

LIQUID DIELECTRICS, THEIR CLASSIFICATION, PROPERTIES, AND BREAKDOWN STRENGTH

From the point of view of molecular arrangement, a liquid can be described as “highly compressed gas” in which the molecules are very closely arranged. This is known as kinetic model of the liquid structure. A liquid is characterized by free movement of the constituent molecules among themselves but without the tendency to separate. However, the movement of charged particles, their microscopic streams, and interface conditions with other materials cause a distortion in the otherwise undisturbed molecular structure of the liquids. The well known terminology describing the breakdown mechanisms in gaseous dielectrics—such as impact ionization, mean free path, electron drift, and so on—are, therefore, also applicable for liquid dielectrics.

Liquid dielectrics are accordingly classified in between the two states of matter; that is, gaseous and solid insulating materials. Wide range of application of liquid dielectrics in power apparatus also characterizes this intermediate position of liquid dielectrics. Insulating oils are used in power and instrument transformers, power cables, circuit breakers, power capacitors, and so on. Liquid dielectrics perform a number of functions simultaneously, namely:

- insulation between the parts carrying voltage and the grounded container, as in transformers
- impregnation of insulation provided in thin layers of paper or other materials, as in transformers, cables and capacitors, where oils or impregnating compounds are used
- cooling action by convection in transformers and oil filled cables through circulation
- filling up of the voids to form an electrically stronger integral part of a composite dielectric
- arc extinction in circuit breakers

- achieve higher capacitance with liquid dielectrics having high permittivity in power capacitors

A large number of natural and synthetic liquids are available that can be used as dielectrics. These possess a very high electric strength and their viscosity and permittivity vary in a wide range. The appropriate application of a liquid dielectric in an apparatus is determined by its physical, chemical and electrical properties on the one hand, and on the other, it depends upon the requirements for the specific functions to be performed.

The application of liquid dielectrics in power apparatus has been gradually declining in the recent past by the countries adopting more advance technologies. The developments in SF₆ gas and vacuum technology since the 1970s are responsible for this trend.

6.1 CLASSIFICATION OF LIQUID DIELECTRICS

Dielectric materials can be divided into two broad classifications: organic and inorganic. Organic dielectrics are basically chemical compounds containing carbon. Earlier, under organic chemistry only those compounds, which were derived from either plant or animal organism, were considered. This concept underwent changes with concurrent developments in chemical technology. Carbon compounds, in general, are now called organic. Among the main natural insulating materials of this type are petroleum products and mineral oils. The most important and widely used organic liquid dielectrics for electrical power equipment are mineral oils. The other natural organic insulating materials are asphalt, vegetable oils, wax, natural resins, wood, and fiber plants (fibrins).

A large number of synthetic organic insulating materials are also produced. These are nothing but substitutes of hydrocarbons in gaseous or liquid forms. In gaseous forms are fluorinated and chlorinated carbon compounds. Their liquid forms are chlorinated diphenyles, besides some nonchlorinated synthetic hydrocarbons. The chlorodiphenyles, although possessing some special properties, are not widely used because they are unsafe for humans and very costly.

Among halogenfree synthetic oils are polymerization products, the polyisobutylenes and the siliconpolycondensates. Polyisobutylene offers better dielectric and thermal properties than mineral oils for its application in power cables and capacitors, but it is many times more expensive. Silicon oils are top grade, halogenfree synthetic insulating liquids. They have excellent stable properties, but because of being costly, have so far found limited application for special purposes in power apparatus.

Among inorganic liquid insulating materials, highly purified water, liquid nitrogen, oxygen, argon, sulphurhexafluoride, helium etc. have been investigated for possible use as dielectrics. Liquefied gases, having high electric strength, are more frequently used in cryogenic applications. Water and water mixtures are being actively investigated for use as dielectrics in pulse power capacitors and pulsed power modulators, and son on, because of their high relative permittivity, low cost, easy handling and disposal.

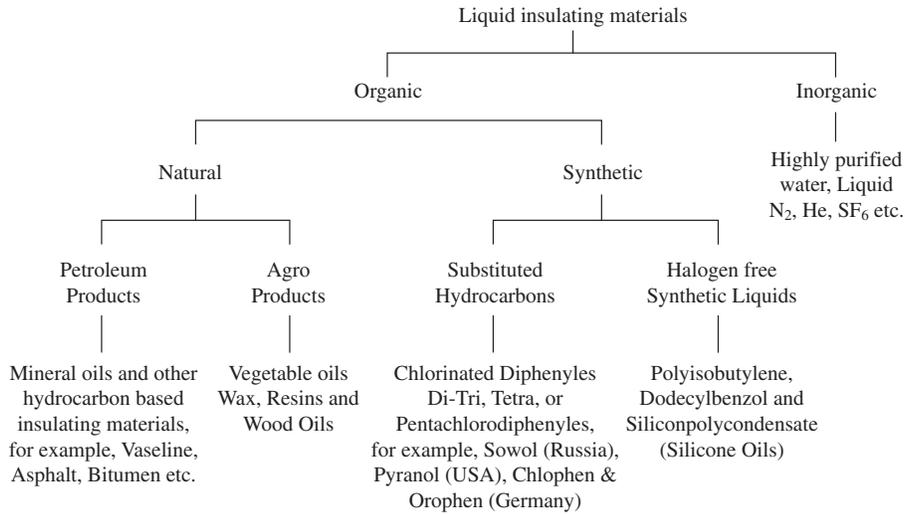


Figure 6.1 Classification of liquid insulating materials.

To summarize the classification of liquid dielectrics explained above, a schematic is drawn in Figure 6.1. The insulating liquids, commonly applied in high voltage apparatus, are classified as illustrated in this figure.

6.1.1 Mineral Insulating Oils

Amongst the liquid dielectrics used in power equipment, mineral oils are most important. Mineral oils are the suitably refined mixtures of different hydrocarbons obtained by fractional distillation of natural petroleum. The properties of individual oils strongly depend upon their chemical compositions. These oils mainly consist of saturated hydrocarbons of paraffinic and naphthenic (C_nH_{2n}) structures, besides having unsaturated aromatic hydrocarbons (C_nH_{2n-6}) in different proportions. The molecular structure and the range of percentage proportions of hydrocarbon bases are illustrated in Figure 6.2. An oil base is known as naphthenic or paraffinic when the content of either of them exceeds the other. If their contents are of equal amounts, the oil is known as mixed oil. Further, an oil is known as a weak aromatic when the aromatic content is less than 5%, and highly aromatic if its proportion exceeds 10%. Naphthenic mineral oils are more in use as dielectrics because they do not have a wax type consistency, which reduces their fluidity at low temperatures.

