

GOVERNMENT COLLEGE OF ENGINEERING, KALAHANDI



Lecture notes
on
HIGH VOLTAGE ENGINEERING
(Module II)



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MODULE-II

CONDUCTION AND BREAKDOWN IN LIQUID DIELECTRICS

2.1 Introduction

Liquid dielectrics are used mainly spreading through in high voltage cables and capacitors and for filling transformers, circuit breakers, etc. In addition to their function as a dielectric, liquid dielectrics have additional functions in certain applications. For example, liquid dielectrics act as heat transfer agents (i.e. for cooling) in transformers and as arc quenching media in circuit breakers. Petroleum oils are most commonly used as liquid dielectrics. For certain applications Synthetic hydrocarbons and halogenated hydrocarbons and for very high temperature applications, silicone oils and fluorinated hydrocarbons are used. In recent times, certain vegetable oils and esters are also being used.

Liquid dielectrics normally are mixture of hydrocarbons and are weakly polarized. When used for electrical insulation purposes they should be free from moisture, products of oxidation, and other contaminants. The most important factor that affects the electrical strength of insulating oil is the presence of water in the form of fine droplets suspended in the oil. The presence of even 0.01 % water in transformer oil reduces the electrical strength to 20 % of the dry oil value. The dielectric strength of the oil reduces more sharply, if it contains fibrous impurities in addition to water. The three most important properties, of liquid dielectrics are

- (i) the electrical conductivity,
- (ii) dielectric constant, and
- (iii) the dielectric strength.

In addition, the physical and chemical properties such as viscosity, thermal stability, specific gravity, etc. are also important. Examples for the breakdown strength at 20°C on 2.5 mm standard sphere gap are 15 kV/mm for Transformer Oil, 30 kV/mm for Cable Oil, 20 kV/mm for Capacitor Oil, 20-25 kV/mm for Askarels, 30-40 kV/mm for Silicone Oils. In practice, the choice of a liquid dielectric for a given application is made mainly on the basis of its **chemical stability**.

In addition, other factors like *saving of space, cost, previous usage, and susceptibility to the environmental influences* are also considered. In capacitors, replacement of the capacitor oil by askarel spreading through in the overall size of the capacitor by more than 30%. In practice, a liquid found satisfactory over a long period of usage is preferred to a new one. Petroleum liquid are widely used because of their low cost.

2.2 PURE LIQUIDS AND COMMERCIAL LIQUIDS

Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 10^9 , and are structurally simple.

Examples of such simple pure liquids are :

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

By using simple and pure liquids, it is easier to separate out the various factors that influence condition and breakdown in them.

On the other hand, the commercial liquids which are insulating liquids like oils, not chemically pure, normally consist of mixture of complex organic molecules which cannot be easily specified or reproduced in a series of experiments.

2.2.1 Purification

The main impurities in liquid dielectrics are dust, moisture, dissolved, gases and ionic impurities. Various methods employed for purification are filtration (through mechanical filters, spray filters, and electrostatic filters), centrifuging, degassing and distillation, and chemical treatment (adding ion exchange material such as alumina, fuller's earth etc. filtering).

Dust particles when present become charged and reduce the breakdown strength of the liquid dielectrics, and they can be removed by careful filtration.

Liquid will normally contain moisture and dissolved gases in small quantities. Gases like oxygen and carbon dioxide significantly affect the breakdown strength of the liquids, and hence it is necessary to control the amount of gas present. This is done by distillation and degassing.

Ionic impurity in liquids, like water vapor which easily dissociates, leads to very high conductivity and heating of the liquid depending on the applied electric field. Water is removed using drying agents or by vacuum drying.

Sometimes, liquids are shaken with concentrated sulphuric acid to remove wax and residue and washed with caustic soda and distilled water. A commonly used closed-cycle liquid purification system to prepare liquids as per the above requirements is shown in Fig.2.1.

