h*** is the Planck's constant, ***c*** is the velocity of light; λ is the wavelength of the incident radiation and $\mathbf{V_i}$ is the ionization energy of the atom is in electron volts.

- Substituting for ***h*** and ***c***, we get –

$$\lambda \leq \left(\frac{1.27}{V_i}\right) \times 10^{-6}\text{cm}$$

(c) Secondary ionization Processes

Secondary ionization processes by which secondary electrons are produced –

(i) *Electron Emission due to Positive Ion Impact:*

- A positive ion approaching a metallic cathode can cause emission of electrons from the cathode by giving up its kinetic energy on impact.
- If the total energy of the positive ion, namely, the sum of its kinetic energy and the ionization energy, is greater than twice the work function of the metal, then one electron will be ejected and a second electron will neutralize the ion.
- The probability of this process is measured as γ_i- which is called the Townsend's secondary ionization coefficient. γ_i increases with ion velocity and depends on the kind of gas and electrode material used

(ii) *Electron Emission due to Photons:*

- To cause an electron to escape from a metal, it should be given enough energy to overcome the surface potential barrier. The energy can also be supplied in the form of a photon of ultraviolet light of suitable frequency.
- Electron emission from a metal surface occurs at the critical condition

$$h.\nu \geq \varphi$$

Where,φ is the work function of the metallic electrode. The frequency (ν) is given by the relationship as fallows and is known as threshold frequency.

$$\nu = \frac{\varphi}{h}$$

(iii) *Electron Emission due to Metastable and Neutral Atoms:*

- Electrons can be ejected from the metal surface by the impact of excited (metastable) atoms, provided that their total energy is sufficient to overcome the work function.
- A metastable atom or molecule is an excited particle whose lifetime is very large (10^{-3}s) compared to the lifetime of an ordinary particle (10^{-8}s).
- This process is most easily observed with metastable atoms, because the lifetime of other excited states is too short for them to reach the cathode and cause electron emission, unless they originate very near to the cathode surface.

Townsend Discharge:

- The Townsend discharge or Townsend avalanche is a gas ionisation process where free electrons are accelerated by an electric field, collide with gas molecules, and consequently free additional electrons.

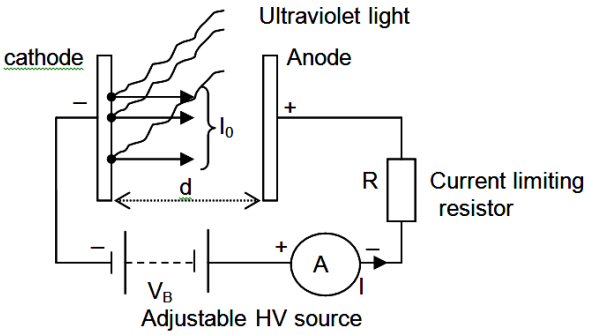


Fig. Arrangement for study of a Townsend discharge

- In a Townsend avalanche, electrons are accelerated by an electric field and ionize a background gas of neutral atoms or molecules.

- Each ionization event creates an additional electron that will also be accelerated and eventually produce more ionization events of its own.
- This process of repeated doubling results in an exponential increase in the number of electrons.
- Consider a simple electrode arrangement as shown in the fig below, having two parallel plate electrodes separated by a distance d and immersed in a gas at pressure *p*.
- A uniform *E* is applied between two electrodes. Due to any external radiation free electrons are liberated at the cathode.

- When an electron, *e* is placed in an *E* it will be accelerated with a force *eE* towards the anode, and it gains energy.

$$u = eEx = \frac{1}{2} mv^2$$

  - Where: *x* is the distance traveled by the electron from the cathode, *m* is the mass and *v* is the velocity of the electron.
- This electron collides with the other gas molecules while it is traveling towards the anode.
- If the energy of the electron is sufficiently large (about 12.2 eV for N_2 or 15.5 eV for O_2), on collision it will cause a break-up of the atom or molecule into positive ion and electron, so the new electrons and positive ions are created.
- Thus created electrons form a group or an avalanche and reach the anode. This is the electric current and if it is sufficiently large it results in the formation of a conducting path between the electrodes resulting in the breakdown of the gap.
- Townsend conducted experiments on the growth of these currents which led to breakdown under d.c. voltage conditions, and he proposed a theory to explain the phenomenon.

Townsend's First ionization Co-efficient (α):

- The average number of ionizing collisions made by an electron per centimeter travel in the direction of field is called Townsend's first ionization co efficient (α) and it depend on E/P and pressure (P).
- Let n_0 be the number of electronics leaving the cathode
  n_x be the number of electronics at the distance x from the cathode.

  When n_x electrons travels a small distance dx, produces-

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

- Separating the variable in equation above, we get-

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

  Integrating equation above equation on both sides, we get-

$$\int \frac{dn_x}{n_x} = \int \alpha dx$$
$$ln\ n_x = \alpha x + K \quad \text{.....(i)}$$

Find the value of K:

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

Substituting in equation (i), we get-

$$ln\ n_0 = K \quad \text{.....(ii)}$$

Substituting equation (i) in equation (ii), we get-

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

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

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

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

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

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

$$\therefore n_d = n_0 e^{\alpha d}$$

$$\text{Average current in the gap, } I = I_0 e^{\alpha d}$$

Where, I_0 = Initial current at the cathode.

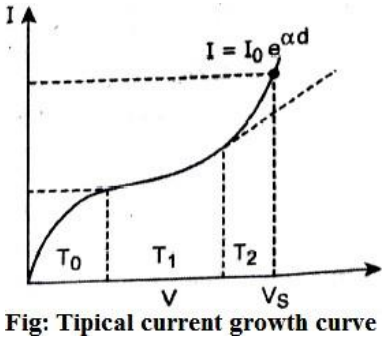


Fig: Tipical current growth curve

Townsend's Second ionization:

- Initial process of ionization in gaseous dielectric, caused by electric field also known as 'electron avalanche'

****mechanism for producing additional electrons to create avalanches***

- 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, emissions of electrons take place.
- The excited particle or metastable particles may diffuse back, causing electron emission.
- The electrons produced by these processes are called secondary electrons.

Townsend's Second ionization Co-efficient (γ):

- The number of secondary electrons produced per incident positive ions, photons, excited particles or metastable particles and the total value of all is called Townsend's Second ionization Co-efficient (**γ**).
- The secondary ionization coefficient **γ** is defined in the same way as **α** and is a function of the gas pressure p and E/p.
- Following Townsend's procedure for current growth

- Let

  n'_0 = number of secondary electrons produced due to secondary **γ** processes.

  n''_0 = total number of electrons leaving the cathode.

  Then $n''_0 = n_0 + n'_0$

let n is the total number of electrons leaving the anode.

$$n = n_0'' e^{\alpha d} = (n_0 + n_0') e^{\alpha d} \quad \text{.....(i)}$$

Number of electronics released from the gas,

$$n_0' = n - (n_0 + n_0')$$
$$n_0' = n\gamma - n_0\gamma - n_0'\gamma$$
$$n_0'[1+\gamma] = \gamma[n - n_0]$$
$$n_0' = \frac{\gamma}{1+\gamma}[n - n_0] \quad \text{.....(ii)}$$

To eliminate n_0", substitute the equation (ii) in equation (i), we get-

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

Total average current in the gap before breakdown $\Big\}$ $I = \dfrac{I_0 e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)}$

Townsend's Criterion for Breakdown

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

- 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 $d = d_s$

$$1 - \gamma[\exp(\alpha d) - 1] = 0$$

- 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 $\gamma[\exp(\alpha d) - 1] = 1$
- Normally, exp (αd) is very large, and hence the above equation reduces to

  y exp (ad) = $\gamma \exp(\alpha d) = 1$
- 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 ofα 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.

Breakdown in Electronegative Gases:

- Electronegative gases are the gases that have similarity towards electrons.
- When electron comes into contact with these gas molecules, the gas molecule attracts the electrons and becomes negative ion.
- The gases, which are lacking in one or two electrons in their outer shell are known as **electronegative gases.**
- 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
- The most common attachment processes encountered in gases are -
  a) Direct attachment: An electron directly attaches to form a negative ion.

$$AB + e \cdot \rightarrow AB^{-}$$

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

$$AB + e \cdot \rightarrow A + B^{-}$$

- 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,

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

  - 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,

$$\gamma \frac{\alpha}{\alpha - \eta} = 1 \text{ or } \alpha = \frac{\eta}{1 - \gamma}$$

- Normally γ is very small $\left(\leq 10^{-4}\right)$ 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 $Vcm^{-1}torr^{-1}$, for CCl_2F_2 121 $Vcm^{-1}torr^{-1}$ both at 20˚C. η values can also experimentally determined. Typical values of η in SF_6 are shown in above figure (2).

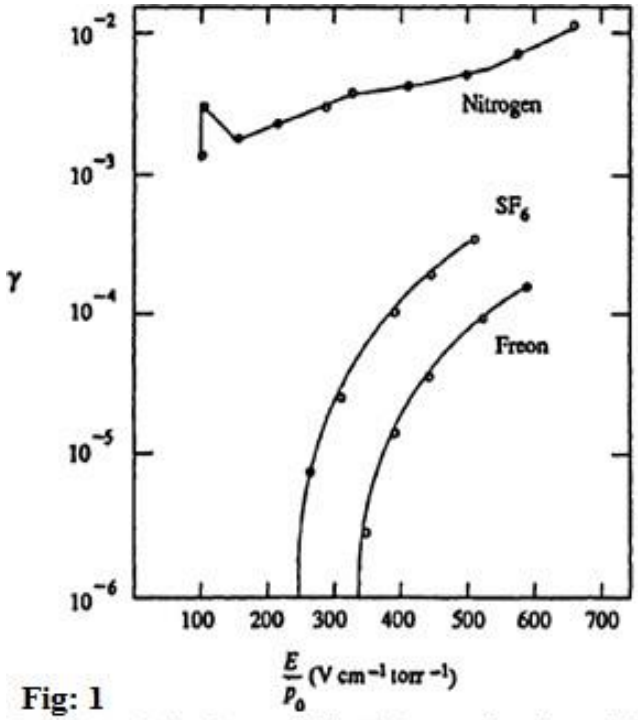


Fig: 1

Secondary ionization coefficient (γ) as a function of *E/p* in nitrogen, freon and SF_6 gases

