CHAPTER 4
BREAKDOWN in SOLID DIELECTRICS

4.1 INTRODUCTION

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

Studied of the breakdown of solid dielectrics are of extreme importance in insulation studies. When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field removed.

The mechanism of breakdown is a complex phenomenon in the case of solids, and varies depending on the time of application of voltage as shown in Fig. 4. 1. The various breakdown mechanisms can be classified as follows:

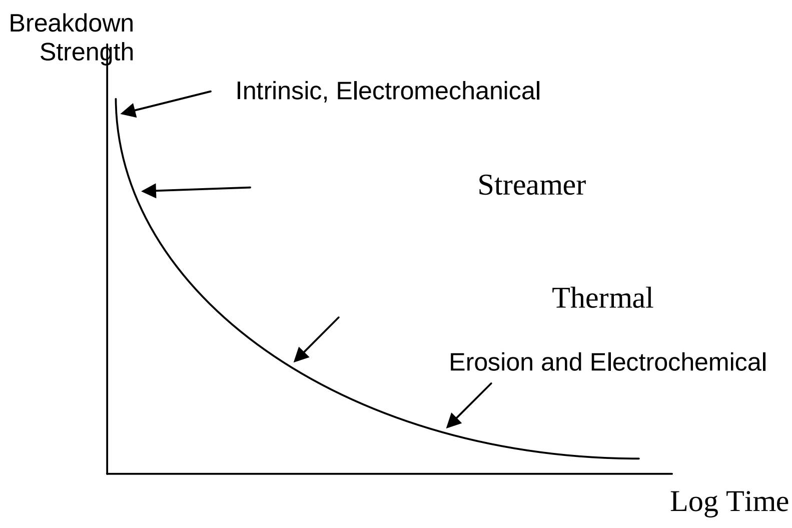

Fig.4.1Variation of breakdown strength with time after application of voltage

a) Intrinsic or ionic breakdown,
b) electromechanical breakdown,
c) failure due to treeing and tracking,

d) thermal breakdown,
e) electrochemical breakdown, and
f) breakdown due to internal discharges.

4.2 INTRINSIC BREAKDOWN

When voltages are applied only for short durations of the order of 10^{8} s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. Experimentally, this highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature. The maximum electrical strength recorder is 15 MV/cm for polyvinyl-alcohol at -196^{0}C. The maximum strength usually obtainable ranges from 5 MV/cm.

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

i) Electronic Breakdown

Intrinsic breakdown occurs in time of the order of 10^{-8} s and therefore is assumed to be electronic in nature. The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisions occur. When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valence band to the conduction band. When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown.

ii) Avalanche or Streamer Breakdown

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

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

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

4.3 ELECTROMECHANICAL BREAKDOWN

When solid dielectrics are subjected to high electric fields, failure occurs due to electrostatic compressive forces which can exceed the mechanical compressive strength. If the thickness of the specimen is d_0 and is compressed to thickness d under an applied voltage V, then the electrically developed compressive stress is in equilibrium.

4.4 THERMAL BREAKDOWN

In general, the breakdown voltage of a solid dielectric should increase with its thickness. But this is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction.

When an electric field is applied to a dielectric, conduction current however small it may be, flows through the material. The current heats up the specimen and the temperature rise. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat radiated out, equals the heat generated. The heat generated under d. c. stress E is given as

$W_{d.c.} = E^2 \sigma \, W/cm^3$ (4.4) where σ is the d. c. conductivity of the specimen.

Under a. c. fields, the heat generated

$W_{a.c.} = \frac{E^2 f_{\varepsilon r} \tan \delta}{1.8 \times 10^{12}} W/cm^3$ (4.5) where, f= frequency in Hz, $\delta =$ loss angle of the dielectric material, and E= rms value. The heat dissipated (W_r) is given by

$W_r = C_v \frac{dT}{dt} + \text{div (K grad T)}$ (4.6) where, C_v= specific heat of the specimen,

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

Equilibrium is reached when the heat generated $(W_{d.c} \text{ or } W_{a.c})$ becomes equal to the heat dissipated (W_r). In actual practice there is always some heat that is radiated out.