Electrical and other important properties of different insulating oils are brought together in Table 6.1.

Mineral oils are used in transformers, CTs, PTs, oil filled cables, condensers and circuit breakers. In the case of cables and condensers, high quality and low viscosity oils are preferred to achieve smoother circulation, hence a better convection of heat.

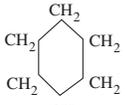
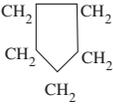
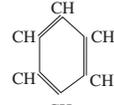
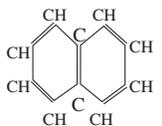
Saturated Hydrocarbons		Unsaturated Hydrocarbons
Paraffins	Naphthenes	Aromatics
$---CH_2-CH_2-CH_2-CH_2-$ (Chain) or (branched) $---CH_2-$ $ $ $---CH_2-CH-CH_2-CH-CH_2---$ $ $ $CH-$ $ $ $---CH_2-$	 or 	 or 
40 - 60 %	30 - 50 %	5 - 20 %

Figure 6.2 Molecular structure and proportion of basic constituent of mineral oils.

6.1.1.1 Mineral Insulating Oil in Transformers “Transformer oil”, the petroleum-based mineral insulating oil is refined specifically to meet the requirements of electrical insulation and heat transfer for its application in transformers. The transformers in electric power transmission and distribution systems are expected to provide reliable and efficient service for their life expectancy of at least forty years. The quality of the oil in a transformer plays a very important role in satisfactorily performing its functions.

Petroleum-based transformer oils are the most widely used electrical insulating liquids in the world for the past century. The amount of oil contained in transformers varies significantly. It mainly depends upon the power rating of the transformer; for example, a 25 kVA transformer may contain about 20 gallons whereas a 400 MVA may contain more than 10,000 gallons (U.S.) of oil. According to an estimate made by Rouse [6.1], there were more than 30 million transformers in service just in the United States in 1998. The total volume of oil contained in these was estimated to be of the order of a billion gallons (U.S.). The different quality insulating oil sales in U.S. were 74 million gallons in 1996 as reported by “National Petroleum Refiners Association” in September 1997.

The crude oils are complex mixtures of many individual hydrocarbon compounds. The relative proportions of these hydrocarbons could be quite variable in crude oils from different sources. Like the crude oils, the compositions of acceptable transformer oils also vary substantially. The limits for concentration of the various hydrocarbons in transformer oils are not clearly specified by the standards. Some specified important physical and electrical properties are listed in Table 6.1. For transformer oils, viscosity and breakdown strength are the principal parameters for heat transfer and electrical insulation respectively required for design calculations.

6.1.2 Vegetable Oils

Besides mineral oils, some vegetable oils have also found their application in electrical equipment for their suitable properties. A large number of vegetable oils are

TABLE 6.1 Nominal/standard values of some properties of pure insulating liquids in high voltage applications [6.2, 6.3 and 6.5]

Insulating liquids	Relative permittivity		Loss tangent		Dynamic viscosity*		Density at 20°C	Electric strength		Application
	ϵ_r		$\tan \delta$		Pa.s	$\text{g}/(\text{cm}^3)$	kV/cm	E_b		
Mineral insulating oils (Transformer oil)	at 20°C		at 50 Hz		at 40°C	<0.895	350 ... 500		Power Transformers CTs, PTs Circuit Breakers Bushings Cables and Condensers	
	50 Hz \approx 2.0		$20^\circ\text{C} \leq 10^{-3}$ $90^\circ\text{C} \leq 4 \times 10^{-3}$		0.0067–0.0143 Tr, oil at 27°C 0.0243 (IS–335)		Minimum value for transformers ≥ 300 For Circuit Breakers ≥ 175			
Linseed oil	at 20°C		at 50 Hz		at 40°C \approx 0.0260	0.930	—		—	
Castor oil	50 Hz \approx 3.2		$20^\circ\text{C} > 10^{-3}$		at 100°C \approx 0.0067					
	at 20°C		at 50 Hz		at 40°C \approx 0.2684	0.96–0.97	175–250		Condensers	
	50 Hz between 4.2 and 4.5		$20^\circ\text{C}, <10^{-2}$		at 100°C \approx 0.0192					
Chlorinated Diphenyles	at 20°C		at 20°C, 50 Hz		at 20°C \approx 0.0600	1.400–1.550	250–500		Transformers Condensers (prohibited in some countries) Cables Condensers Bushings	
	50 Hz between 4–6		between 10^{-4} – 10^{-3}		at 90°C \approx 0.0040					
Silicone oils	at 20°C		at 20°C		at 20°C	0.960–0.970	300–400			
	50 Hz \approx 2.6		50 Hz $< 10^{-4}$		0.0096–0.9700					

*Dynamic Viscosity (cP) = Kinematic Viscosity (cSt) \times Density (g/cm^3), cP-centipoise, cSt-centistokes, Pa.s Pascal second, Pa.s (N/m^2).s = 10 P.

available, for example castor, linseed, rapeseed, soya, groundnut, corn, olive, sunflower, mustard, clove almond, mangoseed, cottonseed oils, and so on. They are basically fatty acids accumulated in vegetable seeds. Chemically, these are ester compounds produced from sebacic acids and glycerine. On the other hand, the volatile vegetable oils, for example turpentine oil, have a strong odor and are produced from leaves, wood and roots of special plants. The higher the molecular weight of these oils, the more is the specific resistance and lower the dielectric loss tangent, ($\tan \delta$) [6.2].

Linseed, soya and castor oils are important components for the production of "oil modified alkaline resins". Such resins incorporate the advantages of oils to improve their elasticity as against the hard dried resins. Soya oil with epoxyresin is known as "softener" for some synthetic materials. Castor oil, which has hydroxide contents of about 5%, is an important polyisocyanide reagent. The chemical composition of this unsaturated oil is given as $C_{18}H_{32}OHCOOH$, [6.3], which has a high relative permittivity between 4.2 and 4.5. Castor oil has therefore found wide application as an impregnating agent in power capacitors. Using castor oil considerably reduces the size of the capacitors for a desired value of capacitance. Some of these oils are often mixed with suitable solvents in order to improve the soaking or impregnating properties. Turpentine oil can dissolve lac, and thus serves as a solvent. It also affects the drying and used for lac polishing because of high percentage of peroxide contents.