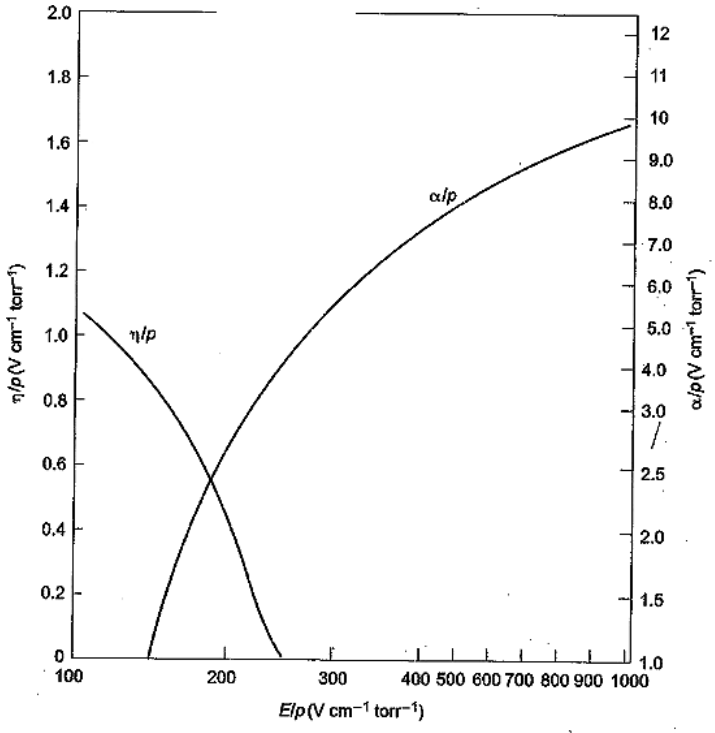
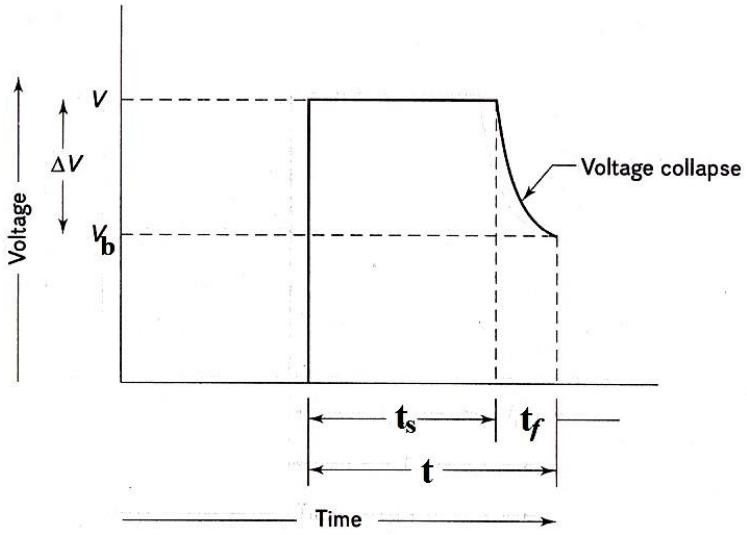


Fig. 2 *Values of α/p and η/p as a function of E/p in SF_6 at 20°C*

Time Lags for Breakdown

- There is a time difference between the application of voltage sufficient to cause breakdown and the occurrence of breakdown in dielectric. This time difference is called as the time lag.
- The figure shows a breakdown with a step function voltage pulse.

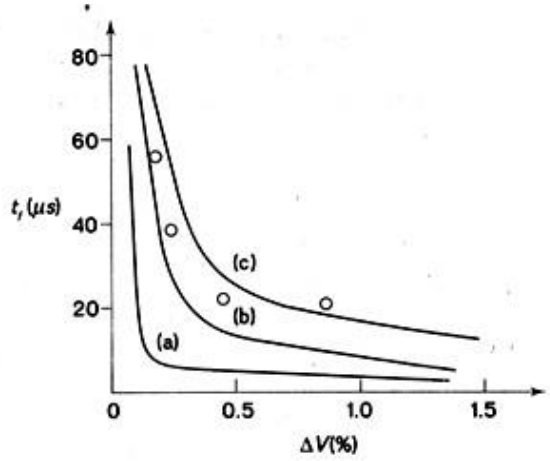


Breakdown with a step function voltage pulse. t_s = statistical time; t_f = formative time; t = total time

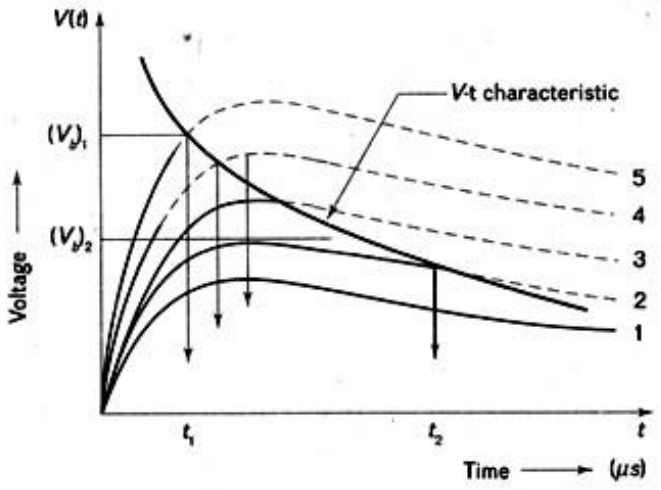
- The time *t* which lapses between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag (**t_s**) of the gap.
- After the appearance of the electron, a time ***t_f*** is required for the ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag ***(t_f)*.**
- The total time **t_s**+ ***t_t* = *t*** is called the total time lag.
- The difference in voltage ΔV = V- V_b is called the overvoltage, and the ratio V/V_b is called the impulse ratio.

<u>Time lag characteristics:</u>

- The time lag characteristic is the variation of the breakdown voltage with time of breakdown, and can be defined for a particular wave shape.
- The time lag characteristic based on the impulse waveform is shown in below.
- In uniform and fairly non-uniform field gaps, the characteristic is sharply defined and rises steeply with increasing rate of rise of the applied voltage.



Formative time lag (t_f) as a function of ΔV. a, b, c are for different gap spacings, ○ experimental point–calculated



Voltage-time characteristics

- In non-uniform field gaps there will be a large scatter in the results, and the time to breakdown will be less sensitive to the rate of rise of applied voltage.
- Hence fairly uniform field gaps such as sphere gaps are often used as protective devices against over-voltages in electric power systems.

Limitations of Townsend Theory :

1. 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.
2. 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.
3. Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular.

STREAMER THEORY OF BREAKDOWN IN GASES:

- Around 1940, Raether and Meek and Loeb independently proposed the Streamer Theory of Breakdown in Gases.
- Avalanche breakdown or streamer breakdown is a phenomenon that can occur in both insulating and semiconducting materials.
- When the field is uniform and space charge due to ions lesser than electrical field E, the charges present in between the electrodes increase by a factor $e^{\alpha d}$. Where d id gap distance and α is Townsend's coefficient.

Streamer Mechanism:

- The Streamer theory predicts the development of a spark discharge directly from a single avalanche.
- The space charge produced in the avalanche causes sufficient distortion of the electric field that those free electrons move towards the avalanche head, and in so doing generate further avalanches in a process that rapidly becomes cumulative.
- As the electrons advance rapidly, the positive ions are left behind in a relatively slow-moving tail.

- The field will be enhanced in front of the head. Just behind the head the field between the electrons and the positive ions is in the opposite direction to the applied field and hence the resultant field strength is less.
- Again between the tail and the cathode the fieldis enhanced as shown in below figure.

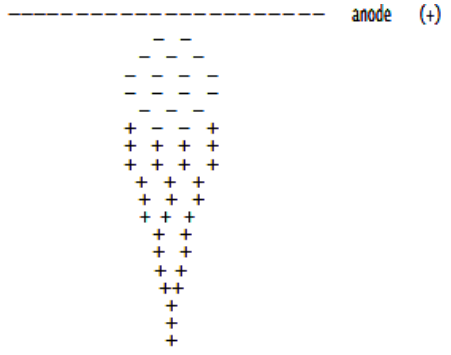


Figure – Streamer Mechanism

- Due to the enhanced field between the head and the anode, the space charge increases, causing a further enhancement of the field around the anode.
- The process is very fast and the positive space charge extendsto the cathode very rapidly resulting in the formation of a streamer.
- The below figures shows the breakdown process.

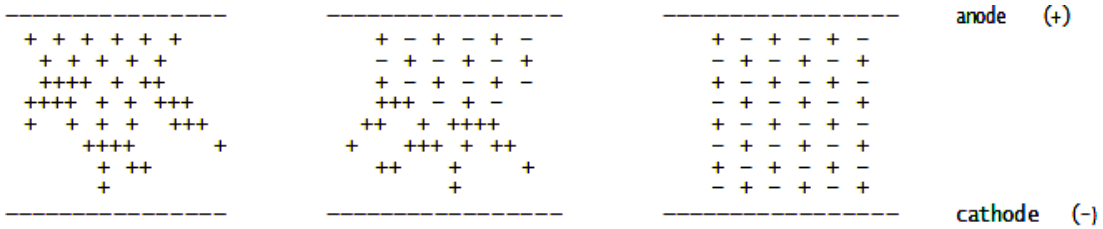


Figure - Streamer breakdown

Streamer discharge:

- **A streamer discharge**, also known as filamentary discharge, is a type of transientelectrical discharge.
- We know that the charges in between the electrodes separated by a distance d increase by a factor $e^{\alpha d}$ when field between electrodes is uniform.
- This is valid only if we assume that the field $E_0 = V/d$ is not affected by the space charges of electrons and positive ions.
- Raether has observed that if the charge concentration is higher than 10^6 but lower than 10^8 the growth of an avalanche is weakened i.e., $dn/dx < e^{\alpha d}$.

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

- Whenever the concentration exceeds 10^8, the avalanche current is followed by steep rise in current and breakdown of the gap takes place.
- The weakening of the avalanche at lower concentration and rapid growth of avalanche at higher concentration gives the modification of the electric filed E due to the space charge filed.

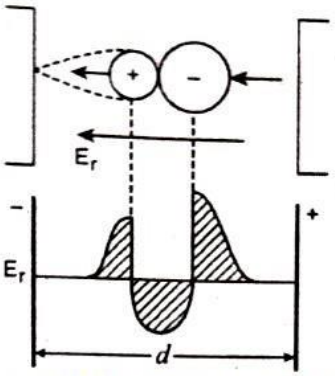


Fig: Filed distortion in a gap due to space charge

- The filed distortion in a gap due to space charge as shown in figure.
- The space charge at the head of the avalanche is assumed to have a sphere containing negative charge at its top.
- Due to filed lines from anode, the field get enhanced at the top of avalanche.
- At the bottom of avalanche, the field between electrodes opposes the applied field, thereby reduces the applied voltage (E).
- Still further decreasing the field between cathode and positive ions get enhanced. Thus filed distortion takes place.
- At the charge density in avalanche is n = 10^8, streamer breakdown occurs.
- Now space charge filed = Applied electrical filed.
- Thus space charge filed plays an important role in the growth of avalanche in corona and non- uniform filed 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.

Formation of secondary avalanche:

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

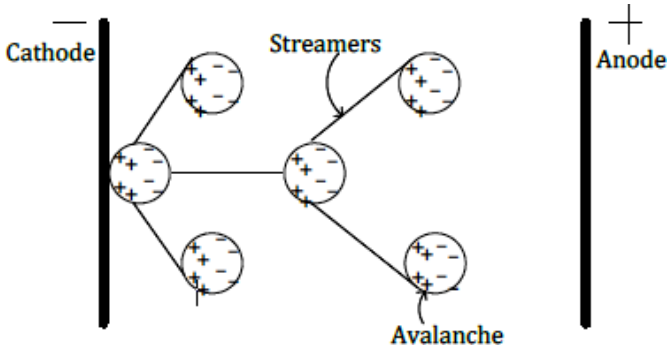


Fig: Formation of secondary avalanches due to photoionization

Expression for streamer spark criterion is,

$$\alpha x_c = 17.7 + ln\, x_c + ln\left[\frac{E_r}{E}\right]$$

where, E_r = Space charge field.

E = Applied electric field.

Condition for transition from avalanche to streamer is,

$$E_r = E$$

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

Minimum breakdown value occurs when $x_c = d$

where, d = Gap length

$\therefore$ Breakdown criterion is $\alpha d = 17.7 + ln\, d$

Meek's Expression:

- Space charge filed, Er

$$E_r = 5.27 \times 10^{-7} \frac{\alpha e^{\alpha x}}{\left(\frac{d}{p}\right)^{\frac{1}{2}}}$$

Where α is the Townsend's ionization coefficient

p= Gas pressure in torr.

- To determine minimum breakdown voltage,
  Substitute Er = E and x =d in equation above, we get-

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

- taking *ln* on both sides, we get-

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

- Substituting *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 the corresponding E/p values are used to solve this equation using trial and error method.
- Values of α/p and E/p are chosen until the equation is satisfied.