Breakdown occurs when $W_{d.c.} \text{or } W_{a.c.}$ exceeds W_r. The thermal instability condition is shown in Fig. 4.2. Here, the heat lost is shown by a straight line, while the heat generated at fields $E_1 \text{and } E_2$ is shown by separate curves. At field E_2 breakdown occurs both at temperatures $T_A \text{and } T_B$ heat generated is less than the heat lost for the field E_2, and hence the breakdown will not occur.

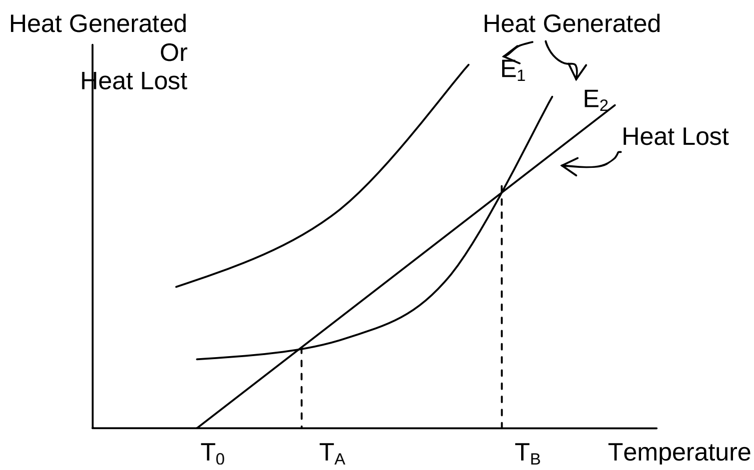

Fig.4.2 Thermal instability in solid dielectrics

The thermal breakdown voltages of various materials under d.c. and a.c. fields are shown in the table 4.1

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Table 4.1

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

It can be seen from this table 4.1 that since the power loss under a.c. fields is higher, the heat generation is also high, and hence the thermal breakdown stresses are lower under a.c. conditions than under d.c. conditions.

4.5 BREAKDOWN OF SOLID DIELECTRICS IN PRACTICE

There are certain types of breakdown which do not come under either intrinsic breakdown, but actually occur after prolonged operation. These are, for example, breakdown due to tracking in which dry conducting tracks act as conducting paths on the insulator surfaces leading to gradual breakdown along the surface of the insulator. Another type of breakdown in this category is the electrochemical breakdown caused by chemical transformations such as electrolysis, formation of ozone, etc. In addition, failure also occurs due to partial discharges which are brought about in the air pockets inside the insulation. This type of breakdown is very important impregnated paper insulation used in high voltage cables and capacitors.

4.5.1 Chemical and Electrochemical Deterioration and Breakdown

In the presence of air and other gases some dielectric materials undergo chemical changes when subjected to continuous stresses. Some of the important chemical reactions that occur are:

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

-Hydrolysis: When moisture or water vapor is present on the surface of a solid dielectric, hydrolysis occurs and the material loses their electrical and mechanical properties. Electrical properties of materials such as paper, cotton tape, and other cellulose materials deteriorate very rapidly due to hydrolysis. Plastics like polyethylene undergo changes, and their service life considerably reduces.

-Chemical Action: Even in the absence of electric fields, progressive chemical degradation of insulating materials 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. Since different insulating materials come into contact with each other in any practical reactions occur between these various materials leading to reduction in electrical and mechanical strengths resulting in a failure.

The effects of electrochemical and chemical deterioration could be minimized by carefully studying and examining the materials. High soda content glass insulation should be avoided in moist and damp conditions, because sodium, being very mobile, leaches to the surface giving rise to the formation of a strong alkali which will cause deterioration. It was observed that this type of material will lose its mechanical strength within 24 hrs, when it is exposed to atmospheres having 100% relative humidity at 70^0 C. In paper insulation, even if partial discharges are prevented completely, breakdown can occur due to chemical degradation. The chemical and electrochemical deterioration increases very rapidly with temperature, and hence high temperatures should be avoided.

4.5.2 Breakdown Due to Treeing and Tracking

When a solid dielectric subjected to electrical stresses for a long time fails, normally two kinds of visible markings are observed on the dielectric material. They are:

a) the presence of a conducting path across the surface of the insulation:

b) a mechanism whereby leakage current passes through the conducting path finally leading to the formation of a spark. Insulation deterioration occurs as a result of these sparks.