6.1.3 Synthetic Liquid Dielectrics, the Chlorinated Diphenyles

Among synthetic liquid dielectrics, chlorinated diphenyles have very good electrical properties for their suitable usage in power capacitors. Replacing two to five hydrogen atoms of each molecule by chlorine atoms produces these. Accordingly di, tri, tetra or penta-chlorodiphenyles are produced; for example, trichlorodiphenyle ($C_{12}H_7Cl_3$) and pentachlorodiphenyle ($C_{12}H_5Cl_5$). These dielectrics are also known by different commercial names in different countries; for example, Sowol (Russia), Pyranol (the United States), Chlophen, Orophen (Germany), and so on. Because of the electronegative effect of chlorine atoms, the chlorodiphenyles have comparatively higher relative permittivity number of the order of 5.6 at 20°C. The relative permittivity of paper is of the order of 6.8, therefore the impregnation of paper with these oils gives rise to a more uniform distribution of field compared to natural mineral oils that have relatively lower permittivity of the order of 2 to 2.3. For a desired capacitance the total size of the high voltage condenser is reduced considerably because of smaller volume of insulation thus required.

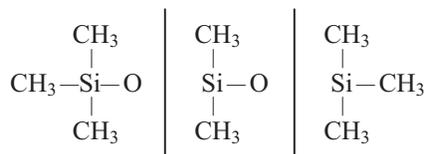
The chlorodiphenyles are highly stable and do not decompose easily under normal conditions. They are oxidation, flame/fire resistant and do not show other forms of aging. They do not endanger any explosion and cause no damage to metals. By mixing trichlorobenzol ($C_6H_3Cl_3$) their viscosity can be brought down to a level of 0.004 Pa.s at 90°C, which is desirable for the use in transformers as a cooling agent.

However, the chlorodiphenyles cause serious problems as they do have a number of undesirable properties. They appear to dissolve organic matter, but to a limited extent, and cause damage to such materials. They also get decomposed by electric arcs and above all, are injurious to health. By inhalation or by direct contact, these can cause serious health hazards. Compared to mineral oils, synthetic liquids are about ten times costlier. Because of the above mentioned behavior, the use of chlorodiphenyle insulating hydrocarbons is prohibited in some countries. In other countries, where these liquids are used for transformers and power capacitors, their use is restricted to completely sealed units in order to prevent any spillage. Moreover, a very strict control of their disposal is observed.

6.1.3.1 Halogen Free Synthetic Oils Among pure hydrocarbon synthetic liquid dielectrics, polyisobutane and dodecylbenzole have found their application in power cables and condensers. Polyisobutane, a chemically stable compound, is a polymerization product of butane of the series polyolefin. It is used as a high viscosity impregnating agent for mass impregnated power cables and condensers.

Dodecylbenzole is a low viscosity insulating material from the series Alkalinebenzole. It is used for low-pressure oil filled cables and also for condensers.

The most important halogen free synthetic insulating liquids are pure polydimethylsiloxane, as shown below,



Polydimethylsiloxane (Silicone oils)

Although incorrect, these are commonly known as “silicone oils”. Silicone oils are very stable liquids and do not show signs of aging under the working conditions of electrical equipment. They are stable thermally up to 300°C and chemically, that is under oxidation with air, up to, 180°C. The viscosity of silicone liquids depend upon their chain structure/length, “*n*”, which is only marginally affected by the temperature of the liquid. Hence silicone oils with their viscosities in a very wide range are available, Table 6.1. Their relative permittivity is about 2.6 at 20°C but reduces to 2.3 at temperatures around 200°C. The dielectric loss tangent ($\tan \delta$) varies only between 10^{-4} and 2×10^{-4} in this wide temperature range of 20 to 200°C. Since silicone oils have a very low surface tension, these are water resistive, that is, water collects as separate drops instead of getting mixed with the oil. One can say in other words that silicone oils have a property to reject water. Therefore, even a thin layer of silicone oil on insulators protects them from water conductive contaminants. Silicone oils are used in power cables and condensers where they are required to be in service over a wide range of temperatures. An extensive use of silicone oils is restricted only because of their high cost.

6.1.4 Inorganic Liquids as Insulation

Extremely purified water has a relative permittivity of the order of 80 and comparatively possesses a high conductivity. Application of water as an insulation is therefore suitable only for high frequency pulse lines. Due to electrical discharge in water, high energy impulse waves and divergent currents are produced. By providing proper shape to the metal plates, these high energy impulse waves can be successfully used in communication for pulse-power capacitors, pulse-forming transmission lines, and switches, Zahn et al. [6.4]. Ethylene glycol is added to water as it maintains the high permittivity with a large resistivity and also allows low temperature operation without freezing.

There is a significant space charge injection into highly purified water when high voltage is applied. It causes anomalous voltage-current characteristics and distortions in the electric field. The nature (+ve or -ve) and the magnitude of space charge strongly depend upon the electrode materials. Thus, by appropriate choice of electrode material combinations and voltage polarity, it is possible to have uncharged, unipolar charged (negative or positive), or bipolar charged water. The recent charge injection analysis, terminal voltage-current measurements, and Kerr electro-optic field mapping measurements by Zahn et al. [6.4] have shown significant space charge effects on the electric field distribution in water.

In Table 6.1, nominal/standard values of some important properties of insulating liquids, used in high voltage equipment, are brought together as given in [6.2, 6.3 and 6.5]. Single values of these properties are not possible as they strongly depend upon the temperature, as well as on the methods and conditions of measurements. Moreover, the entrapped gases, humidity, foreign particles and above all the aging conditions of the liquid also considerably affect the properties. The electric strengths given in this table are either measured by different investigators or required by various specifications. These are measured according to VDE-0370 (Germany), BIS-335 (2005) and 1866 (2000) (India), ASTM D-3487 (USA) or IEC-296, as described in the text.

6.1.5 Polar and Nonpolar Dielectrics

The dielectrics, which have permanent dipoles, are known as polar. In such dielectrics, the asymmetry in their molecular structure leads to a permanent displacement of the positive and negative charge centers even without an external electric field. However, the field vectors in these isotropic materials are distributed in a way such that from outside the material behaves electrically neutral.

The polar dielectrics have a high relative permittivity ϵ_r . The relative permittivity number determines the extent of their being polar. Typical examples of polar dielectrics are, among liquefied gases; ammonia (NH_3) and hydrochloric gas (HCl), and among liquids; water (H_2O), propylene carbonate and $\text{C}_2\text{H}_5\text{NO}_2$. PVC and epoxy resins are the solid dielectrics belonging to the polar group. Highly purified water ($\epsilon_r = 80$) and propylenecarbonate ($\epsilon_r = 69$) are known as strongly polar liquids. In these liquids the enhancement of dissociation process by the applied electric field is very limited. Hence the dissociation rate in these can be considered to be constant. The polar liquids are often good solvents and are commonly used in electrochemistry.