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:

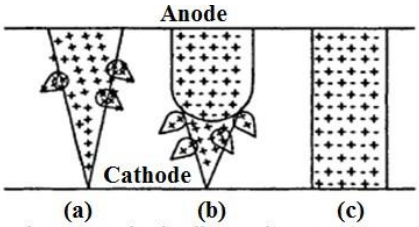


Figure : Cathode-directed streamer as envisaged by Meek and Loeb: (a) First Avalanche Crossing the Gap (b) Streamer Extending from the Anode (c) Streamer Crossing the Gap.

- 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, $E_r = \kappa E \quad where\ \kappa \approx 1$

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

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.

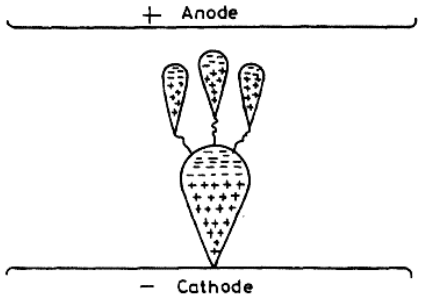


Figure: Anode-directed streamer as envisage by Raether

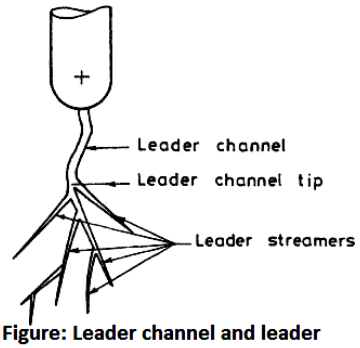


Figure: Leader channel and leader streamers

Paschen Breakdown | Paschen's Law | Paschen Curve:

- 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.

$$V=f(pd)$$

- Townsend's breakdown criterion for gases is,

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

- where α, ɣ are the Townsend's ionization coefficients and are function of E/p

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right) \Rightarrow \alpha = p \cdot f_1\left(\frac{E}{p}\right) \quad \text{--------} \textbf{ (ii)}$$

$$\gamma = f_2\left(\frac{E}{p}\right) \quad \text{----------}\textbf{(iii)}$$

- Substituting equations (ii) and (iii) in equation (i), we get-

$$f_2\left(\frac{E}{p}\right)\left[e^{p\cdot f_1\left(\frac{E}{p}\right)d}-1\right] = 1 \quad \textbf{-------(iv)}$$

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

- Equation (iv) becomes-

$$f_2\left(\frac{V}{pd}\right)\left[e^{pd\,f_1\left(\frac{V}{pd}\right)}-1\right] = 1$$

- This equation shows a relationship between voltage and p d.
- Knowing the nature of functions f_1 and f_2, we can rewrite equation above as-

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

- The breakdown voltage of a uniform filed gap is a unique function of the production 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 figure below.

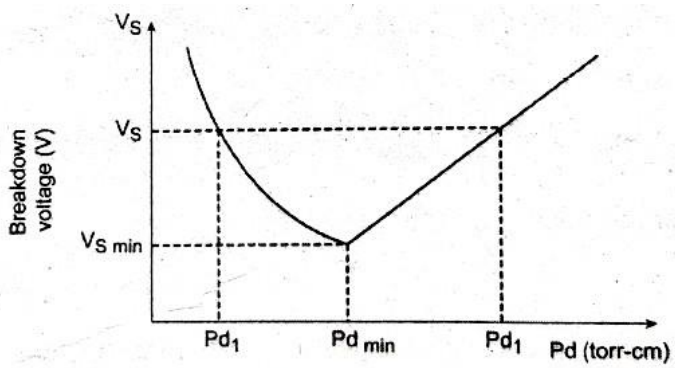


Fig.Paschen's curve

- Paschen's curve shows that the Vs value decreases initially as pd increases and reaches minimum value at Vs_{min} and then increses linearly.
- To account the effect of temperature, Paschen's law becomes

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

where, N = Density of air molecules.

From gas law $pv = NRT$

$$\Rightarrow N = \frac{pv}{RT}$$

where, v = Volume of the gas.

R = Constant.

T = Temperature.

Note:

- We know that $V = f(p\,d)$. The relationship between *V and pd* is not linear and has has a minimum value for any gas. The minimum breakdown voltages for various gases are as follow-

Gas	V_{min} (V)	p.d at V_{min}(torr-cm)
Air	327	0.567
Argon	137	0.9
Hydrogen	273	1.15
Helium	156	4.0
Carbon dioxide	420	0.51
Nitrogen	251	0.67
Nitrous oxide	418	0.5
Oxygen	450	0.7
Sulphur dioxide	457	0.33
Hydrogen Sulphide	414	0.6

CORONA DISCHARGE:

- 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 filed 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 phenomenan of faint violet glow, hissing noise and ozone gas produced in the transmission lines during rainy seasons is called as corona.
- 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 luminescence.

a. This is accompanied by a hissing noise.
b. The air surrounding the corona region becomes converted into ozone.
c. It is responsible for considerable loss of power from high voltage transmission lines
d. 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.
e. It also gives rise to radio interference.

Mechanism of Corona formation on a two conductor line:

- When a gradually increasing voltage is applied across two conductors, initially nothing will be seen or heard.
- As the voltage is increased, the air surrounding the conductors get ionised, and at a certain voltage a hissing noise is heard caused by the formation of corona.
- This voltage is known as the disruptive critical voltage (d_{cv}).
- A further increase in the voltage would cause a visible violet glow around the conductors. This voltage is the visual corona inception voltage.
- The formation of corona causes the current waveform in the line, and hence the voltage drop to be non- sinusoidal. It also causes a loss of power.

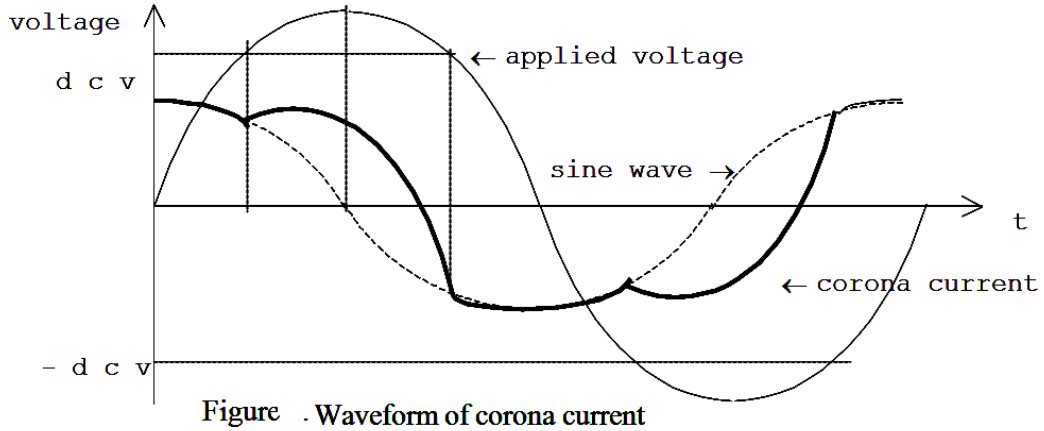
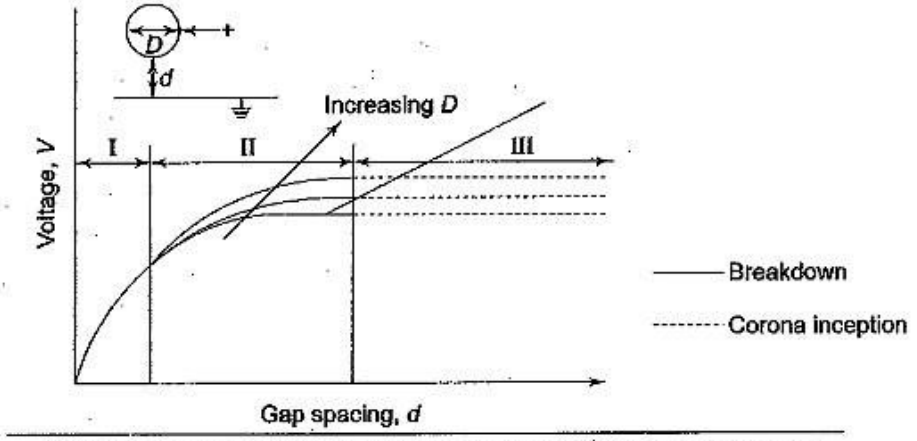


Figure . Waveform of corona current

- At sufficiently high voltage, current amplification increases rapidly with voltage, up to a current of about 10^{-7} A, after which the current becomes pulsed with repetition frequency of about 1 kHz composed of small bursts.
- This form of corona is called **burst corona**. The average current then increases steadily with applied voltage leading to breakdown.



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

- The **corona inception** and breakdown voltages of the sphere-plane arrangement are shown in above figure. From this figure it can be seen that
  - At small spacings (region I), the field is uniform, and the breakdown voltage mainly depends on the spacing;
  - at fairly large spacings (region II), the field is non-uniform, and the breakdown voltage depends both on the sphere diameter and the spacing; and
  - at large spacings (region III), the field is non-uniform, and the breakdown is preceded by corona and is controlled only by the spacing. The Corona Discharges inception voltage mainly depends on the sphere diameter.
- 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

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

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

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

- 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 °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.

Comparison between Townsend's Theory and Streamer's Theory:

S. No	Townsend's Theory	Streamer's Theory
1	Theory states, current growth occurs as a result of ionization processes only.	Theory states, breakdown voltages were bound to depend on gas pressure and geometry of the gap.
2	This mechanism predicts a very diffused form of discharge.	This mechanism predicts discharges were found to be filamentary irregular.
3	Theory gives equation to prove Townsend's criterion Y [exp (αd) – 1] = 1	Theory gives equation αd + *l*n (α/p) 14.5 *l*n (E/p) + 1/2 *l*n(d/p) this tells streamer's criterion.
4	Primary and secondary ionization causes avalanche breakdown.	The space charges fields play an important role in growth of avalanche in corona a spark discharges in non-uniform field gaps.
5	The mechanism predicts time lags of order of 10^{-5} sec.	Breakdown occurs at very short times of the order of 10^{-8} sec.
6	Townsend's mechanism operates for pd values below 1000 torr-cm and gas pressures varying from 0.01 to 350 torr.	Streamer's mechanism operates for higher values of pressure and higher value of pd.

Breakdown in Non-Uniform Fields:

1. It is an electric discharge mainly occurring at non uniform electric field
2. Visual and audible discharge
3. The corona will occur when the strength of the electric field around a conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects.
4. It is often seen as a bluish (or other color) glow in the air adjacent to pointed metal conductors carrying high voltages, and emits light by the same property as a gas discharge lamp.
5. Potential difference between two electrodes should be greater than threshold value (30kV).