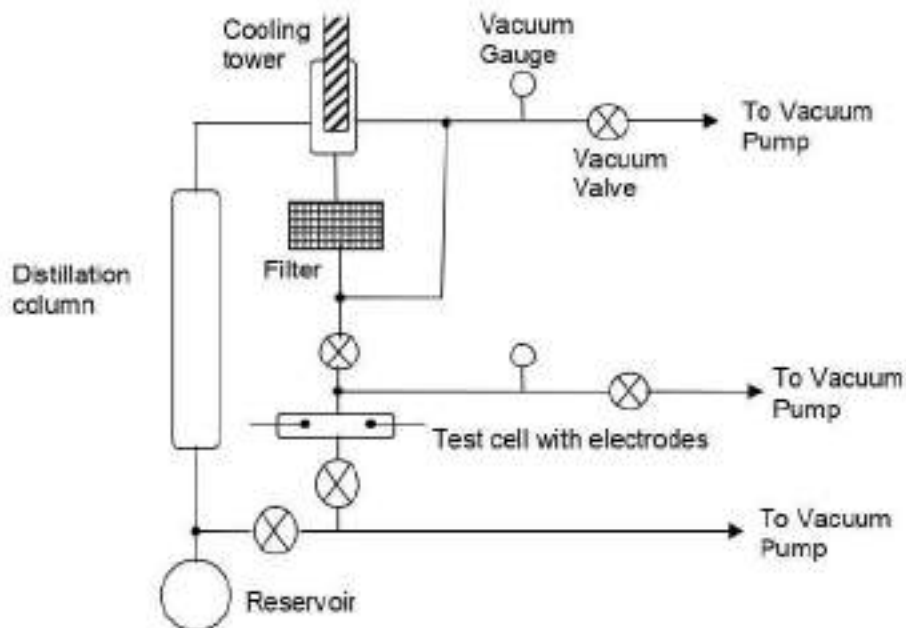


Fig. 2.1 Liquid purification system with test cell.

This system provides for cycling the liquids. The liquid from the reservoir flows through the distillation column where ionic impurities are removed. Water is removed by drying agents or frozen out in the low-temperature bath. The gases dissolve in the liquid are removed by passing them through the cooling tower and/or pumped out by the vacuum pumps. The liquids then pass through the filter where dust particles are removed. The liquid thus purified is then used in the test cell. The used liquid then flows back into the reservoir. The vacuum system thus helps to remove the moisture and other gaseous impurities.

OIL Breakdown Tests

Breakdown tests are normally conducted using test cell. For testing pure liquids, the test cells used are small so that less quantity of liquid is used during testing. Also, test cells are usually an integral part of the purification system as shown in Fig. 3.1. The electrodes used for breakdown voltage measurement 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 measurement 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. The breakdown strengths and d.c conductivities obtained in pure liquids are very high, of the order of 1 MV/cm and 10^{-18} - 10^{-20} mho/cm respectively, the conductivity being measured at electric field of the order of 1 kV/cm. However, the corresponding values in commercial liquids are relatively low.

2.2 CONDUCTION AND BREAKDOWN IN PURE LIQUIDS

When low electric fields less than 1 kV/cm are applied, conductivities of 10^{-18} - 10^{-29} mho/cm are obtained. These are probably due to the impurities remaining after purification. However, when the fields are high (>100 kV/cm) the currents not only increase rapidly, but also undergo violent fluctuations which will die down after some time. A typical mean value of the conduction current in hexane is shown in Fig. 2.2. This is the condition nearer to breakdown.

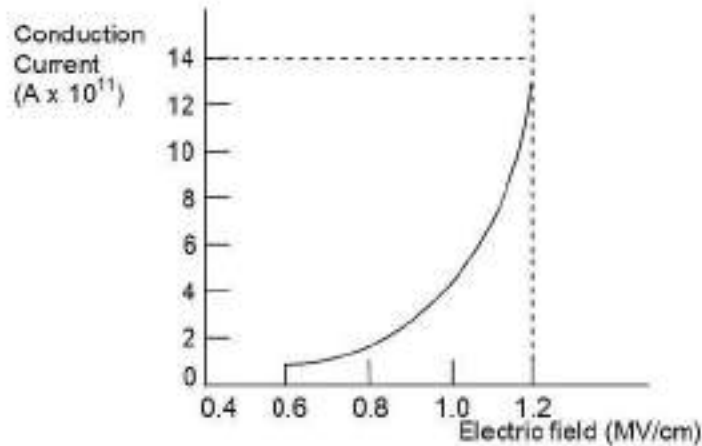


Fig.2.2 Conduction current-electric field characteristics in hexane at high fields

However, if this figure is redrawn starting from very small currents, a current-electric field characteristics as shown in Fig. 2.3, can be obtained. This curve will have three distinct regions as shown. At very low fields the current is due to the dissociation of ions. With intermediate fields the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from the cathode gets multiplied in the liquid medium by a Townsend type of mechanism. The current multiplication also occurs from the electrons generated at the interfaces of liquid and impurities. The increase in current by these processes continues till breakdown occurs. The exact mechanism of current growth is not known; however, it appears that the electrons are generated from the cathode by field emission of electrons.