The dielectrics, which do not build dipoles appreciably without an external electric field, are known as nonpolar. The dipoles formed in such dielectrics on applying an electric field are not permanent. In other words, in nonpolar dielectrics the atoms return back to their original state on removing the electric field. The liquids included in Table 6.1 may be regarded as nonpolar liquids.

6.2 DIELECTRIC PROPERTIES OF INSULATING MATERIALS

The electrical properties of liquid and solid dielectrics are described in the following sections.

6.2.1 Insulation Resistance Offered by Dielectrics

The dc resistance offered by an insulating material represents the concept of insulation resistance of a dielectric. It is generally described as specific insulation resistance “ ρ_{ins} ”, which is reciprocal of the dc conductivity κ_{dc} ,

$$\rho_{ins} = \frac{1}{\kappa_{dc}} \quad \Omega \cdot m \quad (6.1)$$

Consider a direct voltage U_{dc} applied across two uniform field electrodes separated by a block of insulating material having an area A and length d as shown in Figure 6.3. From the equivalent circuit diagram constituting a capacitance C and a dc resistance R_{dc} in parallel, the following relation can be derived,

$$R_{dc} = \rho_{ins} \frac{d}{A} \quad (6.2)$$

$$i_{dc} = \frac{U}{R_{dc}} = \frac{U \cdot A}{\rho_{ins} \cdot d} \quad (6.3)$$

for a uniform field where $E = \frac{U}{d}$,

$$\begin{aligned} i_{dc} &= \frac{E \cdot A \cdot d}{\rho_{ins} \cdot d} = \frac{E \cdot A}{\rho_{ins}} \\ &= \kappa_{dc} \cdot A \cdot E \end{aligned} \quad (6.4)$$

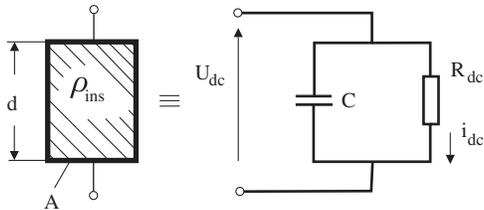


Figure 6.3 An insulating material and its equivalent circuit diagram.

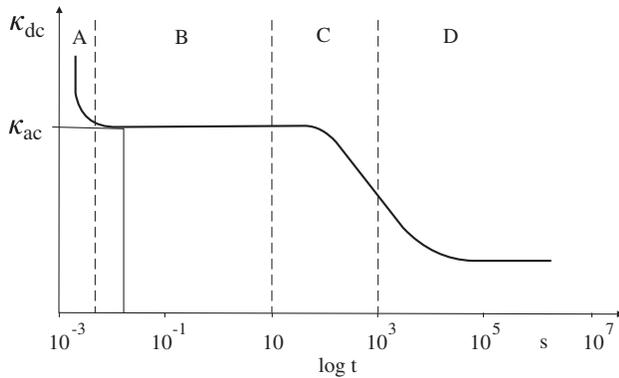


Figure 6.4 A schematic of dc conductivity of an insulating oil with respect to the time of applied voltage.

Like κ_{dc} , the specific insulation resistance also strongly depends upon the temperature.

The specific insulation resistance, or the *dc* conductivity is a function of time for which the voltage is applied. Schematic illustration of the variation of κ_{dc} with respect to the time of application of the direct voltage for an insulating oil is shown in Figure 6.4. The *dc* conductivity, which is very high initially (region A), is determined by the orientation of dipoles in the dielectric present even before the application of voltage.

In region B, the conductivity is determined by the movement of free charge carriers under the influence of applied electric field. The magnitude of conductivity in this region also represents the *ac* power frequency conductivity " κ_{ac} ". The region C in the figure represents the development of space charge in front of the electrodes. The steady ion current due to dissociation is depicted by region D, which is achieved after considerable amount of time of application of the voltage.

In every dielectric matter, including those which have a low concentration of free charge carriers, a conductive current through the dielectric is always present on applying a voltage across the volume of the dielectric. Small currents may also flow along the surfaces of the dielectric. Accordingly, two different conductivities, the volume and the surface conductivities of a dielectric, are distinguished. Reciprocal of these are the specific volume and surface insulation resistances, respectively. The specific insulation resistance ρ_{ins} described above represents the specific volume resistance, " ρ_v ", of the dielectric and it has a unit of $\Omega \cdot m$. The specific surface resistance, " ρ_s ", has accordingly a unit of Ω only. These are properties of the material also known as volume and surface resistivities, respectively.

Surface Resistance " R_s " is defined as the *dc* electrical resistance between two electrodes in contact with an insulating material surface. It is derived as the ratio of the voltage applied to that portion of the material between the two electrodes to the current flowing between the two electrodes. Since it is the current that creeps over the surface of the dielectric, it is also known as "creepage current". Surface or creepage currents of solid dielectrics depend upon their surface resistivity or the specific

surface resistance, “ ρ_s ”, which is determined by the ratio of *dc* voltage drop per unit length to the surface current per unit width of the material.

The surface resistivity of solid dielectrics may have strong variation in its value influenced by the condition of the surface of the material. Temperature, moisture, pollution, composition of the pollution layer, hydrophobicity of the material, and so on, affect the performance of the surface considerably. The surface or the creepage currents of solid dielectrics depend upon their effective surface resistivity.

6.2.2 Permittivity of Insulating Materials

An important electrical parameter of insulating materials is the capacitance offered by them between given electrode systems. The capacitance thus formed is always accompanied with some losses determined by the permittivity “ ϵ ” and the specific insulation resistance ρ_{ins} of the material.

The permittivity of insulating materials ϵ is defined as the product of absolute permittivity of free space (vacuum) “ ϵ_o ” and the relative permittivity “ ϵ_r ” of the material or the medium,

$$\epsilon = \epsilon_o \epsilon_r$$

The absolute permittivity of free space, ϵ_o , is constant and has a value,

$$\epsilon_o = 8.854 \cdot 10^{-12} \text{ F/m}$$

On the contrary, the relative permittivity of a material “ ϵ_r ” is not a constant. It depends upon the thermal conditions of the material as well as the magnitude and frequency of the applied voltage. “ ϵ_r ” is often mentioned as dielectric number or permittivity number in the literature. “ ϵ_r ” of a dielectric is defined as the quotient of the capacitances C_x to C_o . Where C_x , the capacitance of a condenser, when the given material constitutes as the dielectric and C_o , the capacitance of the same condenser when vacuum constitutes as the dielectric,

$$\epsilon_r = \frac{C_x}{C_o} \quad (6.5)$$

The phenomenon of polarization in a dielectric material under the influence of an external electric field can be explained on the basis of the displacement of charges making up electric dipoles. These charged particles have mass and inertia. Considering the effect of frequency of the applied field, it can be predicted that the polarization will decrease with increasing frequency. In other words, as the frequency of the applied field increases, the inertia of the particles will tend to prevent the particle displacement from following the field (in time). Hence, it can be concluded that the displacement will have in phase as well as out of phase components. Accordingly, for the mathematical analysis taking into account the losses in the dielectric due to polarization process at high frequencies prevalent in the communication network, it was necessary to introduce the complex relative permittivity “ $\bar{\epsilon}_r$ ” described as,

$$\bar{\epsilon}_r = \epsilon_r' - j\epsilon_r'' \quad (6.6)$$

where

ϵ_r' is the real part of the complex relative permittivity, which is related to the stored energy within the medium. Hence it is also called the *ac* capacitance, and,