Explanation:

- In Breakdown 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 [$\gamma \exp(\alpha d) = 1$] is rewritten by replacing αd by-

$$\alpha d \text{ by } \int_0^d \alpha \, dx$$

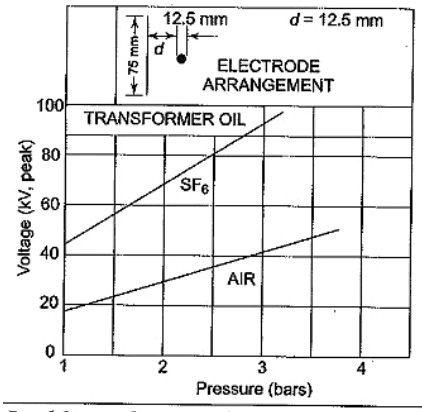
- Townsend's criterion for breakdown now becomes-

$$\gamma \left\{ \exp \left[\int_0^d \alpha \, dx \right] - 1 \right\} = 1$$

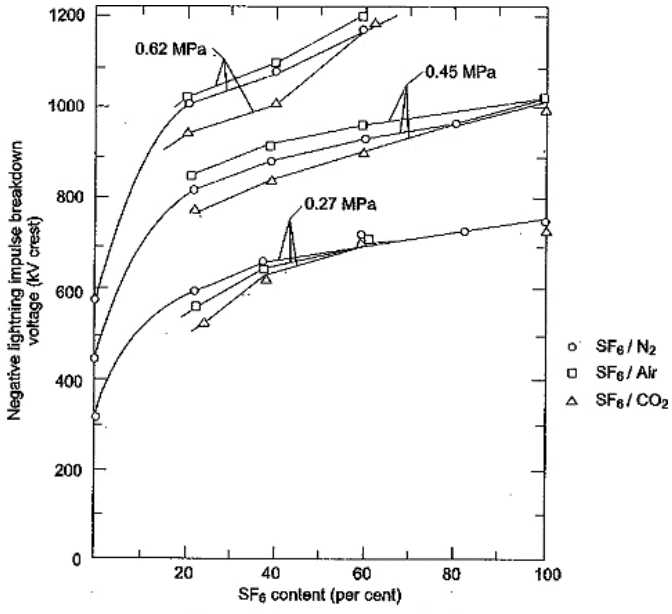
- Meek and Raether also discussed the non-uniform field breakdown process as applied to their Streamer theory, and the Meek's equation [$\gamma \frac{\alpha}{(\alpha - \eta)} = 1$; or $\alpha = \frac{\eta}{(1-\gamma)}$ f] or the radial field at the head of an avalanche when it has crossed a distance x is modified as

$$E_r = \frac{5.27 \times 10^{-7} \, \alpha_x \exp\left(\int_0^x \alpha \, dx \right)}{(x/p)^{1/2}} \text{ V/cm}$$

- where α_x is the value of α at the head of the avalanche, and p is the gas pressure.



Breakdown voltage as a function of pressure in SF_6



Negative lightning impulse (1.2/40 μs) breakdown Voltage in mixtures of SF_6 with N_2, Air and CO_2 for coaxial electrode system

- The criterion for the formation of the streamer is reached when the space charge field E_r approaches a value equal to the applied field at the head of the avalanche.
- This equation has been successfully used for determining the corona onset voltages of many non-uniform geometries.
- Figures below shows the breakdown characteristics for SF_6 and SF_6/N_2 mixtures.

Sulphurhexafluoride (sf6) insulation:

- Sulphurhexafluoride (SF6) possess most of the above requirements.
- Dielectric strength is the most important property of a gaseous dielectric for practical use.
- From the figures and the table, it can be seen that SF6has high dielectric strength and low liquification temperature, and it can be used over a wide range of operating conditions.
- SF6was also found to have excellent arc-quenching properties. Therefore,
- It is widely used as an insulating as well as arc-quenching medium in high voltage apparatus such as high voltage cables, current and voltage transformers, circuit breakers and metal enclosed substations.

Vacuum insulation:

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.

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.
- According to the Townsend theory, the growth of current in a gap depends on the drift of the charged particles.
- In the absence of any such particles, as in the case of perfect vacuum, there should be no conduction and the vacuum should be a perfect insulating medium.
- However, in practice, the presence of metallic electrodes and insulating surfaces within the vacuum complicate the issue and, therefore, even in vacuum, a sufficiently high voltage will cause a breakdown.

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

Properties of Perfect Vacuum

The properties of perfect vacuum should be

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

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.

Classifications of breakdown mechanism in Vacuum

1. Particle Exchange Mechanism
2. Field Emission Mechanism
3. Clump Theory

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 the absorbed gases.
- These particles accelerate and impinge on the first electrode when voltage is applied and produces more number of original type particles.
- A chain reaction takes place when this process repeats and leads to breakdown of gases.

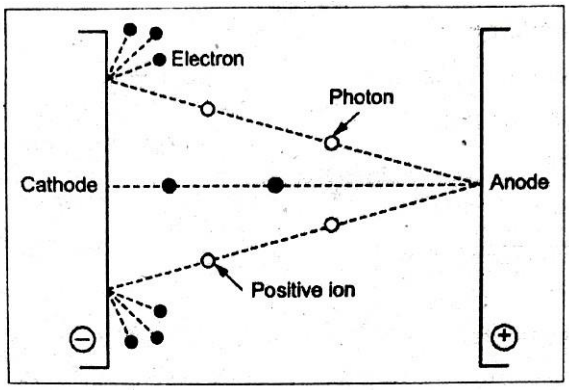


Fig. Particle exchange mechanism of vacuum breakdown

- Break down criterion (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

- Modifications (AB+EF)>1,

where, E = Number of electrons liberated by positive ions.

F = Number of electrons liberated by photons.

- Product Ef closer to unity for copper, aluminum, and stainless electrodes.

2. Field Emission Theory:

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

(a) Anode Heating Mechanism:

- Cathode produce electrons due to field emission mechanism. These electrons accelerate and bombard the anode and increase temperature and releases gases in ions.
- These electrons ionize the atoms of the gas and produce positive ions.
- These positive ions accelerate toward cathode and increase the number of electrons emitted due to space change formation.
- This process continue until breakdown of vacuum occurs as in Townsend breakdown.

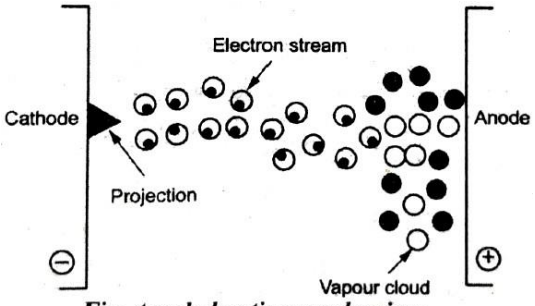


Fig. Anode heating mechanism

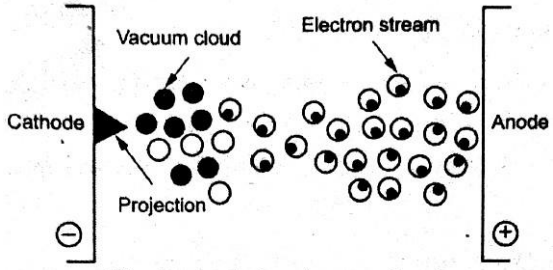


Fig. Cathode heating mechanism

(b) Cathode Heating Mechanism:

- The pre-breakdown current causes resistive heating at the projections in the cathode. tip melts due to heating and explodes and injects vacuum discharge. This is called as cathode heating mechanism. The initiation of breakdown depends on the conditions and properties of cathode surface. (Breakdown strength-106 to 107 V/cm)

3. Clump Mechanism

The assumptions on the clamp mechanisms are:

- A loosely bound particle (Clump) exist on one of the electrode.
- Clump particle get charged, accelerated in the gap when high voltage is applied.
- The particles reaches the other electrode and discharges vapour and breakdown occurs.

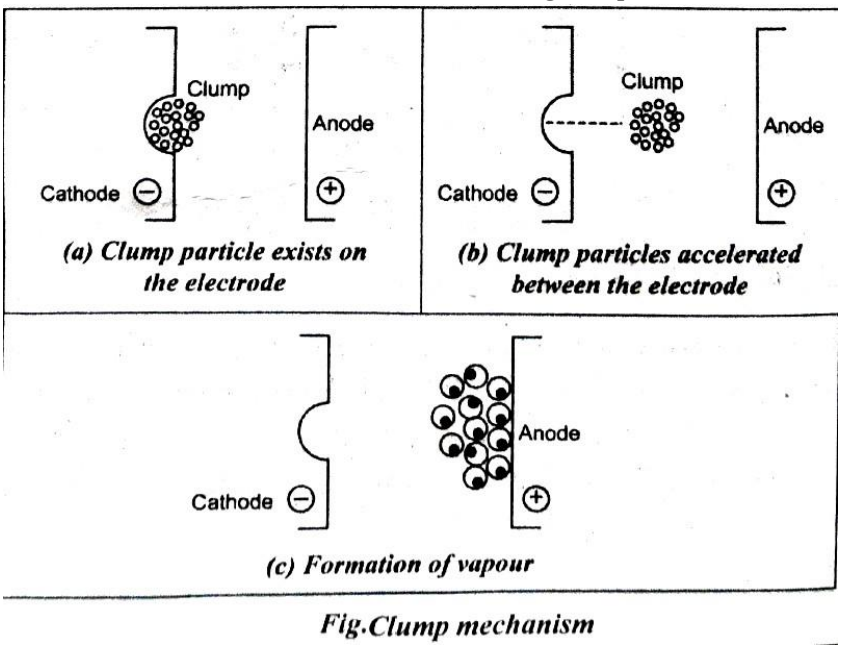


Fig.Clump mechanism

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

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

$$\therefore \quad W = V \times E = C' \qquad \ldots (1)$$

This is the criterion for breakdown.

For parallel plane electrodes, $E = \frac{V}{d}$ $\qquad \ldots (2)$

where, d = Distance between the electrodes.

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

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

$$V^2 = C' d$$

$$V = \sqrt{C' d} \qquad \ldots (3)$$

This is the generalized criterion for breakdown.

Breakdown strength of Air:

- Based on the experimental results, the breakdown potential of air is expressed as a power function in *pd as*

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

- The breakdown strength of air at room temperature (*2O°C / 293°K)*and at atmospheric pressure (760 torr) is

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

- This equation yields *a value of* 30 kV/cm for *d= 1 cm gap.*

LIQUIDS AS INSULATORS

- In highly purified liquid dielectrics, breakdown is controlled by phenomena similar to those for gasses and the electric strength is high (of the order of 1 MV/cm).
- Unfortunately, liquids are easily contaminated, and may contain solids, other liquids in suspension and dissolved gasses. The effect of these impurities is relatively small for short duration pulses (10μs).

Table — Dielectric Properties of Some Liquid Dielectrics

Property	Transformer oil	Cable oil	Capacitor oil	Askerels	Silicone oils
Breakdown strength at 20°C on 2.5 mm standard sphere gap	15 kV/mm	30 kV/mm	20 kV/mm	20-25 kV/mm	30-40 kV/mm
Relative permittivity (50 Hz)	2.2-2.3	2.3-2.6	2.1	4.8	2-73
Tan δ (50 Hz)	0.001	0.002	0.25×10^{-3}	0.60×10^{-3}	10^{-3}
(1 kHz)	0.0005	0.0001	0.10×10^{-3}	0.50×10^{-3}	10^{-4}
Resistivity (ohm-cm)	10^{12}-10^{13}	10^{12}-10^{13}	10^{13}-10^{14}	2×10^{12}	3×10^{14}
Specific gravity at 20°C	0.89	0.93	0.88-0.89	1.4	1.0-1.1
Viscosity at 20°C (CS)	30	30	30	100-150	10-1000
Acid value (mg/gm of KOH)	Nil	Nil	Nil	Nil	Nil
Refractive index	1.4820	1.4700	1.4740	1.6000	1.5000-1.6000
Saponification (mg of KOH/gm of oil)	0.01	0.01	0.01	< 0.01	< 0.01
Expansion (20 – 100°C)	7×10^{-4}/°C	7×10^{-4}/°C	7×10^{-4}/°C	7×10^{-1}/°C	5×10^{-4}/°C
Maximum permissible water content (in ppm)	50	50	50	< 30 (negligible)	< 30 (negligible)

- Oil is about 10 times more efficient than air or nitrogen in its heat transfer capability when used in transformers
- Liquid dielectrics are used mainly as impregnates in high voltage cables and capacitors, and for filling up of transformers, circuit breakers etc. Liquid dielectrics also act as heat transfer agents in transformers and as arc quenching media in circuit breakers.
- Petroleum oils (Transformer oil) are the most commonly used liquid dielectrics. Synthetic hydrocarbons and halogenated hydrocarbons are also used for certain applications.
- Liquid dielectrics normally are mixtures of hydrocarbons and are weakly polarized. When used for electrical insulation purposes they should be free from moisture, products of oxidation and other contaminants.