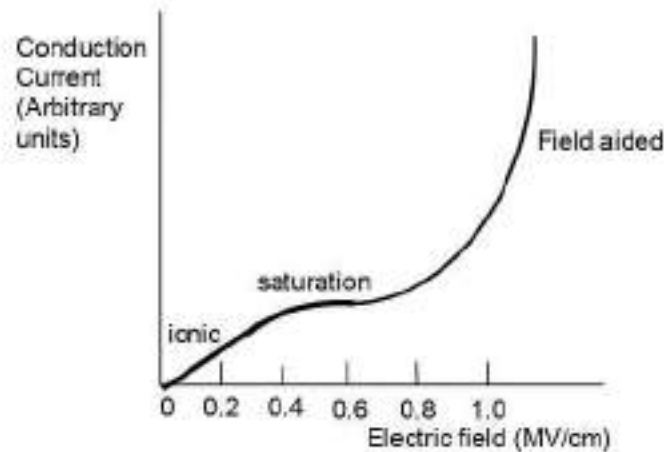


Fig.2.3 Conduction current-electric field characteristics in hydrocarbon liquid

The electrons so liberated get multiple by a process similar to Townsend's primary and secondary ionization in gases. As the breakdown field is approached, the current increases rapidly due to process similar to the primary ionization process and also the positive ions reaching the cathode generate secondary electrons, leading breakdown. The breakdown voltage depends on the field, gap separation, cathode work-function, and the temperature of the cathode. In addition, the liquid viscosity, the liquid temperature, the density, and the molecular structure of the liquid also influence the breakdown strength of the liquid. Typical maximum breakdown strengths of some highly purified liquids and liquefied gases are given in Table 2.1.

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	1.1-1.42

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.

To sum up, this type of breakdown process in pure liquids, called the electronic breakdown, involves emission of electrons at fields greater than 100 kV/cm. This

emission occurs either at the electrode surface irregularities or at the interfaces of impurities and the liquid. These electrons get further multiplied by Townsend's type of primary and secondary ionization processes, leading to breakdown.

2.3 CONDUCTION AND BREAKDOWN IN COMMERCIAL LIQUIDS

As already mentioned commercial insulating 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 mechanisms are also considerably influenced by the presence of these impurities. In addition, when breakdown occurs in these liquids, additional gases and gas bubbles are evolved and solid decomposition products are formed. The electrode surfaces become rough, and at times explosive sounds are heard due to the generation of impulsive pressure through the liquid. The breakdown mechanism in commercial liquids is dependent on several factors, such as, the nature and condition of the electrodes, the physical properties of the liquid, and the impurities and gases present in the liquid. Several theories have been proposed to explain the breakdown in liquids, and they are classified as follows:

- a) **Electronic breakdown**
- b) **Suspended Particle Mechanism**
- c) **Cavitation and Bubble Mechanism**
- d) **Stressed Oil Volume Mechanism**

2.3.1 *Electronic breakdown*

Both the field emission and the field-enhanced thermionic emission mechanisms discussed earlier have been considered responsible for the current at the cathode. Conduction studies in insulating liquids at high fields show that most experimental data for current fit well the Schottky-type equation in which the current is temperature dependent. Breakdown measurements carried out over a wide range of temperatures, however, show little temperature dependence. This suggests that the cathode process is field emission rather than thermionic emission. It is possible that the return of positive ions and particularly positively charged foreign particles to the cathode will cause local field enhancement and give rise to local electron emission. Once the electron is injected into the liquid it gains energy from the applied field. In the electronic theory of breakdown it is assumed that some electrons gain more energy from the field than they lose in collisions with molecules. These electrons are accelerated until they gain sufficient energy to ionize molecules on collisions and initiate avalanche. The condition for the onset of electron avalanche is obtained by equating the gain in energy of an electron over its mean free path to that required for ionization of the molecule.

$$eE\lambda = ch\nu$$

where E is the applied field, λ the electron mean free path, $h\nu$ the quantum of energy lost in ionizing the molecule and c an arbitrary constant. The electronic theory satisfactorily predicts the relative magnitude of breakdown strength of liquids, but the observed formative time lags are much longer than predicted by electronic theory.

2.3.2 **Suspended Particle Theory**

Solid impurities may be present in the liquid either as fibres or as dispersed solid particles and their presence of solid impurities cannot be avoided. The permittivity of these particles ϵ_1 will be different from the permittivity of the liquid ϵ_2 . If we consider these impurities to be spherical particles of radius r , and if the applied field is E , then the particles experience of force F , where

$$F = r^3 \frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + 2\epsilon_2} E \frac{dE}{dx} \quad (2.1)$$

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

The force given by eqn (2.1) increases as the permittivity of the suspended particle (ϵ) increases, and for a conducting particle for which $\epsilon_1 \rightarrow \infty$ the force becomes

$$F = F_c = r^3 E \text{ grad } E$$

Thus the force will urge the particle to move to the strongest region of the field.

In a uniform field gap or sphere gap of small spacing the strongest field is in the uniform region. In this region $\text{grad } E$ is equal to zero so that the particle will remain in equilibrium there. Accordingly, particles will be dragged into the uniform field region. If the permittivity of the particle is higher than that of the medium, then its presence in the uniform field region will cause flux concentration at its surface. Other particles will be attracted into the region of higher flux concentration and in time will become aligned head to tail to form a bridge across the gap. The field in the liquid between the particles will be enhanced, and if it reaches critical value breakdown will follow.

The movement of particles by electrical force is opposed by viscous drag, and since the particles are moving into the region of high stress, diffusion must also be taken into account.