ϵ_r'' is the imaginary part of the complex relative permittivity, which is related to the dissipation (or loss) of energy within the medium. At a given frequency, the imaginary part leads to absorption loss if it is positive and gain if it is negative. ϵ_r'' is also known as the dielectric loss factor or the “loss index” of *ac* signals in a medium, the so called “Lossy Transmission Line”. It can be shown that ϵ_r'' is a positive quantity.

6.2.3 Polarization in Insulating Materials

Polarization in insulating materials is basically a phenomenon of interaction between the applied external electric field and the charge carriers, the atoms, ions or molecules present in the dielectric. Not only does the applied electric field give rise to the polarization, but in turn, polarization modifies the microscopic field within the dielectric. Thus, it is a process of reversible displacement between the positions of positive and negative charges in the molecular structure caused by the applied electric field. The interaction takes place by a force, exercised on the basic structural elements (charge carriers) of the dielectric.

The effect of polarization is analytically described by the relative permittivity ϵ_r . Consider a uniform field electrode system in vacuum applied an electric field E . The electric flux density \vec{D}_o is given by,

$$\vec{D}_o = \epsilon_o \cdot \vec{E} \quad (6.7)$$

For the same electrode and the magnitude of the applied electric field on replacing the vacuum by an insulating material (solid, liquid or gas) the electric flux density in the dielectric \vec{D}_{ins} is increased as given by,

$$\vec{D}_{ins} = \epsilon_o \cdot \epsilon_r \cdot \vec{E} \quad (6.8)$$

The increase in electric flux density “ \vec{D}_p ” is caused by polarization in the dielectric. “ \vec{D}_p ”, therefore, represents the property of the material and is given by,

$$\vec{D}_p = \vec{D}_{ins} - \vec{D}_o = \epsilon_o (\epsilon_r - 1) \vec{E}$$

or

$$\frac{\vec{D}_p}{\vec{D}_o} = (\epsilon_r - 1) = \chi \quad (6.9)$$

The quotient D_p/D_o is known as “dielectric susceptibility” or “polarization capacity” of a dielectric. It is denoted by χ .

Most of the gaseous dielectrics have their ϵ_r nearly equal to one. Hence polarization is not an important phenomenon in gases, but in liquid and solid dielectrics it plays a significant role determining the conductivity and the losses. Different types of polarization mechanisms are described under the following three main categories.

Displacement Polarization

Within a molecular bond, the positive and negative charges of individual molecule or atom are rendered to oscillate in synchronism under the influence of an applied electric field. Similar oscillations also take place between the nucleus and the electron shell of an atom, building dipoles. The displacement caused by the oscillations is proportional to the applied electric field and on removing the electric field the atoms return back to their original state. Where only this type of polarization mechanism is present, the dielectric materials are described to be “nonpolar” and these have no dipole moment. Classic examples of such dielectrics are the gases, which have ϵ_r nearly equal to one.

Space Charge or Boundary Surface Polarization

The heterogeneous dielectrics, for example partially crystalline insulating materials, have the positive and negative ions as free charge carriers. Without an external field, the dielectric is in neutral condition and the positive and negative charges neutralize each other. However, under the effect of an external electric field, the charge carriers in the dielectric move towards opposite polarity electrode surfaces, giving rise to a macroscopic dipole. Like the mechanism described in the previous case, in this case too on removing the applied electric field, the dielectric returns to its original neutral state. Hence it is known as a type of displacement polarization.

Dielectrics having this type of polarization mechanism are also described as nonpolar, that is, these do not build a dipole without an external field. The boundary surface polarization is commonly present in heterogeneous insulating materials, such as impregnated paper insulations, hard pressed boards, taped insulations used in electrical machines and even at voids in solid homogeneous dielectrics. Such materials normally have a low value of ϵ_r .

Orientation Polarization

Orientation polarization is the main polarization mechanism in liquid dielectrics. Usually, the polarization depends upon the applied electric field intensity. However, in some materials a permanent polarization is “frozen” due to the permanent dipoles present in the dielectrics even without an external field. Such dielectrics have an asymmetry in their molecular structure and are described as polar.

On applying an external electric field, the dipoles arrange themselves according to the field lines. The effect of applied external field on the dipoles is determined by their dipole moments. Depending upon the bond between the positive and negative charges in the molecules of the material, the orientation of dipoles takes place. The effective field intensity established in the material is the quantity induced by the external source and the sources within the material itself. The orientation of dipoles may be in the form of an arrangement in an element or they may simply straighten out like a chain, which usually depends upon the local field in which the molecules

are situated. The local microscopic field may not be necessarily equal to the macroscopic applied electric field.

6.2.3.1 Effect of Time on Polarization The displacement of charge or orientation of dipoles is accompanied with a time lag. Depending upon the frequency of the voltage applied, a time constant determines the extent of polarization. Not only the frequency but also the temperature affects the polarization. The effects of variation of voltage with time on polarization are described in the following.

6.2.3.1.1 Polarization under Direct Voltage Consider a uniform field parallel plate condenser of area A and gap distance d , having vacuum in one half of its volume ($\epsilon_{r1} = 1, \kappa_1 = 0$) and let the other half filled with a solid dielectric ($\epsilon_{r2} = 2, \kappa_2$) as shown in Figure 6.5 (a). The equivalent circuit diagram of this condenser is shown in Figure 6.5 (b).