Classification of liquid dielectrics:

- Depending up on the very good electrical, physical and thermal properties the fallowing liquids are used for insulating purpose.

(a) Transformer oil (Mineral oil):

- Transformer oil is the most commonly used liquid dielectric in power apparatus. It is an almost colorless liquid consisting of a mixture of hydrocarbons which include paraffins, iso-paraffins, naphthalenes and aromatics.
- When in service, the liquid in a transformer is subjected to prolonged heating at high temperatures of about 95^0C, and consequently it undergoes a gradual ageing process.
- With time the oil becomes darker due to the formation of acids and resins, or sludge in the liquid. Some of the acids are corrosive to the solid insulating materials and metal parts in the transformer.

(b) Synthetic Hydrocarbons:

- Over 55% Synthetic Hydrocarbons produced worldwide today are polyolefins. These are used for power cables.

- The most commonly used olefins are polybutylene and alkylaromatic hydrocarbons. Their general characteristics are similar to mineral oils.

(c) Chlorinated Hydrocarbons:

- Two aromatic Hydrocarbons, benzene and diphenyl are chlorinated to produce chlorinated aromatic components called askarels or simply polychlorinated biphenyl (PCB).
- They possess high fire point and excellent electrical properties. But they pose serious health hazards.

(d) Silicone oils:

- Silicone oils represent an alternative to PCBs but they are expensive. Even at a temperature of 150^{o}c, they exhibit high long- term thermal stability.
- Silicone oils are resistance to most chemicals and are oxidation resistant, even at higher temperature, so they can use at higher temperature then mineral oils.

(e) Esters:

- Natural esters such as castor oil has been used as a capacitor impregnant for many years, but currently two types of synthetic esters are being used, viz., organic esters and phosphate esters.
- Organic esters have high boiling points in relation to their viscosity and, therefore high fire points.
- They have a good viscosity- temperature relationship and used extensively in capacitors.
- The phosphate esters have high boiling point and low flammability and therefore are used in transformers that they are to be installed in hazardous areas.

(f) Latest developments:

- In recent years some of oils are introduced like high- temperature hydrocarbon oil, tetrachloroethylene and perfluoropolyether.
- High temperature hydrocarbon (HTH) oils have good electrical insulating properties and adequate heat transfer properties. They are similar to regular mineral transformer oil, but possess higher boiling point and high fire point. However , they have higher viscosity which reduces the heat transfer capability.

Characteristics of liquid dielectrics:

- A liquid dielectric should possess good dielectric properties, excellent heat transfer characteristics and must be chemically stable under the range of conditions under which the equipment operates. The characteristics are consider as follows-
  i. Electrical Properties
  ii. Heat transfer characteristics:
  iii. Chemical stability:

(i) Electrical Properties:

- The electrical properties that are essential in determining the dielectric performance of a liquid dielectric are
  a) Its capacitance per unit volume or its relative permittivity
  b) Its resistivity.
  c) Its ability to withstand high electric stresses.
  d) Its loss tangent (tan δ) or its power factor which is an indication of the power loss under a.c. voltage application

(a) permittivity:

- Permittivity of most of the petroleum oils vary from 2.0 to 2.6 while those of silicon oils from 2.0 to 73.
- In case of the non-polar liquids, the permittivity is independent of frequency but in the case of polar liquids, such as water, it changes with frequency.
- For example, the permittivity of water is 78 at 50 Hz and reduces to about 5.0 at 1 MHz.

(b)** Resistivity**:

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

(c) Dielectric strength:

- The dielectric strength depends on the atomic and molecular properties of the liquid itself.
- However, under practical conditions the dielectric strength depends on the material of the electrodes, temperature, type of applied voltage, gas content in the liquid etc., which changes the dielectric strength by changing the molecular properties of the liquid.

(d) Power Factor:

- Power Factor of a liquid dielectric under a.c. voltage will determine its performance under load conditions.
- Power factor is a measure of the power loss and is an important parameter in cable and capacitor systems.
- Pure and dry transformer oil will have a very low power factor varying between 10^{-4} at 20^{o}C and 10^{-3} at 90^{o}C at a frequency of 50 Hz.

(ii) Heat transfer characteristics:

- In dielectric liquids filled equipments (transformers, cables, circuit breakers, etc.) heat is transferred mainly by convection.
- Under natural atmospheric cooling conditions convection (N) is given by -

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

Where, K is thermal conductivity
A is the coefficient of expansion
C is specific heat per unit volume
v is the kinetic viscosity, and
n = 0.25~ 0.33.

- The main factors that control the heat transfer are thermal conductivity (K) and viscosity (v). Higher thermal conductivity (K) is preferable for apparatus operate continuously at a high temperature.
- On other hand low K and viscosity can lead to localizing the overheating or even electrical 'burn out'

(iii) Chemical stability:

- The presents of O_2, water, fiber and solid insulating particles cause degradation of the liquid which results the corrosion, impairment of the heat transfer, deterioration of electrical properties, increased dielectric losses, discharge and arcing. So liquids should be pure and good chemical stability.

Pure Liquids and Commercial Liquids:

- ***Pure liquids***Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 109, and are structurally simple.
- Examples of such simple pure liquids are n- hexane (C_6H_{14}), n-heptane (C_7H_{16}) and other paraffin hydrocarbons.
- The ***commercial liquids*** which are insulating liquids like oils which are not chemically pure, normally consist of mixtures of complex organic molecules which cannot be easily specified or reproduced in a series of experiments.

(i) Purification of a liquid for testing:

a) Removal of dust:

- Small dust particles can become charged and cause local stresses which can initiate breakdown.
- They can also coalesce to form conducting bridges between electrodes.
- Careful filtration can remove dust particles greater in size than 1 μm. The strength of the liquid then increases and greater stability is achieved.

b) Removal of dissolved gasses:

- Liquid insulation will normally contain dissolved gas in small but significant amounts.
- Some gases such as Nitrogen and Hydrogen do not appear to upset the electrical properties to a great extent, but oxygen and carbondioxide can cause the strength to change significantly.
- Thus it is necessary to control the amount of gasespresent. This is done by distillation and degassing.

c) Removal of ionic impurities:

- Ionic impurities in the liquid (particularly residual water which easily dissociates) leads to abnormal conductivity and heating of the liquid.
- Water can be removed by drying agents, vacuum drying, and byfreezing out in low temperature distillation.

(ii) Breakdown Tests:

- Breakdown tests are normally conducted using test cells.
- For testing pure liquids, the test cells used are small so that less quantity of liquid is used during testing.

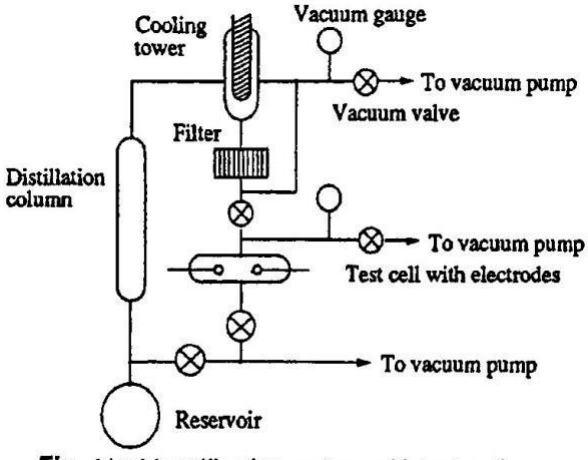


Fig. Liquid purification system with test cell

- The electrodes used for breakdown voltage measurements are usually spheres of 0.5 to 1 cm in diameter with gap spacing of about 100-200 μm.
- The gap is accurately controlled by using a micrometer.
- Electrode separation is very critical in measurements with liquids, and also the electrode surface smoothness and the presence of oxide films have a marked influence on the breakdown strength.
- The test voltages required for these tests are usually low, of the order of 50-100 kV, because of small electrode spacing.

Conduction and breakdown in pure liquids:

- Pure liquids are chemically pure and do not contain any other impurities even when traces of 1 in 10^9, and has simple structures.
  Examples: n- Hexane, n- Heptane, Other paraffin hydrocarbons
- When low electric field < 1 KV/cm, conductivities of 10^{-18} – 10^{-20} mho/cm are obtained. These are probably due to the impurities present after purification.
- When electric fileds > 100 kV/cm), the currents increase rapidly and violent fluctuations occurs. The fluctuations reduces and die out after some tim. This is condition for breakdown of pure liquids. which will die down after some time.
- A typical mean value of the conduction current in hexane is shown below

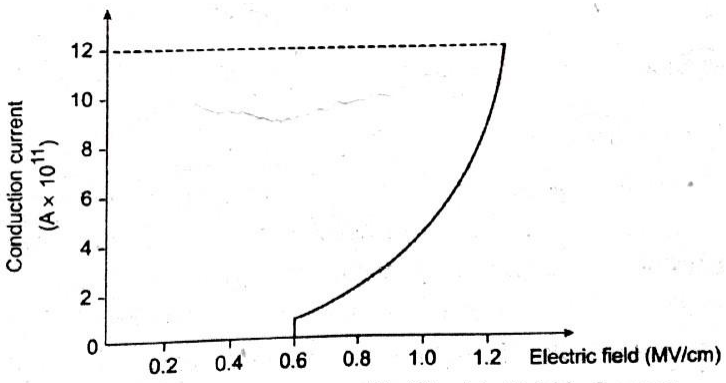


Fig. Conduction current Vs Electric field in hexane

- This is the condition nearer to breakdown. However, if this figure is redrawn starting from very small currents, a current-electric field characteristic as shown in fig below-

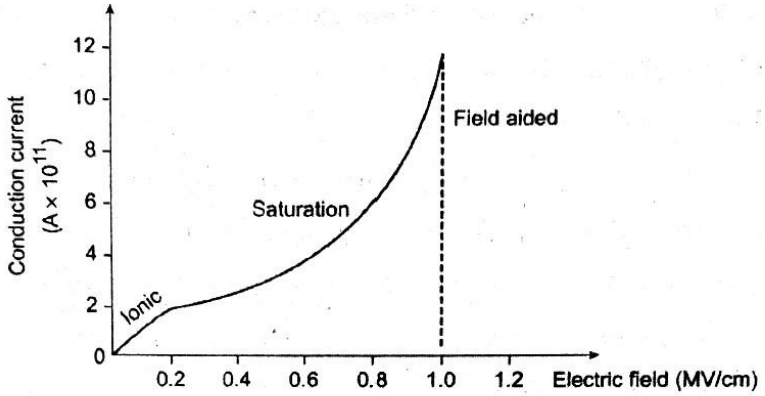


Fig. Conduction current Vs Electric field in hydrocarbon

- **This curve has three regions-**
  (i) Ionic region- At law fields
  - At very low fields the current is due to the dissociation of ions.

(ii) Saturation region- At intermediate fields

- 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 increase in current by these processes continues till breakdown occurs.