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

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

2.3.3. Cavitation and the Bubble Theory

It was experimentally observed that in many liquids, the breakdown strength depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of

vapor bubble formed is responsible for breakdown. The following processes have been suggested to be responsible for the formation of the vapor bubbles:

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

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

The electric field in a spherical gas bubble which is immersed in a liquid of permittivity ϵ_2 is given by $E_b = 3E_0/(\epsilon_2+2)$; where E_0 is the field in the liquid in the absence of the bubble. When the field E_b becomes equal to the gaseous ionization field, discharge takes place which will lead to decomposition of the liquid and breakdown may follow. Kao has developed more accurate expression for the breakdown field as

$$E_0 = \frac{1}{(\epsilon_1 - \epsilon_2)} \left[\frac{2\pi\sigma(2\epsilon_1 - \epsilon_2)}{r} \left\{ \sqrt{\frac{V_b}{2rE_0}} - 1 \right\} \right]^{\frac{1}{2}} \quad (2.2)$$

where σ is the surface tension of the liquid, ϵ_1 is the permittivity of the liquid, ϵ_2 is the permittivity of the gas bubble, r is the initial radius of the bubble assumed as a sphere and V_b is the voltage drop in the bubble (corresponding to minimum on the Paschen's curve). From this equation it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid. But this theory does not take into account the production of the initial bubble and hence the results given by this theory do not agree well with the experimental results.

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

2.3.4. Stressed Oil Volume Theory

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

and 0.9 (E_{max}) contour. According to this theory the breakdown strength is inversely proportional to the stressed oil volume.

The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage. The variation of the breakdown voltage stress with the stressed oil volume is shown in Fig. 2.4.

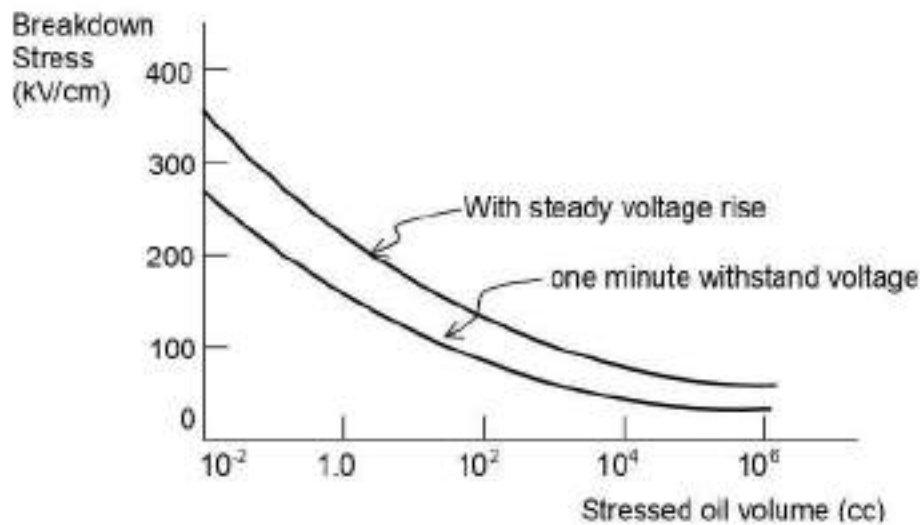


Fig 2.4 Power frequency (50 Hz) a.c breakdown stress as function of stressed oil volume

2.4 CONCLUSIONS

All the theories discussed above do not consider the dependence of breakdown strength on the gap length. They all try to account for the maximum obtainable breakdown strength only. However, the experimental evidence showed that the breakdown strength of a liquid depends on the gap length, given by the following expression,

$$V_b = Ad^n \quad \text{where, } A = \text{constant, and} \\ n = \text{constant, always less than 1.}$$

The breakdown voltage also depends on the nature of the voltage, the mode in which the voltage is applied, and the time of application. The above relationship is of practical importance, and the electrical stress of given oil used in design is obtained from this. During the last ten years, research work is directed on the measurements of discharge inception (starting) levels in oil and the breakdown strengths of large volumes of oil under different conditions.

BREAKDOWN IN SOLID DIELECTRICS

3.1 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.

Studies 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. 3. 1.

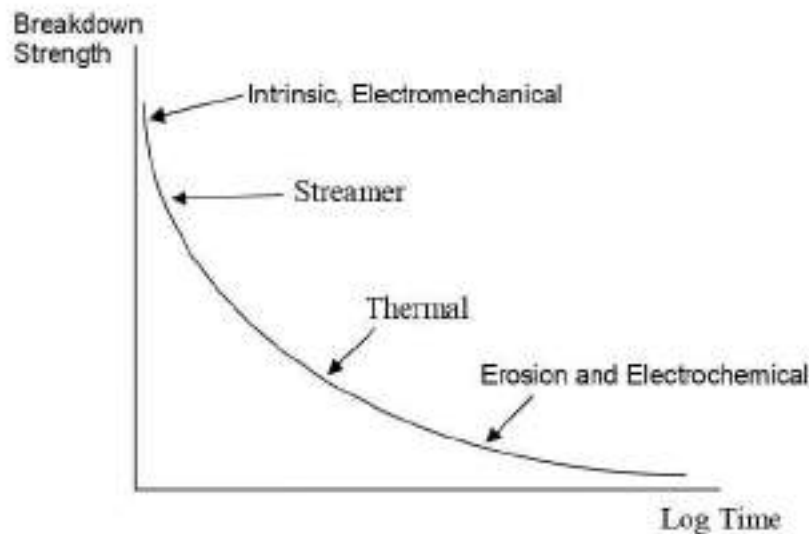


Fig.3.1 Variation of breakdown strength with time after application of voltage

The various breakdown mechanisms can be classified as follows:

- (a) Intrinsic or ionic breakdown,
- (b) electromechanical breakdown,
- (c) failure due to treeing and tracking,
- (d) thermal breakdown,
- (e) electrochemical breakdown, and
- (f) breakdown due to internal discharges.

3.2 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°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.

3.3 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 if

$$\epsilon_0 \epsilon_r = \frac{V^2}{2d^2} = Y \ln \left[\frac{d_0}{d} \right] \quad (3.1) \quad \text{where } Y \text{ is the Young's modulus. From Eq. (3.1)}$$

$$V^2 = d^2 \left[\frac{2Y}{\epsilon_0 \epsilon_r} \right] \ln \left[\frac{d_0}{d} \right] \quad (3.2)$$

Usually, mechanical instability occurs when $d/d_0 = 0.6$ or $d_0/d = 1.67$

Substituting this Eq.3.2, the highest apparent electric stress before breakdown,

$$E_{\max} = \frac{V}{d_0} = 0.6 \left[\frac{Y}{\epsilon_0 \epsilon_r} \right]^{\frac{1}{2}} \quad (3.3)$$

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.

3.4 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

$$W_{d.c.} = E^2 \sigma \text{ W/cm}^3 \quad (3.4) \text{ where } \sigma \text{ is the d. c. conductivity of the specimen.}$$

Under a. c. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \epsilon_0 \tan \delta}{1.8 \times 10^{12}} \text{ W/cm}^3 \quad (3.5) \text{ where, } f = \text{frequency in Hz, } \delta = \text{loss angle of the}$$

dielectric material, and E= rms value. The heat dissipated (W_r) is given by

$$W_r = C_v \frac{dT}{dt} + \text{div} (K \text{ grad } T) \quad (3.6) \text{ where, } C_v = \text{specific heat of the specimen,}$$

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

Equilibrium is reached when the heat generated ($W_{d.c.}$ 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 $W_{d.c.}$ or $W_{a.c.}$ exceeds W_r . The thermal instability condition is shown in Fig. 3.2. Here, the heat lost is shown by a straight line, while the heat generated at fields E_1 and E_2 is shown by separate curves. At field E_2 breakdown occurs both at temperatures 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.

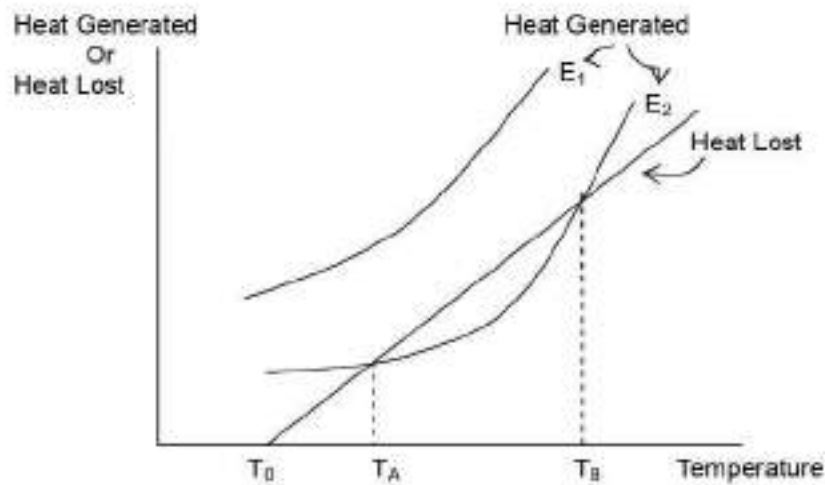


Fig.3.2 Thermal instability in solid dielectrics

The thermal breakdown voltages of various materials under d.c. and a.c. fields are shown in the table 3.1

Table 3.1

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 3.1 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.

3.5 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.

3.5.1 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^o 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.

3.5.2 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.

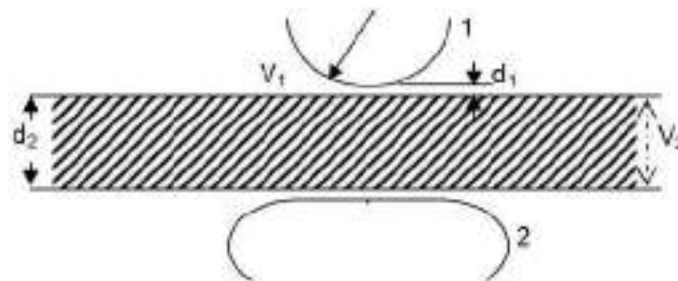


Fig.3.3 Arrangement for study of treeing phenomena. 1 and 2 are electrodes.