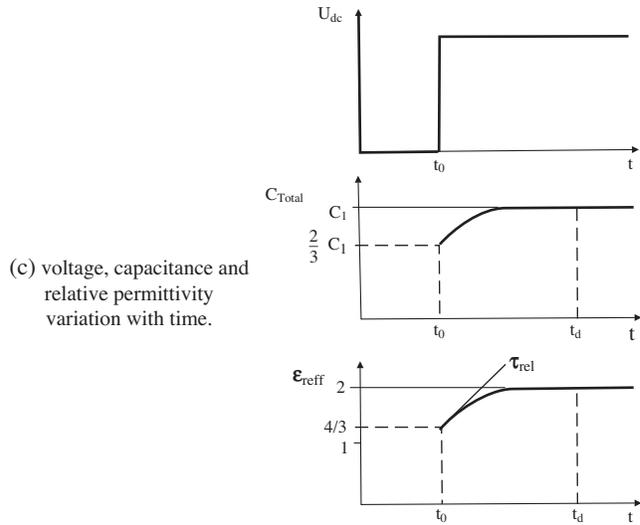
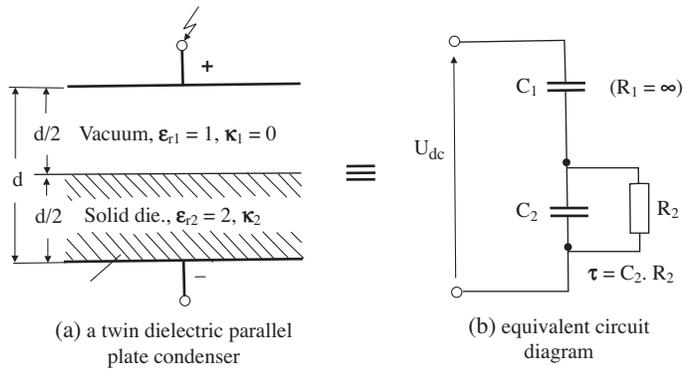


Figure 6.5 Polarization under direct voltage.

On applying a direct voltage across this condenser at time $t = t_o$, at first no current flows through the condenser because of the time lag of ions present in the solid dielectric. In other words, there is no space charge polarization present immediately after the application of voltage. The total capacitance of the condenser at the instant t_o is given by,

$$\frac{1}{C_{Total}} = \frac{1}{C_1} + \frac{1}{C_2}$$

or

$$C_{Total} = \frac{C_1 \cdot C_2}{C_1 + C_2} \quad (6.10)$$

Since ϵ_{r2} is equal to $2\epsilon_{r1}$, C_2 is then equal to $2C_1$. Putting this value in equation (6.10).

$$C_{Total} = \frac{2}{3} C_1 \quad (6.11)$$

as shown in Figure 6.5 (c). The capacitance of the parallel plate condenser shown in Figure 6.5 (a) is given by,

$$C = \frac{\epsilon \cdot A}{d} \quad (6.12)$$

Using this relation for the equivalent capacitance, the combined or the effective relative permittivity at $t = t_o$ is determined as follows,

$$\frac{1}{C_{Total}} = \frac{1}{C_1} + \frac{1}{C_2}$$

or

$$\frac{d}{\epsilon_{r(eff)} A} = \frac{d/2}{\epsilon_{r1} \cdot A} + \frac{d/2}{\epsilon_{r2} \cdot A}$$

or

$$\epsilon_{r(eff)} = \frac{2\epsilon_{r1} \cdot \epsilon_{r2}}{\epsilon_{r1} + \epsilon_{r2}}$$

or

$$\epsilon_{r(eff)} = \frac{4}{3} \quad (6.13)$$

The conductivity of the solid dielectric, represented by the resistance R_2 in the equivalent circuit diagram, is shown in Figure 6.5 (b). On applying the voltage, a displacement of charge within the solid dielectric takes place. The capacitance C_2 is discharged over R_2 with a time constant τ equal to $C_2 R_2$. Let C_2 be completely discharged by the time t_d , where t_d is greater than $(t_o + 3\tau)$. Under this condition, the total applied voltage stands across C_1 . The effective capacitance of the given condenser, after a time lag of t_d , is therefore C_1 , Figure 6.5 (c). For a time $t \geq t_d$, the following relationship is derived,

$$C_{Total} = C_1$$

or

$$\frac{\epsilon_{r(eff)}A}{d} = \frac{\epsilon_{r1} \cdot A}{d/2}$$

or

$$\epsilon_{r(eff)} = 2\epsilon_{r1} = 2 \quad (6.14)$$

This process can be interpreted by the phenomena of displacement of space charge in the solid dielectrics. The space charge polarization leads to an increase in effective relative permittivity, and hence also the capacitance. However, the polarization is effective only when the time required for the formation of dipoles as well as their displacement is provided. The time required for this process is known as “Relaxation time”. In Figure 6.5 (c), the tangent to the curve showing increase in $\epsilon_{r(eff)}$ with time, represented by τ_{rel} is a measure of the time required for polarization process, hence it can also be denoted by τ_p .

The relaxation times required by different types of polarizations vary considerably from each other. For example, the relaxation time is of the order of 10^{-15} s for electron polarization, whereas for ion polarization it is 10^{-12} s. For orientation polarization it is 10^{-8} s, and for space charge or boundary surface polarization, the longest relaxation time of the order of 10^{-3} s is required.

6.2.3.1.2 Polarization under Alternating Voltage On applying alternating field to a dielectric, the dipoles or the charges must change their direction every half cycle. If the frequency of alternating field is very low, in other words, if the duration of the half cycle is very long compared to the required “relaxation time” of the dipoles, then the polarization caused by orientation of dipoles would have its maximum effect. Let this be represented by ϵ_{r1} in Figure 6.6. In the equivalent circuit diagram shown in this figure for the region of the frequency ($\omega \ll \omega_e$), C_p represents the increase in capacitance caused by polarization, whereas R_p represents the pure resistance required to interpret the time dependence of polarization. The time constant is given by,

$$\tau_p = C_p \cdot R_p$$

At very high frequencies, where the duration of a half cycle is very short compared to the relaxation time, the dipoles are not in a position to follow the change in the field intensity. This reduces the polarization caused by orientation of dipoles that ultimately diminishes to zero at very high frequencies as illustrated by the right hand side of the curve in Figure 6.6. It is represented by a lower constant value of relative permittivity, ϵ_{r2} . The total effective capacitance in this region of very high frequency is C , as shown in the equivalent circuit diagram.