(iii) Filed aided electron emission from cathode- At high fields

- As the breakdown field is approached, the current increases rapidly due to a 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
  - Filed gap separation
  - Cathode work-function
  - Temperature of the cathode
  - Liquid viscosity
  - Liquid temperature
  - Density of the liquid
  - Molecular structure of the liquid
  - Hydrostatic pressure
- Typical maximum breakdown strengths of some highly purified liquids and liquefied gases are given in Table-

Table — Maximum Breakdown Strengths of Some Liquids

Liquid	Maximum breakdown strength (MV/cm)
Hexane	1.1-1.3
Benzene	1.1
Transformer oil	1.0
Silicone	1.0-1.2
Liquid Oxygen	2.4
Liquid Nitrogen	1.6-1.9
Liquid Hydrogen	1.0
Liquid Helium	0.7
Liquid Argon	1.10-1.42

- It has been observed that the increase in breakdown strength is more, if the dissolved gases are electronegative in character (like oxygen).
- Similarly, the increase in the liquid hydrostatic pressure increases the breakdown strength. These properties are shown in Figs.

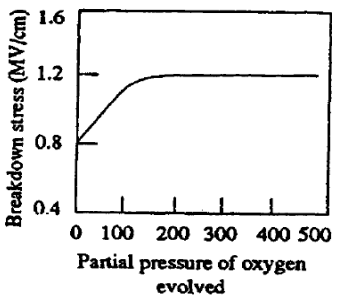


Fig. Effect of oxygen gas evolved on the breakdown stress in *n*-hexane.

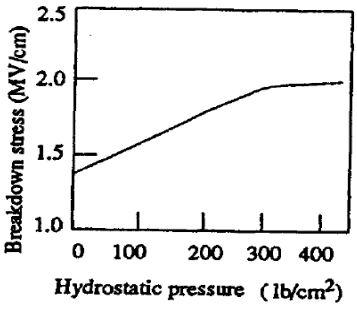


Fig. Effect of hydrostatic pressure on breakdown stress in *n*-hexane

- To sum up, this type of breakdown process in pure liquids, called the electronic breakdown, involves emission of electrons at fields greater than100 kV/cm.

Conduction and breakdown in commercial liquids:

- We know that Conduction and Breakdown in Commercial Liquids are not chemically pure and have impurities like gas bubbles, suspended particles, etc.
- These impurities reduce the breakdown strength of these liquids considerably.
- The breakdown mechanism in commercial liquids is dependent on 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 Mechanism

- In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres or as dispersed solid particles.
  Consider spherical particles of radius 'r' of permittivity ε_2 *(*epsilon) will be different from the permittivity of the liquid (ε_1). If the applied field is *E*, then the particles experience a force F, where

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

- In commercial liquids, solid impurities like fiber, paper or dispersed solid particles are present.
- If $\varepsilon_2 > \varepsilon_1$, the force 'F' is directed the impurities towards areas of maximum stress.
- If $\varepsilon_2 < \varepsilon_1$, the force 'F' is directed the impurities towards the area of lower stress when gas bubbles are present.
- If the numbers of particles present are large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

(b) Cavitation and Bubble Mechanism

- A kind of vapour bubble formed is responsible for breakdown.
- The following processes have been suggested to be responsible for the formation of the vapour bubbles:
    (a) Gas pockets at the surfaces of the electrodes.
    (b) Electrostatic repulsive forces between space charges which may be sufficient to overcome the surface tension
    (c) Dissociation o products by electron collisions giving rise to gaseous products.
    (d) Liquid Vapourization by corona type discharges from sharp points and irregularities on the electrodes.

Breakdown mechanism:

- When a gas bubble is formed it will elongate in the direction of the electric field. The volume of the enlongated bubbles remain constant.
- Breakdown occurs when,

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

- The breakdown strength depends on:
  - Initial size of the bubble
  - Hydrostatic pressure
  - Temperature
- The electric filed in a gas bubble immersed in a liquid of permittivity 'ε_1' is given by

$$E_{\text{gas bubble}} = \frac{3\,E_0}{\varepsilon_1 + 2}$$

- The breakdown field is given as

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma\,(2\varepsilon_1 + \varepsilon_2)}{r}\left(\frac{\pi}{4}\sqrt{\frac{V_b}{2rE_0} - 1}\right)\right]^{\frac{1}{2}}$$

where σ is the surface tension of the liquid

$\varepsilon_1$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

(c) Stressed Oil Volume Mechanism

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

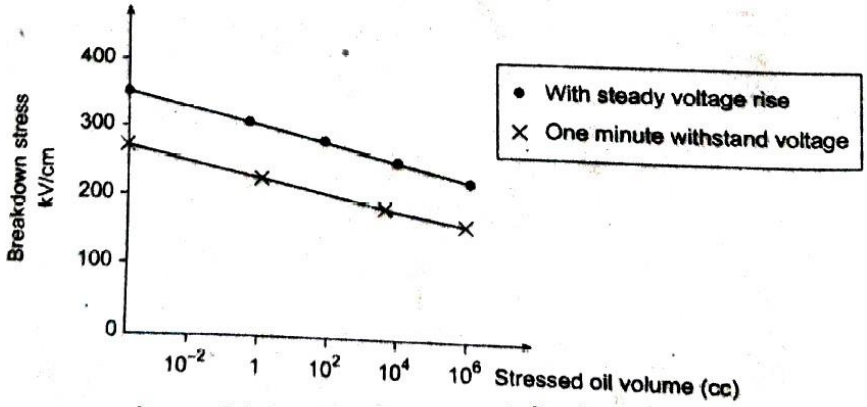


Fig: Breakdown stress Vs stressed oil volume

Thermal Mechanism of Breakdown:

- Another mechanism proposed to explain breakdown under pulse conditions is thermal breakdown.
- This mechanism is based on the experimental observations of extremely large currents just before breakdown.
- This high current pulses are believed to originate from the tips of the microscopic projections on the cathode surface with densities of the order of 1 A/cm^3.
- These high density current pulses give rise to localised heating of the oil which may lead to the formation of vapour bubbles.
- The vapour bubbles are formed when the energy exceeds 10^7 J/cm^2. When a bubble is formed, breakdown follows, either because of its elongation to a critical size or when it completely bridges the gap between the electrodes.
- In either case, it will result in the formation of a spark. According to this mechanism, the breakdown strength depends on the pressure and the molecular structure of the liquid.
- For example, in n-alkanes the breakdown strength was observed to depend on the chain length of the molecule.
- This theory is only applicable at very small lengths ($\leq$100μm) and does not explain the reduction in breakdown strength with increased gap lengths.

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SOLID DIELECTRICS

- The majority of the insulating systems used in practice are solids.
- They can be broadly classified into three groups:
    1. Organic materials
    2. Inorganic materials and
    3. Synthetic polymers.

Table Classification of Solid Insulating Materials

Organic materials	Inorganic materials	Synthetic polymers	
		Thermoplastic	Thermosetting
Amber	Asbestos	Polyethylene	Bakelite
Cotton	Ceramics	Perspex	Epoxy resins
Paper	Glass	Polypropylene	**Phonolics**
Pressboard	Mica	Polystyrene	**Elastomers**
Rubber		Polyvinyl chloride	**Melamine**
Wax			
Wood			

1. Organic materials: *(Examples are paper, wood and rubber)*

- These are produced from vegetable or animal matter.
- Their mechanical and electrical properties always deteriorate rapidly when the temperature exceeds 100°C.
- They are good insulators and can be easily adopted for practical applications.
- Therefore, they are generally used after treating with a varnish or impregnation with oil. Examples are paper and press board used in cables, capacitors and transformers.

2. Inorganic materials: *(Examples are mica, glass and porcelain)*

- Their electrical and mechanical properties almost up to 250^{o}C.
- Important inorganic materials used for electric applications are glasses and ceramics.
- They are widely used for the manufacture of insulators, bushings etc., because of their resistance to atmospheric pollutants and their excellent performance under varying conditions of temperature and pressure.

3. Synthetic polymer: *(Examples are Perspex, PVC, epoxy resins)*

- These are the polymeric materials which possess excellent insulating properties and can be easily fabricated and applied to the apparatus.
- These are generally divided into two groups:
    a) Thermoplastic and
    b) Thermosetting plastic types.
- Although they have low melting temperatures in the range 100-120^{o}C, they are very flexible and can be molded and extruded at temperatures below their melting points.
- They are widely used in bushings, insulators etc. Their electrical use depends on their ability to prevent the absorption of moisture.

*****

Solid dielectric materials:

- Solid dielectrics have higher breakdown strength compared to liquids and gases.
- A good solid dielectric should have
    - Low dielectric loss
    - High mechanical strength
    - Free from gaseous particles and moisture
    - Resistant to thermal and chemical deterioration.
    - High breakdown strength than liquids
- When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field is removed.
- The various breakdown mechanisms can be classified as follows:
    1. Intrinsic or ionic breakdown
    2. Electromechanical breakdown
    3. Thermal breakdown
    4. Failure due to treeing and tracking
    5. Electrochemical breakdown
    6. Breakdown due to internal discharges.
- The mechanism of failure of a solid dielectric changes as the time of voltage application increases as shown-

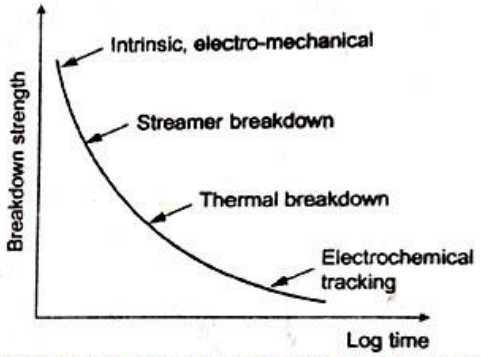


Fig: Variation of breakdown strength with log time

(1) Intrinsic or Ionic Breakdown:

- When voltages are applied only for short durations of the order of 10^{-8} Seconds, the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the 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:

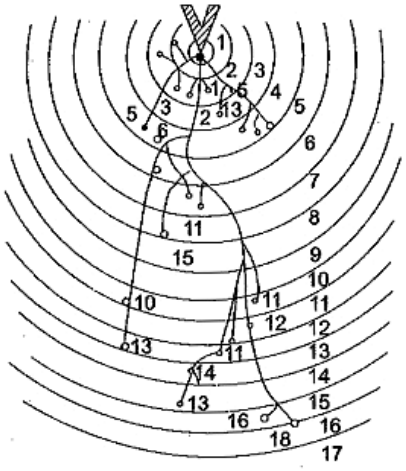
- Free electrons present in the solid dielectric are capable of migration in the lattice of the dielectric.
- These electron conduction takes place due to structural imperfections and small amounts of impurities presents in solid dielectrics.
- Due to the applied electric filed and temperatures, these impurities act as conduction electrons.
- When increase if electric field, more electrons are released and conduction takes place i.e. breakdown occurs.
- Based on this principle, **two types** of intrinsic breakdown mechanisms have been proposed
  a) Electronic breakdown
  b) Avalanche or streamer breakdown:

***(i) Electronic breakdown*:**

- Assumed to be electronic in nature (occurs in time 10^{-8} Sec)
- Initial density of conduction (free) electrons assumed to be large and electron-electron collisions occurs.
- When electric field is applied across the solid dielectric, the density of free electrons are more collision occurs between electrons.
- These electrons gains energy from the electric filed and cross the forbidden energy gap from the valency band to the conduction band.
- This process repeated, more electrons are produced and breakdown of dielectric occurs due to the conduction of electrons.

(ii) Avalanche or streamer breakdown:

- Similar to breakdown in gases due to cumulative ionization.
- 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.
- The breakdown occurs due to many avalanche and leads to streamer.
- In practice, breakdown does not occur by the formation of a single avalanche itself, but occurs as a result of many avalanches formed within the dielectric and extending step by step through the entire thickness of the material as shown in Fig



Breakdown channels in perspex between point-plane electrodes. Radius of point 0.01 in, thickness 0.19 in. Total number of impulses 190. Number of channels produced 16; (n) point indicates end of nth channel. Radii of circles increases in units of 10^{-2} in.