When a dielectric material lies between two electrodes as shown in Fig. 3.3, 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,

$$V_1 = \frac{V \cdot d_1}{d_1 + \left(\frac{\epsilon_1}{\epsilon_2}\right) d_2} \quad (3.7) \quad \text{where } V \text{ is the applied voltage.}$$

Since $\epsilon_2 > \epsilon_1$, 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 repellent 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.

3.5.3 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. 3.4.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. 3.4.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

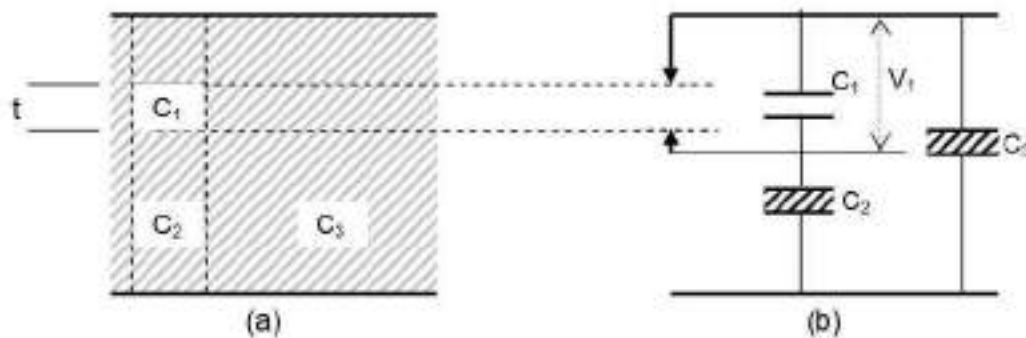


Fig.3.4 Electrical discharge in a cavity and its equivalent circuit

When the applied voltage is V , the voltage across the void, V_1 is given by the same equation as (3.7)

$$V_1 = \frac{Vd_1}{d_1 + \left(\frac{\epsilon_0}{\epsilon_1}\right)d_2}$$

where d_1 and d_2 are the thickness of the void and the dielectric,

respectively, having permittivities ϵ_0 and ϵ_1 . Usually $d_1 \ll d_2$, and if we assume that the cavity is filled with a gas, then

$$V_1 = V_{cr} \left(\frac{d_1}{d_2} \right) \quad (3.8) \text{ where } \epsilon_r \text{ is the relative permittivity of the dielectric.}$$

When a voltage V is applied, V_1 reaches the breakdown strength of the medium in the cavity (V_1) and breakdown occurs. V_1 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.

3.6 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.

Questions

- 3.1 What do you understand by 'intrinsic strength' of a solid dielectric? How does breakdown occur due to electrons in solid dielectric?
- 3.2 What is 'thermal breakdown' in solid dielectrics, and how is practically more significant than other mechanism?
- 3.3 How does the 'internal discharge' phenomenon lead to breakdown in solid dielectrics?

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

3.5. Determine the specific heat generated in the test specimen due to dielectric loss if the dielectric constant and loss angle of the specimen are 3.8 and 0.0085 respectively. The electric field is 40kV/cm at 50HZ.

37 SOLID DIELECTRICS USED IN PRACTICE (Not in course but useful in GATE/IES and other PSU Examns)

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. Some of the important materials and their properties are discussed here.

3.7.1 Paper

The kind of paper normally employed for insulation purposes is a special variety known as tissue paper or Kraft paper. The thickness and density of paper vary depending on the application. 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.

Paper is hygroscopic. Therefore, it has to be dried and impregnate with impregnants, such as mineral oil, chlorinated diphenyl and vegetable oils. The relative dielectric constant of impregnated paper depends upon the permittivity of cellulose of which the paper is made, and permittivity of the impregnant and the density of the paper. Table 3.2 gives the dielectric constants for different densities of paper impregnated with different oils.

Table 3.2 Dielectric constant of paper with different densities

Impregnant	Density (g/cm^3)		
	0.8	1.0	1.2
Trichlorodiphenyl at 20°C $\epsilon = 6.1$	6.28	6.30	6.40
Trichlorodiphenyl at 50°C $\epsilon = 5.6$	6.0	6.14	6.24
Pentachlorodiphenyl at 20°C $\epsilon = 5.7$	5.71	5.88	6.06
Transformer oil $\epsilon = 2.2$	3.26	3.72	4.30

When very thin (thickness 8-20 μm) paper is used, it is very essential to see that the number of conducting particles on the surface of the paper is minimum. The conventional method of detecting conducting particles is by means of using a roller and place, the conduction being indicated by means of head phones.

3.7.2 Fibers

Fibers when used for electrical purposes will have the ability to combine strength and durability with extreme fitness and durability with extreme fitness and flexibility. 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. Figures 4.5 and 4.6 show the variation of ϵ_r and $\tan \delta$ of various fibrous materials as a function of the frequency. It can be observed from these figures that ϵ_r decreases with frequency, while $\tan \delta$ is higher lower frequencies. Most of the perfectly-dried fibers have a dielectric constant between 3 and 8. 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.