The transition domain of frequency is also known as the “dispersion domain”. The relative permittivity ϵ_r depends strongly upon the frequency. Corresponding to the relaxation time τ_p , the eigen frequency “ ω_e ” of the dipoles is defined as:

$$\omega_e = \frac{1}{\tau_p} \quad (6.15)$$

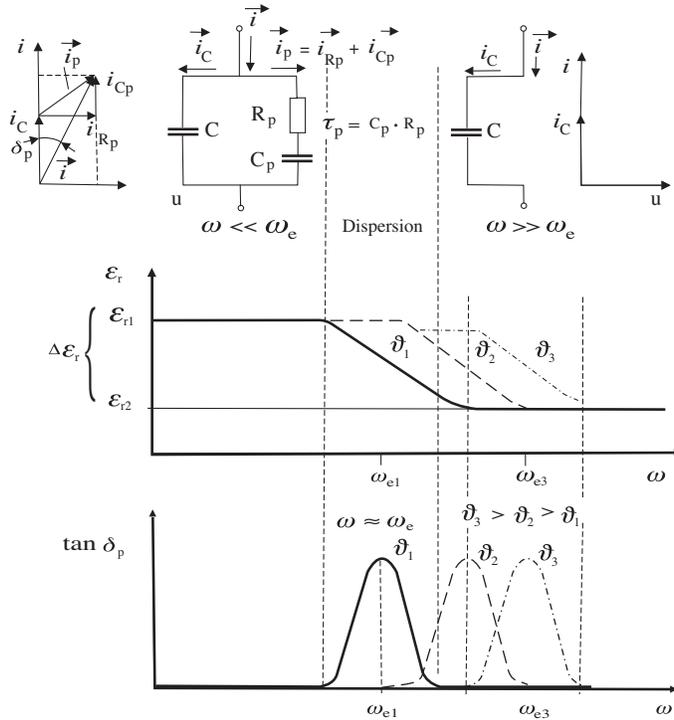


Figure 6.6 Polarization under alternating voltage and the effect of frequency and temperature on ϵ_r and polarization losses.

The eigen frequency ω_e of a dielectric is its characteristic property and may vary considerably for different dielectrics. For example, it is 10kHz for hard pressed boards, whereas for highly purified water, it is of the order of 100MHz. Eigen frequency of dielectrics is also a function of temperature. It is influenced by the binding energy of the material, which in turn is affected by temperature. Consequently, at higher temperatures the eigen frequency of a dielectric increases, as shown in Figure 6.6. From this figure the following can be concluded,

for

$$\omega \ll \omega_e, \quad C_{Total} = C + C_p$$

and for

$$\omega \gg \omega_e, \quad C_{Total} = C$$

Taking into account the polarization losses, the total admittance offered can be calculated as,

$$Y_{Total} = j\omega C + \frac{j\omega C_p}{1 + j\omega R_p C_p} \quad (6.16)$$

The total admittance offered across the terminals can also be given by,

$$Y_{Total} = j\omega \epsilon_r \cdot C_o \quad (6.17)$$

where C_o is the capacitance of the same electrode system with air or vacuum as dielectric. By equating the two equations given above, we get,

$$\epsilon_r = \frac{C}{C_o} + \frac{C_p}{C_o} \cdot \frac{1}{1 + j\omega R_p \cdot C_p} \quad (6.18)$$

Putting $R_p \cdot C_p = \tau_p = 1/\omega_e$ in the above equation,

$$\epsilon_r = \frac{C}{C_o} + \frac{C_p}{C_o} \cdot \frac{1}{[1 + j(\omega/\omega_e)]} \quad (6.19)$$

or

$$\epsilon_r = \frac{C}{C_o} + \frac{C_p}{C_o} \cdot \frac{[1 - j(\omega/\omega_e)]}{1 + (\omega/\omega_e)^2}$$

From Figure 6.6 as explained above, we obtain,

$$\frac{C}{C_o} = \epsilon_{r2} \quad \text{and} \quad \frac{C_p}{C_o} = \Delta\epsilon_r$$

Therefore, equation (6.19) can be rewritten as,

$$\epsilon_r = \epsilon_{r2} + \frac{\Delta\epsilon_r}{1 + (\omega/\omega_e)^2} - j(\omega/\omega_e) \cdot \frac{\Delta\epsilon_r}{1 + (\omega/\omega_e)^2} \quad (6.20)$$

or

$$\bar{\epsilon}_r = (\epsilon_r' - j\epsilon_r'')$$

Equation (6.20) is similar to equation (6.6), proving that $\bar{\epsilon}_r$ is a complex quantity having real and imaginary parts. The complex quantity $\bar{\epsilon}_r$ given by equation (6.20) for the case explained in Figure 6.6 is plotted in Figure 6.7. Like ω_e , the relative permittivity ϵ_r is also a function of temperature.

From the equivalent circuit diagram given in Figure 6.6 for the region $\omega \ll \omega_e$ (for example power frequency region), the total vector current \vec{i} is given by,

$$\vec{i} = \vec{i}_c + \vec{i}_p \quad (6.21)$$

where the polarization current \vec{i}_p constitutes of real \vec{i}_{Rp} and reactive \vec{i}_{cp} parts. The total reactive current is then given by,

$$\vec{i}_{Total(reactive)} = \vec{i}_c + \vec{i}_{cp}$$

and total active current is \vec{i}_{Rp} .

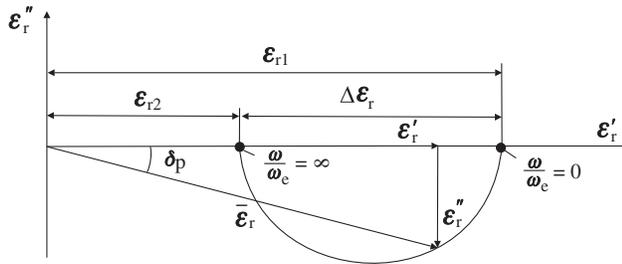


Figure 6.7 Plot of complex relative permittivity variation with frequency of applied voltage.

The angle between total vector current and the total reactive current in the dielectric is known as angle δ_p , which is a measure of the active power loss in the dielectric due to polarization. The tangent of angle δ_p is equal to the ratio of total active to reactive currents, that is, the ratio between the real and imaginary parts of the current in the dielectric due to polarization, as shown by the vector diagram for the currents in Figure 6.6,

$$\tan \delta_p = \frac{i_{Rp}}{i_c + i_{cp}} \quad (6.22)$$

From Figure 6.7 and equation (6.20)

$$\tan \delta_p = \frac{\epsilon_r''}{\epsilon_r'}$$

or

$$\tan \delta_p = \frac{\Delta \epsilon_r(\omega/\omega_e)}{\epsilon_{r2}[1 + (\omega/\omega_e)^2] + \Delta \epsilon_r} \quad (6.23)$$

From Figure 6.7, it is clear that δ_p , hence $\tan \delta_p$ has maximum value in the dispersion domain of the frequency. For $(\omega/\omega_e) \ll 1$ and $(\omega/\omega_e) \gg 1$, $\tan \delta_p$ tends to be equal to zero. Accordingly a schematic plot of $\tan \delta_p$ with respect to the frequency is shown in Figure 6.6. However, since ϵ_r and ω_e , both are functions of temperature, with increasing temperature (θ_2, θ_3) the loss tangent maximum due to polarization in a dielectric also shifts towards higher frequencies with the increase in eigen frequency.