The spreading of spark channels during tracking, in the form of the branches of a tree is called treeing.
Consider a system of a solid dielectric having a conducting film and two electrodes on its surface. In practice, the conducting film very often 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 materials such as paper and bakelite, the dielectric carbonizes at the region of sparking, and the carbonized regions act as permanent conducting channels resulting in increased stress over the rest of the region. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes. This phenomenon, called tracking is common between layers of bakelite, paper and similar dielectrics built of laminates.
On the other hand treeing occurs due to the erosion of material at the tips of the spark. Erosion results in the roughening of the surfaces, and hence becomes a source of dirt and contamination. This causes increased conductivity resulting either in the formation of conducting path bridging the electrodes or in a mechanical failure of the dielectric.

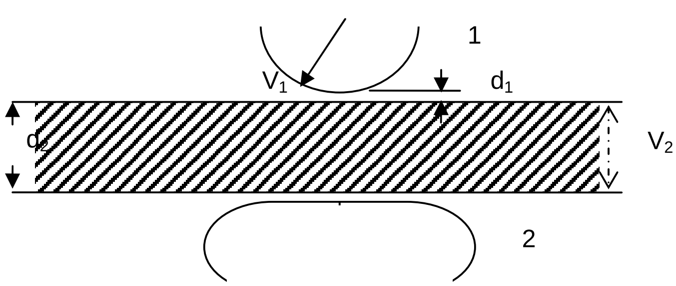

Fig.4.3 Arrangement for study of treeing phenomena.1 and 2 are electrodes.

When a dielectric material lies between two electrodes as shown in Fig. 4.3, there is possibility for two different dielectric media, the air and the dielectric, to come series. The voltages across the two media are as shown (V_1 across the air gap, and V_2 across the dielectric). The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V.d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2} \qquad (4.7)$$ where V is the applied voltage.

Since $\varepsilon_2 \rangle \varepsilon_1$ most of the voltage appears across d_1, the air gap. Sparking will occur in the air gap and charge accumulation takes place on the surface of the insulation. Sometimes the spark erodes the surface of the insulation. As time passes, break-down channels spread through the insulation in an irregular "tree' like fashion leading to the formation of conducting channels. This kind of channeling is called treeing.
Under a.c. voltage conditions treeing can occur in a few minute 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 voltage of the order of about 100 V, whereas treeing requires high voltages. For testing of tracking, low and medium voltage tracking tests are specified. These tests are done at low voltages but for times of about 100 hr or more. The insulation should not fail. Sometimes the tests are done using 5 to 10 kV with shorter durations of 4 to 6 hour. The numerical value that initiates or causes the formation of a track is called "tracking index" and this is used to qualify the surface properties of dielectric materials.

Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment. The materials chosen should be resistant to tracking. Sometimes moisture repellant greases are used. But this needs frequent cleaning and regressing. Increasing creeping distances should prevent tracking, but in practice the presence of moisture films defeat the purpose.
Usually, treeing phenomena is observed in capacitors and cables, and extensive work is being done to investigate the real nature and causes of this phenomenon.

4.5.3 Breakdown Due to Internal Discharges

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

Let us consider a dielectric between two conductors as shown in Fig. 4.4.a. If we divide the insulation into three parts, an electrical network of C_1, C_2, and C_3 can be formed as shown in Fig. 4.4.b. In this, C_1 represents the capacitance of the void or cavity, C_2 is the capacitance of the dielectric which is in series with the void, and C_3 is the capacitance of the dielectric.