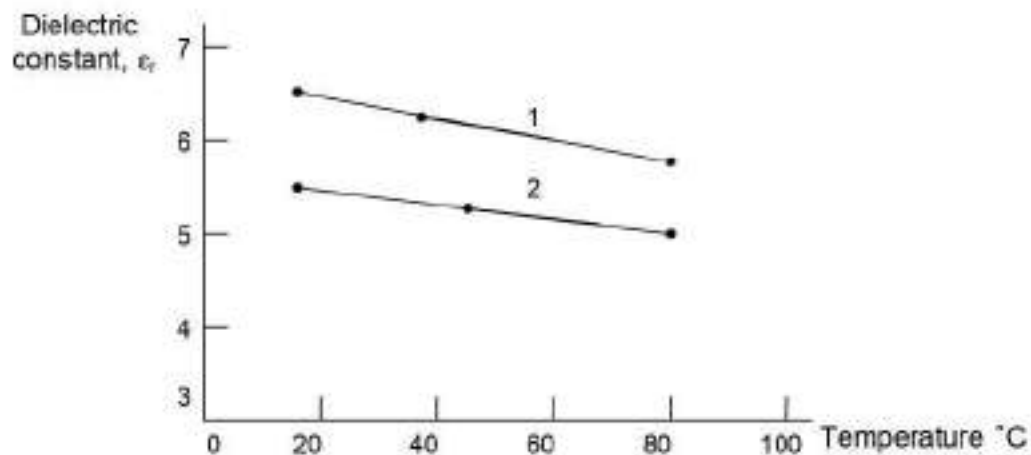


Fig.3.5 Variation of dielectric constant, ϵ_r with temperature for paper
1. Trichlorodiphenyl impregnated paper, 2. Pentachlorodiphenyl impregnated paper

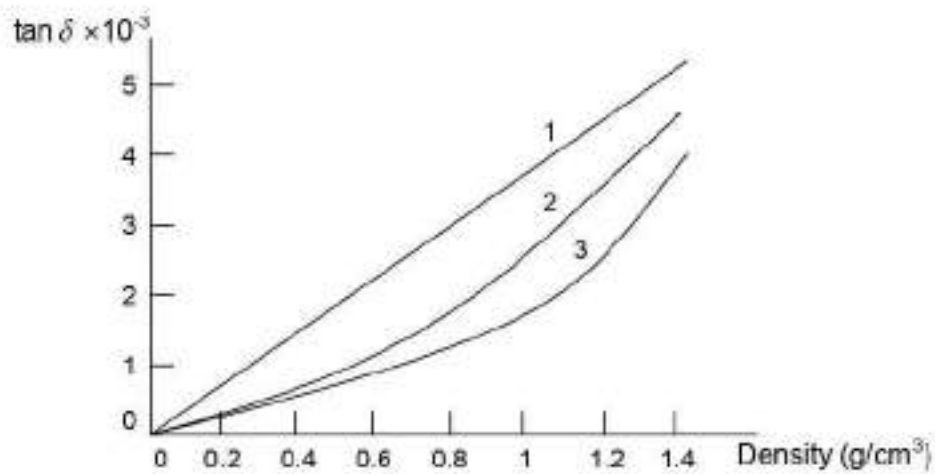


Fig.3.6 Variation of $\tan \delta$ with the density of paper
 1.Trichlorodiphenyl impregnated paper, 2. Mineral oil impregnated paper 3. Dry paper

Table 3.3 gives the density, ϵ_r , and $\tan \delta$ of various fibers.

Table 3.3

Fibers	Density	ϵ_r	$\tan \delta$
Vegetable fiber-Natural			
Cotton	1.53	4.4-7.3	0.120
Flax	1.53	4.4-7.3	0.120
Jute	1.53	4.4-7.3	0.120
Animal fiber-Natural			
Wool	1.31	1.52	0.016
Silk	1.30	3.4	0.016
		4.4 with no air voids	
Man-made Fibers			
Rayon	1.52	2.03	0.031
Acetate	1.33	2.2	0.015
Nylon	1.14	2.51	0.053
Terylene	1.38	1.97	0.030
Teflon	2.38	1.9-2.2	0.001-0.003
Fiberglass	2.34	5-7	0.001-0.0025

3.7.3 Mica and Its Products

Mica is the generic name of a class of crystalline into four main groups:

- (i) muscovite,
- (ii) phlogopite,
- (iii) fibrolite, and
- (iv) lipidolite.