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2. Electromechanical Breakdown:

- When an electric field is applied to a dielectric between two electrodes, a mechanical force will be exerted on the dielectric due to the force of attraction between the surface charges.
- This compression decreases the dielectric thickness thus increasing the effective stress. This is shown in figure below

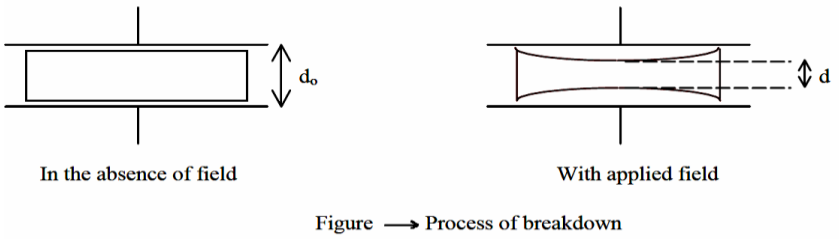


Figure ⟶ Process of breakdown

- Compressive force Pc = ½ D E
- The compressive forces arise due to attraction between surface charges.
  Let
  - d_0 = Thickness of the specimen
  - d = compressed thichness when electric field is applied
  - Y = Young's modulus
  - ε_0 = Permittivity of free space
  - ε_r = Relative permittivity
  - V = Applied voltage

  The highest apparent electric stress before breakdown is:

$$E_{max} = \frac{V}{d_0} = 0.6\sqrt{\left(\frac{Y}{\varepsilon_0 \varepsilon_r}\right)}$$

- Mechanical instability occurs when $d/d_0 = 0.6$ or $d_0/d = 1.67$
- The above equation is only approximate as Y depends on the mechanical stress.
- Also when the material is subjected to high stresses the theory of elasticity does not hold good and plastic deformation has to be considered.

---

3. *Thermal breakdown:*

- When an electric field is applied to a dielectric, conduction current flows thru the material. Current heats up the specimen and the temperature rises.
- Heat generated is transferred to the surrounding medium by conduction and radiation.
- Condition for instability or thermal breakdown,

Heat Generation > Heat Conduction

$$\therefore \text{Heat input to the element} = \{\text{Heat conducted}\} + \{\text{Heat used to increase lattice temperature}\}$$

- Equilibrium is reached when the heat generated (W_{dc} or W_{ac}) is equal to heat dissipated (W_T). Breakdown occurs when W_{dc} or W_{ac} exceeds W_T.
- The heat generated under d.c. stress E is given as

$$\text{Heat generated under D.C. stress } W_{D.C} = E^2 \sigma \ \text{W/cm}^3$$

where, σ = d.c. conductivity of the specimen.

- The heat generated under a.c. stress E is given as

$$\text{Heat generated under A.C. stress } W_{A.C} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \ \text{W/cm}^3$$

where, E = Stress in rms value
δ = Loss angle of the dielectric
W_T = W_{dc} or W_{ac}
ε_r = Relative permittivity

- The heat dissipated (W_T) is given by:

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

where

C_V = specific heat of the specimen,
T = temperature of the specimen,
K = thermal conductivity of the specimen, and
t = time over which the heat is dissipated.

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

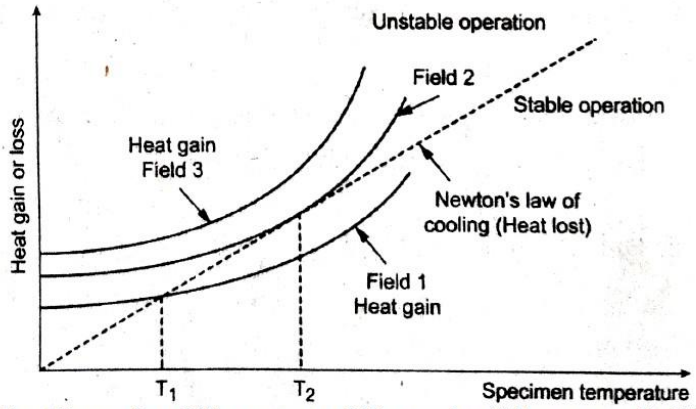


Fig: Thernal stability or unstability under different applied field

- Breakdown occurs when $W_{d.c.}$ or $W_{a.c.}$ exceeds W_T.
- The thermal instability condition is shown in figure below.

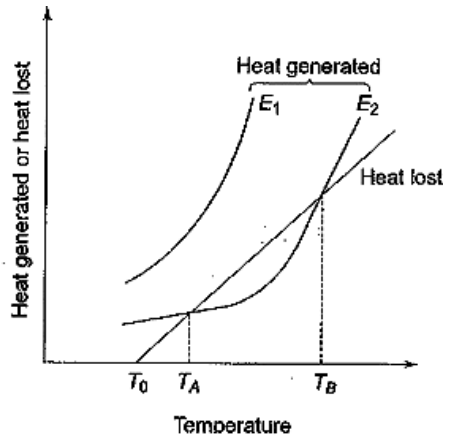


Fig: Thermal instability in solid dielectrics

- Here, the heat lost is shown by a straight line, while the heat generated at fields E_1 and E_2 are shown by separate curves.
- At field E_2 breakdown occurs both at temperatures T_A and T_B.
- In the temperature region of T_A and T_B heat generated is less than the heat lost for the field E_2, and hence the breakdown will not occur.

Table : *Thermal Breakdown Stresses in Dielectrics*

Material	*Maximum thermal breakdown stress in MV/cm*	
	d.c.	*a.c.*
Muscovite mica	24	7.18
Rock salt	38	1.4
High grade porcelain	—	2.8
H.V. Steatite	—	9.8
Quartz—perpendicular to axis	1200	—
—parallel to axis	66	—
Capacitor paper	—	3.4–4.4
Polythene	—	3.5
Polystyrene	—	5.0

---

4. Breakdown due to Treeing and Tracking:

- When a solid dielectric subjected to electrical stresses during a long time, breakdown takes place in the solid dielectrics.
- Breakdown occurs due to the following-
    1. Formation of conducting path across the surface of the insulation due to surface erosion.
    2. 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 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 surface starts drying and sparks are produced to damage the dielectric. this leads the 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 figure.

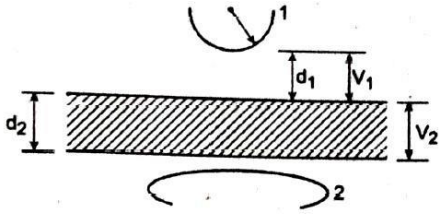


Fig. Dielectric material is arranged between electrodes

- When a dielectric material lies between two electrodes as shown in figure, there is a possibility for two different dielectric media, the air and the dielectric, to come in series.
- The voltages across the two media are as shown and The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2}$$

Where V_1 = Voltage across the air gap
V_2 = Voltage across the dielectric
V = Applied voltage
ε_1 = Permittivity of the air and
ε_2 = Permittivity of the dielectric

- Mostly, $\varepsilon_2 > \varepsilon_1$, therefore voltage across d_1 is more.
- Charge accumulates on the surface of the insulator due to sparing.
- As time increases, the conducting paths increase abd spreads through in an irregular tree like fashion. This forms treeing.

---

5. Electrochemical Breakdown:

- Electrochemical breakdown was caused by chemical transformations due to electrolysis, formation of ozone gas, etc.
- When electric filed 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.
- Some of the important chemical reactions that occur are:

(i) Oxidation:

  - Cranks are formed due to oxidation in the presence of air or oxygen in materials such as rubber and polyethylene.

(ii) 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.

(iii) Chemical Action:

- Chemical degradation of dielectrics can occur due to a variety of processes such as chemical instability at high temperatures, oxidation and cracking in the presence of air and ozone, and hydrolysis due to moisture and heat.
- Chemical reactions occur between various materials leading to reduction in electrical and mechanical strength resulting in failure.

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6. Breakdown due to internal discharges:

- Solid insulating materials contain voids or cavities within the dielectric.
- These voids and cavities are generally filled with gas or liquids. The dielectric strength of filling medium is less than that of dielectric. When the voltage is applied, electric field strength of filling material may exceed its breakdown strength and produce internal discharges. Due to this breakdown may occurs.
- Let us consider a dielectric between two conductors as shown in Figure below-

Let C_1 = Capacitance of the void or cavity.

C_2 = Capacitance of the dielectric which is series with the void

C_3 = Capacitance of the rest of the dielectric

d = Thickness of the insulation

t = Thickness of cavity.

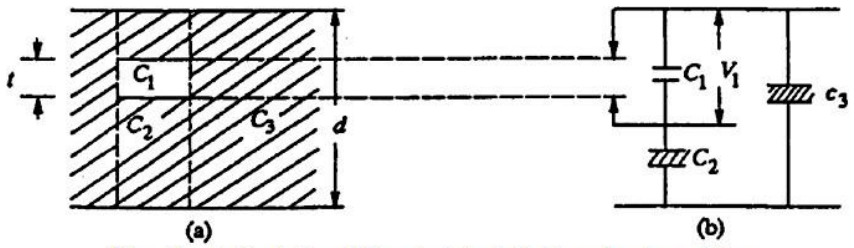


Fig: Equivalent circuit for electrical discharging in cavities

- The voltage across the void, V_1 is given by,

$$V_1 = \frac{Vd_1}{d_1 + \left(\frac{\varepsilon_0}{\varepsilon_1}\right)d_2}$$

Where,

d_1 = Thickness of void

d_2 = Thickness of the dielectric

ε_0 = Permittivity of void

ε_1 = Permittivity of the dielectric

ε_r = Relative permittivity of the dielectric

- Usually $d_1 \ll d_2$, and if we assume that the cavity is filled with a gas, then

$$V_1 = V\varepsilon_r\left(\frac{d_1}{d_2}\right)$$

Where,

V = Applied Voltage

ε_r = Relative permittivity of the dielectric

Breakdown mechanism:

- When a voltage V is applied, V_1 reaches the breakdown strength of the medium in the cavity (V_i) and breakdown occurs. V_i is called "**discharge inception voltage**".
- The voltage across the cavity V_1 again increases and several discharges formed and resulting in breakdown.

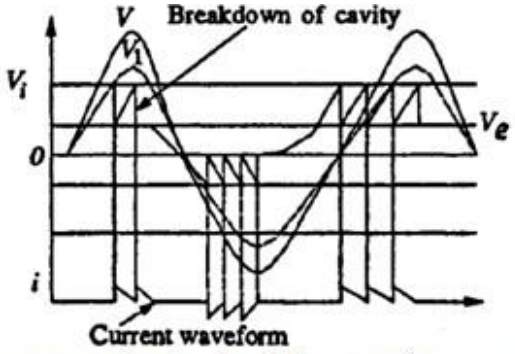


Fig: Sequence of cavity breakdown under a.c. voltage

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

<u>Breakdown in Composite Dielectrics:</u>

Composite Dielectrics:

- Usually more than one insulating material will be involved, either in series, parallel or both Such insulation systems are called ***composite dielectrics.*** (For example: air or SF_6 gas in parallel with solid insulation or in series with one another)
- This type of composite dielectric is widely used in a variety of low and high voltage apparatus such as cables, capacitors, transformers, oil-filled switchgear, bushings etc.
- In recent years solid/SF_6 gas technology has become more acceptable.