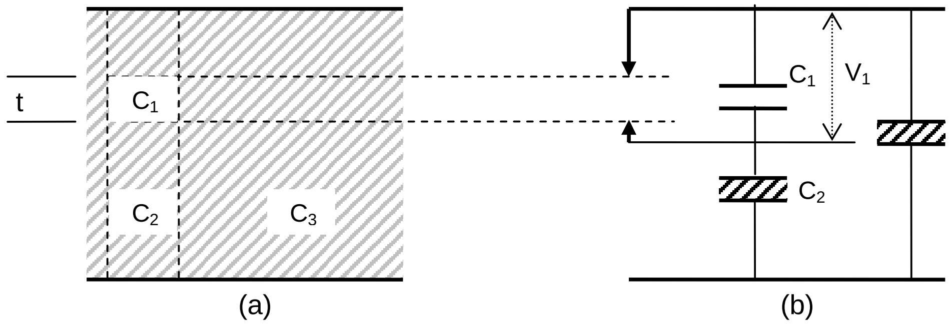

Fig.4.4 Electrical discharge in a cavity and its equivalent circuit

When the applied voltage is V, the voltage across the void, V_1 is given by the same equation as (4.7)

$V_1 = \dfrac{Vd_1}{d_1 + \left(\dfrac{\varepsilon_0}{\varepsilon_1}\right) d_2}$ where d_1 and d_2 are the thickness of the void and the dielectric, respectively, having permittivities ε_0 and ε_1. Usually $d_1 \langle d_2$, and if we assume that the cavity is filled with a gas, then

$V_1 = V_{\varepsilon r}\left(\dfrac{d_1}{d_2}\right)$ (4.8) where ε_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 the "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. When the first breakdown across the cavity occurs the breakdown voltage across it becomes zero. When once the voltage V_1 becomes zero, the spark gets extinguished and again the voltage rises till breakdown occurs again. This process repeats again and again, and current pulses will be obtained both in the positive and negative half cycles.

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

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

4.6 BREAKDOWN OF COMPOSITE INSULATION

A single material rarely constitutes the insulation in equipment. Two or more insulating materials are used either due to design considerations or due to practical difficulties of fabrication.

In certain cases the behavior of the insulation system can be predicted by the behavior of the components. But in most cases, the system as a whole has to be considered. The following considerations determine the performance of the system as a whole:

(i) The stress distribution at different parts of the insulation system is distorted due to the component dielectric constant and conductivities,
(ii) the breakdown characteristics at the surface are affected by the insulation boundaries of various components,
(iii) the internal or partial discharge products of one component invariably affect the other components in the system, and
(iv) the chemical ageing products of one component also affect the performance of other components in the system.

Another important consideration is the economic life of the system; the criterion being the ultimate breakdown of the solid insulation. The end point is normally reached by through puncture, thermal runaway, electrochemical breakdown, or mechanical failure leading to complete electrical breakdown of the system. Hence, tests for assessing the life of insulation (ageing) are very necessary.

Ageing is the process by which the electrical and mechanical properties of insulation normally becomes worse in condition (deteriorate) with time. Ageing occurs mainly due to oxidation, chemical degradation, irradiation, and electron and ion bombardment on the insulation. Tracking is another process by which ageing of the insulation occurs. Usually partial discharge tests are used in ageing studies to estimate the discharge magnitudes, discharge inception, and extinction voltages. Change of loss angle ($\tan\delta$) during electrical stressing provides information of the deterioration occurring in insulation systems. The knowledge of the mechanical stresses in the insulation, controlling of the ambient conditions such as temperature and humidity, and a study of the gaseous products evolved during ageing processes will also help to control the breakdown process in composite insulation. Finally, stress control in insulation systems to avoid high electric stress regions is an important factor in controlling the failure of insulation systems.

4.7 SOLID DIELECTRICS USED IN PRACTICE

Solid insulating materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good insulator should be of low dielectric loss, having high mechanical strength, free from gaseous inclusions and moisture, and should also be resistant to thermal and chemical deterioration.

Solid dielectrics vary widely in their origin and properties. They may be natural organic substances, such as paper, cloth, rubber, etc. or inorganic materials, such as mica, glass and ceramics or synthetic materials like plastics.

Questions

4.1 What do you understand by ‘intrinsic strength’ of a solid dielectric? How does breakdown occur due to electrons in solid dielectric?

4.2 What is ‘thermal breakdown’ in solid dielectrics, and how is practically more significant than other mechanism?

4.3 How does the ‘internal discharge’ phenomenon lead to breakdown in solid dielectrics?

4.4 How do the temperature and moisture affect the breakdown strength of solid dielectrics?

4.5What are the properties that make plastics more suitable as insulating materials?