BREAKDOWN IN SOLID DIELECTRIC

- The requirements of good dielectric:
  - Low dielectric loss,
  - High mechanical strength,
  - Free from gaseous inclusions, and moisture,
  - Resistant to thermal and chemical deterioration.

- Solid dielectrics have higher breakdown strength compared to liquids and gases. When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength.

- Breakdown mechanism varies depending on the time of application of voltage as shown in Figure 1 and can be classified as follows:
  a. Intrinsic or ionic breakdown
  b. Electromechanical breakdown
  c. Thermal breakdown
  d. Electrochemical breakdown
  e. Treeing and tracking
  f. Internal discharges

- Maximum strength usually obtainable ranges from 5 - 10 MV/cm.
- Intrinsic breakdown depends upon the presence of free electron which capable of migration through the lattice of the dielectric. Usually small numbers of conduction electrons are present, with some structural imperfections and small amounts of impurities. The impurity atoms or molecules act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons and trapped are released and participate in the conduction process.
- Two types of intrinsic breakdown mechanisms:
  i. **Electronic breakdown:**
     o Assumed to be electronic in nature (occurs in time 10-8 s)
     o Initial density of conduction (free) electrons assumed to be large and electron-electron collisions occurs.
     o When electric field is applied, electrons gain energy and cross the forbidden gap from the valency to the conduction band. This process repeated, more and more electrons available in conduction band, eventually leading to breakdown.
  ii. **Avalanche or streamer breakdown:**
     o Similar to breakdown in gases due to cummulative ionization.
     o Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atom by collisions.
     o Motion of electron from cathode to anode will gain energy from the field and losses it during collisions. When the energy gained by an electron exceeds the ionization potential, an additional electron will be liberated due to collision of the first electron. This process repeats itself resulting in the formation of an electron avalanche, and breakdown will occur when the avalanche exceeds a certain critical size.
     o In practice, breakdown does not occur by the formation of a single avalanche, but occurs as a result of many avalanches formed and extending step by step through the entire thickness of the material as shown in Figure 2.

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b. Electromechanical Breakdown:

- Failure occurs due to electrostatic compressive forces, which can exceed the mechanical compressive strength.

- If the thickness of specimen, \( d_0 \) and is compressed to a thickness \( d \) under an applied voltage \( V \), the highest apparent electric stress before breakdown is:

\[
E_{\text{max}} = \frac{V}{d_0} = 0.6 \left( \frac{Y}{\varepsilon_0 \varepsilon_r} \right)
\]

where, \( Y \) - Young’s modulus

- Mechanical instability occurs when \( d/d_0 = 0.6 \)

- 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.

c. 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.

- 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 \( W_T \), where,

\[
W_{dc} = \frac{E^2 \sigma}{1.8 \times 10^{12}} \frac{W}{cm^3}
\]

\[
W_{ac} = \frac{E^2 f \tan \delta}{1.8 \times 10^{12}} \frac{W}{cm^3}
\]

where,

- \( f \) : frequency in Hz.
- \( \delta \) : loss angle of the dielectric material
- \( E \) : rms value

- The thermal instability condition is shown in Figure 3.
Thermal breakdown sets-up an upper limit for increasing the breakdown voltage when the thickness of insulation is increased.

- Heat generated is proportional to the frequency and hence thermal breakdown is more serious at high frequency.
- Thermal breakdown stresses (MV/cm) are lower under a.c. condition than under d.c.

**d. BREAKDOWN OF SOLID DIELECTRIC IN PRACTICE**

- There are certain type of breakdown which do not come under either intrinsic breakdown or thermal breakdown but occur after prolonged time, eg. breakdown due to tracking in which dry conducting tracks are formed on the surface of the insulation.
- These tracks act as conducting path - leading to gradual breakdown.
- Another type in this category is electrochemical breakdown caused by chemical transformation such as electrolysis, formation of ozone etc.
- Failure also occurs due to partial discharges which are brought about in the air pockets inside the insulation.

**i. Chemical and Electrochemical Deterioration and Breakdown:**

- In presence of air and other gases, dielectric materials undergo chemical changes when subjected to continuous electrical stresses. Chemical reactions that occur are:

  **Oxidation:** In the presence of air or oxygen, materials such as rubber and polyethylene undergo oxidation giving rise to surface cracks.

  **Hydrolysis:** When moisture or water vapour is present on the surface of the solid dielectric, hydrolysis occurs and the materials lose their electrical and mechanical properties. Materials like paper, cotton tape and other cellulose materials deteriorate very rapidly due to hydrolysis.

  **Chemical Action:** Progressive chemical degradation can occur due to a variety of processes such as chemical instability at high temperature, oxidation, cracking and hydrolysis.

- Chemical and electrochemical deterioration increases very rapidly with temperature.

**ii. Breakdown due to Treeing and Tracking**

- When solid dielectric subjected to electrical stresses for a long time, two kinds of visible marking are observed.
  - a. Presence of conducting path.
  - b. Mechanism whereby leakage current passes through the conducting path, finally leading to the formation of spark.

- Spreading of spark channels during tracking in the form of the branches of a tree is called treeing.

- In practice, the surface of solid dielectric material always aving the conducting film, which is formed due to moisture. On application of voltage, the film starts conducting, resulting in generation of heat, and the surface starts becoming dry. The conducting film becomes separate due to drying, and so sparks are drawn damaging the dielectric surface. With organic insulating material, the dielectric carbonizes at the region of sparking, and carbonized regions act as permanent conducting channels. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes. This phenomenon is called tracking.

- Treeing occurs due to the erosion of material at the tips of the spark and results the roughening of the surface and becomes dirt and contamination. Breakdown channels spread thru the insulation in an irregular “tree” and leading to the formation of conducting channel.

- Under a.c. conditions, treeing can occurs in a few minutes or several hours. Hence care must be taken to see that no series air gaps or other weaker insulation gaps are formed.

- Usually tracking occurs even at very low voltages, whereas treeing requires high voltage.

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

- Treeing can be prevented by having clean, dry and undamaged surfaces and clean environment. Usually treeing phenomena is observed in capacitors and cables.

**iii. Breakdown due to Internal Discharges:**
Solid insulating materials contain voids or cavities within the medium or at the boundaries between the dielectric and the electrodes. These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation.

The electric field strength in the voids is higher than that across the dielectric. Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur.

Let us consider a dielectric between two conductors as shown in Figure 4, where, $C_1$ : capacitance of the void or cavity. $C_2$ : capacitance of the dielectric which is series with the void and $C_3$ : capacitance of the rest of the dielectric.

![Fig. 4 Electrical discharge in a cavity](image)

- 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, $d_1$ and $d_2$ are the thickness of the void and the dielectric respectively, having permittivities $\varepsilon_0$ and $\varepsilon_1$. Usually $d_1 << d_2$, and we assume the cavity is filled with a gas, then;

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

where $\varepsilon_r$ is the relative permittivity of the dielectric.

- 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”. When the applied voltage is a.c., breakdown occurs on both the half cycles and the number of discharges will depend on the applied voltage. The voltage and the discharge current waveforms are shown in Figure 5.

- These internal discharges (also called partial discharges, PD) have the same effect as treeing on the insulation.

![Fig. 5 Sequence of cavity breakdown under a.c. voltages](image)