The last two groups are hard and brittle and hence are unsuitable for electrical insulation purposes. Mica can be split into very thin flat laminae. 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. These have made it possible for it to be used in many electrical apparatus. Very pure mica is used for high frequency applications. Spotted mica is used for low voltage insulation, such as for commutator segment separators, armature windings, switchgear and in electrical heating and cooling equipments. Dielectric strength (up to 30 °C) varies about 700 – 1000 kV/mm, surface resistivity (60% humidity) 10^{10} - 10^{12} ohm-cm and volume resistivity (constant up to 200 °C) 10^{13} - 10^{15} ohm-cm.

Mica is built into sheet form by bonding together with a suitable resin or varnish. Depending on the type of a application, mica can be mixed with the required type of resin to meet the operating temperature requirements. Micanite is another form of mica which is extensively used for insulation purposes. Mica splitting and mica powder are used as fillers in insulating materials, such as glass and phenolic resins. The use of mica as a filler results in improved dielectric strength, reduces dielectric loss and improved heat resistance and hardness of the material.

3.7.4 Glass

Glass is a thermoplastic inorganic material comprising complex systems of oxides (SiO_2). The dielectric constant of glass varies from 3.7 to 10 and the density varies from 2.2 to 6 g/cm³. At room temperature, the volume resistivity of glass varies from 10^{12} to 10^{20} ohm cm. 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 increases in temperature, reaching half the value at 100°C.

Glass is used a cover and for internal supports in electric bulbs, electronic valves, mercury arc switches, x-ray equipment, capacitors and as insulators in telephones.

3.7.5 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 ($\epsilon_r < 12$) are used as insulators, while the high permittivity ceramics ($\epsilon_r > 12$) are used in capacitors and transducers.

Tables 4.5 give the various dielectric properties of some ceramics commonly used for electrical purposes.

Table 3.5 Properties of low permittivity Ceramics

Property	H.T Porcelain	L.T Porcelain	Low loss steatite	lumina	Forsterite
Chemical	50% clay	50% clay	3Mgo,	95%	2MgO

Composition	25% Feldspar 25% Flint	25% Feldspar 25% Flint	4SiO ₂ H ₂ O		SiO
Water Absorption (p.p.m.) Safe	0	0.5 – 2	0	0	0
Temperature (°C)	1000	900	1050	1600	1050
Dielectric Strength (kV/mm)	25	3	8 – 25	16	8 – 12
ϵ_r	5 – 7	5 – 7	6	9	6
$\tan\delta \times 10^4$	50-100	100-200	10	5	3-4

3.7.6 Plastics

Plastics are very widely insulating materials because of their excellent dielectric properties. Many new developments in electrical engineering and electronics would not have been possible without the development of plastics. Plastics are made by combining large numbers of small molecules into a few big ones. When small molecules link to form the bigger molecules of the plastics, many different types of structures result. 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. In view of the large number of plastics available, it will not be possible to deal with all of them, and only material which are commonly used for insulation purposes are described.

-Polyethylene is a thermoplastic material which combines unusual electrical properties, high resistance to moisture and chemicals, easy processability, and low cost. They have got dielectric strengths varying from 170 to 1000 kV/cm and volume resistivity greater than 10^{16} ohm-cm.

-Fluorocarbon Plastics are the best plastics used for insulation because of their excellent electrical and mechanical properties. They have got dielectric strengths varying from 104 to 512 kV/cm and volume resistivity greater than 10^{16} ohm-cm.

-Nylon is a thermoplastic which possesses high impact, tensile and flexural strengths over a wide range of temperature (0 to 300°C) with high dielectric strength and good surface and volume resistivities even after lengthy exposure to high humidity, resistant to chemical action, can be easily moulded, extruded and machined. It has got dielectric strength varying from 154 to 204 kV/cm, volume resistivity greater than 10^{12} ohm-cm.

-Polyvinyl chloride or P.V.C. is used in various commercial in various form. It is chemically resistant to strong acids and alkalis and is insoluble in water, alcohol and organic solvents like benzene. The dielectric strength, volume resistivity and surface resistivity are relatively high. The upper temperature limit of operation is about 60°C.

-Polyesters have excellent dielectric properties and superior surface hardness and are highly resistant to most chemicals. Mylor polyester film is being largely used in preference to paper insulation. It has got a dielectric strength of 2000 kV/cm, volume resistivity is better than 10^{15} ohm-cm at 100°C.

-Polystyrene has a dielectric strength comparable to that of mica about 200-350 kV/cm and volume resistivity is about 10^{15} ohm-cm. They are used in the manufacture of low loss capacitors, which will have a very stable capacitance and extremely high insulation resistance.

3.7.7 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. They have got dielectric strengths varying from 80 to 390 kV/cm and temperature from 60°C to 150°C.

3.7.8 Epoxy Resins

They are thermo settings types of insulating materials. They possess excellent dielectric and mechanical properties. The dielectric strength is 75 kV/mm and volume resistivity is about 10^{13} ohm-cm. It can be formed into an insulator of any desired shape for almost any type of high voltage application. It is used for encapsulation of electronic components, generator windings and transformers, for bonding of very divers materials such as porcelain, wood, metals, plastics, etc. It is very important adhesive used for sealing of high vacuum joints.