Properties of Composite Dielectrics:

- A composite dielectric generally consists of a large number of layers arranged one over the other. This is called "the layered construction" and is widely used in cables, capacitors and transformers.
- ***Three properties*** of composite dielectrics which are important to their performance are given below.
    (a) Effect of Multiple Layers
    (b) Effect of Layer Thickness
    (c) Effect of Interfaces

(a) Effect of Multiple Layers:

- The simplest composite dielectric consists of two layers of the same material. Here, advantage is two thin sheets have a higher dielectric strength than a single sheet of the same total thickness.

- The significant in having a wide variation in dielectric strength values measured at different points on its surface.

(b) Effect of Layer Thickness:

- Increase in layer thickness normally gives increased breakdown voltage.
- The use of layered construction is very important in the case of insulating paper since the paper thickness itself varies from point to point and dielectric strength varies.
- Various investigations on composite dielectrics have shown that
    i. The discharge inception voltage depends on the thickness of the solid dielectric, as well as on both the liquid and solid dielectric constants.
    ii. The difference in the dielectric constants between the liquid and solid dielectrics does not affect the rate of change of electric field at the electrode edge with the change in the dielectric thickness.

(c) Effect of Interfaces:

- The interfaces and the magnitude of the discharge depends on the associated surface resistance and capacitance.
- When the surface conductivity increases, the discharge magnitude also increases, resulting in damage to the dielectric.
- In a composite dielectric, it is essential to maintain low dielectric losses because they normally operate at high electric stresses.

Mechanism of Breakdown in Composite Dielectrics:

- If dielectric losses are low the cumulative heat produced will be low and thermal breakdown will not occur.
- There are two types of breakdown mechanism in composite dielectric. They are-
    a) Short-Term Breakdown
    b) Long-Term Breakdown

(a) Short-Term Breakdown:

- When electric field stress is very high, failure may occur in seconds or even faster without any damaging the insulating surface prior to breakdown is called Short-Term Breakdown.
- When the applied voltage is very close to the breakdown voltage, due to discharges a composite dielectric breakdown occurs.
- Breakdown was occurs more readily when the bombarding particles are electrons, rather than positive ions.
- The thickness of solid insulation play a very important role in causing breakdown under high field conditions

(b) Long-Term Breakdown:

- Long-term breakdown occurs due to ageing of insulation from thermal process and partial discharges. So it is also called the ageing of insulation.
- Partial discharges normally occur within the volume of the composite insulation systems.
- The charge accumulation and conduction on the surface of the insulation also causes ageing and failure of insulation.

(i) Ageing and breakdown due to partial discharges:

- A gas filled cavities will be present within the dielectric or adjacent to the interface between the conductor and the dielectric.
- When a voltage is applied to the dielectric, discharges take place within the gas-filled cavities. These discharges are called the "partial discharges".
- The degree of ageing depends on the discharge inception voltage (V_i)and the discharge magnitude.
- V_i is strongly dependent on the permittivity of the dielectric ε_r and the thickness of the cavity *g*.

$$V_i = \left(\frac{E_g}{\varepsilon_r}\right)(t + \varepsilon_r g) \quad \text{---(1)}$$

Where V_i = Discharge inception voltage

ε_r= Permittivity of the dielectric

t = thickness of the dielectric in series with the cavity'g'

E_g = the breakdown stress of the cavity air gap of thickness *g*

- Assume (g + t) will be constant (C).
- Adding and subtracting $\frac{E_g g}{\varepsilon_r}$ in above V_i equation(1), we get-

$$V_i = \frac{E_g}{\varepsilon_r}(t + g + \varepsilon_r g - g) = \frac{E_g}{\varepsilon_r}[(\varepsilon_r - 1)g + C] \quad \ldots (2)$$

- Differentiating the equation (2) with respect to g, we get-

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

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

$$\frac{dV_i}{dg} = \frac{\varepsilon_r - 1}{\varepsilon_r}\left\{E_g + \frac{dE}{dg}\left(g + \frac{C}{\varepsilon_r - 1}\right)\right\} \quad \text{----(3)}$$

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

- From above equations we have two assumptions they are

(i) $E_g = \varepsilon_r \cdot E$

(ii) $\frac{E_{g(max)}}{E_g} = 1$; where, E = Applied electric field

- When these assumptions are valid, the Paschen law can be used to explain the breakdown of the gas gap (cavity).
- However, the validity of the above assumptions depends upon the shape and dimensions of the cavity.
- From the above analysis the following conclusions can be arrived at
    a) For very small cavities, V_i decreases as the cavity depth increases, following the Paschen curve of gas breakdown.
    b) $E < 2\ V_i$, erosion of cavity occurs but breakdown will not take place and the life of insulation is long.
    c) $E > 2\ V_i$, erosion and breakdown takes place due to aging.

(ii) 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 with 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

****

Some important dielectric materials:

(1) Paper and boards:

- Paper is hygroscopic; generally tissue paper or kraft paper is used for insulation purpose.
- Paper and paper boards are produced from cotton, organic fibers, mica, glass and ceramics,
- Generally, if the thickness of the paper is 0.8 mm or higher it is called paper board.
- Low-density paper (0.8 gms/cm^3) is preferred in high frequency capacitors and cables, while medium density paper is used in power capacitors.
- High-density papers are preferable in d.c. and energy storage capacitors and for the insulation of d.c. machines.

(2) Fibers:

- The fibers used are both natural and man-made. They include cotton, jute, flax, wool, silk (natural fibers), rayon, nylon, terylene, Teflon and fiberglass.
- The properties of fibrous materials depend on the temperature and humidity.
- The presence of ionic impurities (e.g., salt) considerably reduces the electrical resistance of the fiber.
- Artificial fibers, such as terylene and fiberglass absorb very little water and hence have very high resistance.

(3) Mica and Its Products:

- Mica is the generic name of a class of crystalline mineral silicates of alumina and potash. It can be classified into four main groups: (i) muscovite, (ii) phlogopite, (iii) fibiolite, and (iv) lipidolite.
- The last two groups are hard and brittle and hence are unsuitable for electrical insulation purposes. Very pure mica is used for high frequency applications.
- It has got a unique combination of electrical properties, such as high dielectric strength, low dielectric losses, resistance to high temperatures and good mechanical strength.
- Spotted mica is used for low voltage insulation, such as for commutator segment separators, armature windings, switchgear and in electrical heating and cooling equipments.

(4) Glass:

- Glass is a thermoplastic inorganic material comprising complex systems of oxides (SiO2).
- The dielectric constant of glass varies from 3.7 to 10 and the density varies from 2.2 to 6 g/cm^3.
- The dielectric loss of glass varies from 0.004 to 0.020 depending on the frequency. The losses are highest at lowest frequencies.
- The dielectric strength of glass varies from 3000 to 5000 kV/cm and decreases with increase in temperature, reaching half the value at 100°C.
- At room temperature, the volume resistivity of glass varies from 10^{12} to 10^{20} ohm-cm.
- Glass is used as a cover and for internal supports in electric bulbs, electronic valves, mercury arc switches, x-ray equipment, capacitors and as insulators in telephones.

(5) Ceramics:

- Ceramics are inorganic materials produced by consolidating minerals into monolithic bodies by high temperature heat treatment.
- Ceramics can be divided into two groups depending on the dielectric constant.
- Low permittivity ceramics ($\mathcal{E}r$<12) are used as insulators, while the high permittivity ceramics (Ɛr> 12) are used in capacitors and transducers.

(6) Rubber:

- Rubber is a natural or synthetic vulcanizable high polymer having high elastic properties.
- Electrical properties of rubber depend on the degree of compounding and vulcanizing.
- General impurities, chemical changes due to ageing, moisture content and variations in temperature and frequency have substantial effects on the electrical properties of rubber.

(7) Plastics:

- Plastics are very widely used as insulating materials because of their excellent dielectric properties.
- Plastics are made by combining large numbers of small molecules into a few big ones.
- Most thermoplastic resins approximate to a structure in which several thousand atoms are tied together in one direction. The thermosetting resins on the other hand, form a three-dimensional network.

Polyethylene:

- Polyethylene is a thermoplastic material which combines unusual electrical properties, high resistance to moisture and chemicals, easy process ability, and low cost.
- It has got high resistivity and good dielectric properties at high frequencies. they are widely used for power and coaxial cables, telephone cables, multi-conductor control cables, TV lead-in wires, etc.

(7.2) Fluorocarbon Plastics:

- Polytetrafluoroethylene (P.T.F.E.), polychlorotrifluoroethylene (P.C.T.F.E.) and polyvinylidene (P-VJ2) plastics come under this category. P.T.F.E. is the most thermally stable and chemically resistant of all the three.

- It can be used without decomposition up to temperatures of 327°C. It is widely used in almost all applications. P.C.T.F.E. has higher dielectric constant and loss factor than P.T.F.E., but melts at 190°C.
- P.V.F2 can be worked in the temperature range -30 °C to 150°C. It is used as thin wall insulation, as jacketing for computer wires and special control wires, and for tubing and sleeving for capacitors, resistors, terminal junctions, and solder sleeves.

(7.3) Nylon:

- Nylon is a thermoplastic which possesses high impact, tensile, and flexural strengths over a wide range of temperature (O to 300°C).
- It is generally recommended for high frequency low loss applications. Inelectrical engineering, nylon mouldings are used to make coil forms, fasteners,connectors, washers, cable clamps, switch housings, etc.
- There are three different types of nylon commonly used. They are nylon 6/6, nylon 6 and nylon 6/10.

(7.4) Polyvinyl Chloride:

- Polyvinyl chloride or P. V.C. is used commercially in various forms. The upper temperature limit of operation is about 60°C.
- It is chemically resistant to strong acids and alkalis and is insoluble in water, alcohol and organic solvents like benzene.
- The dielectric constant and loss tangent are 3.0-3.3 and 0.015-0.02 respectively, at all frequencies up to 1 MHz.
- P.V.C. is also available as a highly plasticized flexible material, which is used extensively for wire covering, insulated sleeving, and cable sheathing in preference to natural rubber because of its resistance to the action of sunlight, water and oxygen.

(7.5) Polyesters:

- Polyesters have excellent dielectric properties and superior surface hardness, and are highly resistant to most chemicals. These are classified as either saturated or unsaturated types.
- Unsaturated polyesters are used in glass laminates and glass fibre reinforced mouldings, both of which are widely used for making small electrical components to very large structures.
- Saturated polyesters are used in producing fibres and film. Polyester fibre is used to make paper, mat and cloth for electrical applications.
- The film is used for insulating wires and cables in motors, capacitors and transformers. Mylorpolyester film is being largely used in preference to paper insulation.

(7.6) Polystyrenes:

- Polystyrenes are obtained when styrene is polymerized with itself or with other polymers or monomers producing a variety of thermoplastic materials with varying properties in different colours.

- Their volume resistivity is about 10^{19} ohm-cm and the dielectric strength is 200-350 kV/cm. The dielectric constant at 20°C is 2.55, and the loss tangent is 0.0002 at all frequencies up to 10,000 MHz.
- Polystyrene films are extensively used in the manufacture of low loss capacitors, also used for high frequency and cable insulations.

(8) Epoxy Resins:

- They can be easily cast into desired shapes even at room temperature. They are very versatile, and their basic properties can bemodified either by the selection of a curing agent or by the use of modifiers or fillers.
- The dielectric loss factor is very small under power frequency conditions it is lying in the range of 0.003-0.03.
- The dielectric strength is 75 kV/mm, when the specimen thickness is 0.025 mm or 1 mil.
- The volume resistivity of the material is of the order of 1013 ohm-cm. They are highly elastic.
- Insulators, bushings, apparatus, etc. can be made out of epoxy resin. It can also be used for encapsulation of electronic components, generator windings and transformers.
- It is used for bonding of very diverse materials such as porcelain, wood, metals, plastics, etc. It is a very important adhesive used for sealing of high vacuum joints.

======= The End ========