It can be concluded with this analysis that the peak active power loss due to polarization in a dielectric takes place at its eigen frequency. This is important knowledge, which must be taken into consideration while exercising choice of the dielectric for use in high frequency high voltage equipments. The eigen frequency of the dielectric in such an apparatus should in no way be close to its working frequency.

6.2.4 Dielectric Power Losses in Insulating Materials

Besides the capacitive charging currents, real or active currents are also present in the dielectrics. These currents are caused due to different types of conductivities and polarizations present in the materials. As shown in the previous sections, these currents not only depend upon the frequency and magnitude of the applied voltage but also upon the thermal conditions of the dielectric. The conductive currents present in an insulating material determine its dielectric power loss property. Each conductive current mechanism causes currents of different characteristics. These currents contribute to the total dielectric current, " i_{ins} ", as depicted schematically for alternating voltage in Figure 6.8.

The dielectric loss tangent, " $\tan \delta$ " is defined as the quotient of active to reactive power loss in a capacitor or in a volume of dielectric. It is derived from Figure 6.8 as follows,

$$\tan \delta = \frac{\text{Active Power}}{\text{Reactive Power}} = \frac{u \cdot i_{ins} \cos \phi}{u \cdot i_{ins} \sin \phi} = \frac{i_{R(Total)}}{i_{C(Total)}} \quad (6.24)$$

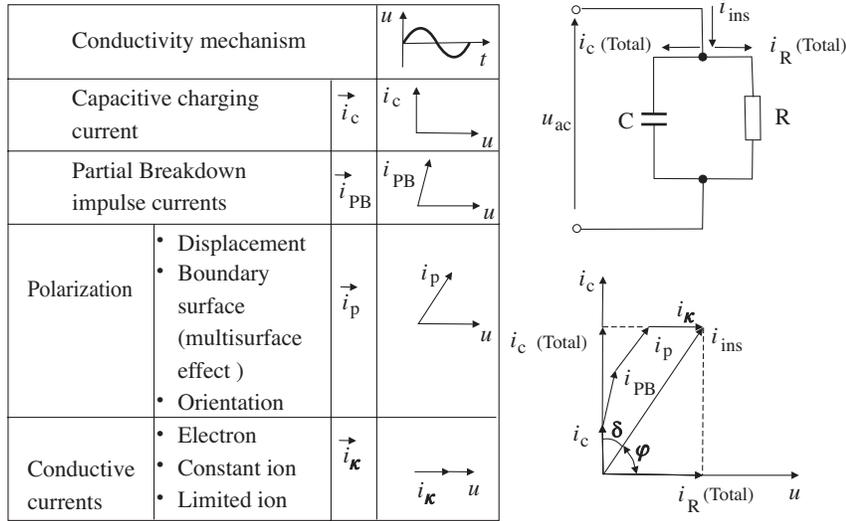


Figure 6.8 Conductive mechanisms in insulating materials for alternating voltage with equivalent circuit and vector diagrams.

The dielectric loss tangent ($\tan \delta$) represents the complete power loss in a dielectric, hence it is a parameter with which the power losses in a capacitor can be estimated. However, $\tan \delta$ is a function of frequency and magnitude of the applied voltage as well as the temperature of the dielectric, because these affect the conductivity κ and the polarization processes in the dielectrics.

When alternating voltage of rms magnitude U and frequency ω is applied to a condenser having total effective capacitance C , the total capacitive conductive current $I_{C(Total)}$ is given by,

$$I_{C(Total)} = \frac{U}{1/\omega C} = \omega \cdot C \cdot U \tag{6.25}$$

The active part of the total insulation current is $(\omega C U \cdot \tan \delta)$, hence the active power loss “ P_{ac} ” is given by,

$$P_{ac} = \omega \cdot C \cdot U^2 \cdot \tan \delta \tag{6.26}$$

where $\omega = 2\pi f$ and if f is in Hz, C in F and U in volts, P is given in Watts. In practice, the capacitance C of the given test object is generally measured.

Considering a parallel plate condenser of area A and gap distance d having dielectric with relative permittivity ϵ_r forming a uniform field E , equation (6.26) can be rewritten as,

$$P_{ac} = \omega \cdot \epsilon_o \epsilon_r \frac{A}{d} \cdot (E \cdot d)^2 \tan \delta$$

or

$$P_{ac} = \epsilon_o \cdot \omega \cdot E^2 \cdot V \cdot \epsilon_r \tan \delta \tag{6.27}$$

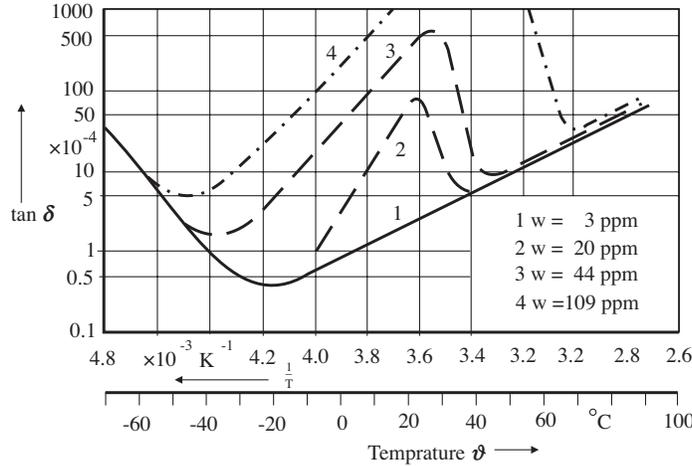


Figure 6.9 Loss tangent “ $\tan \delta$ ” of transformer oil having different ppm moisture contents with varying temperature at 50Hz constant voltage, Holle [6.6].

where V , the volume of the dielectric, is given by (Ad) in this case. Equation 6.27 shows that the dielectric losses depend upon the applied field intensity and its frequency, volume of the dielectric, its relative permittivity, and the loss tangent.

On applying a direct voltage to the dielectric, the losses depend only upon the magnitude of the applied voltage U_{dc} and the dc resistance, “ R_{dc} ” offered by the dielectric, determined by equation (6.3) and (6.4) as follows,

$$P_{dc} = \frac{U_{dc}^2}{R_{dc}}$$

or

$$P_{dc} = E^2 \cdot V \cdot \kappa_{dc} \quad (6.28)$$

Variation in loss tangent of a transformer oil having different moisture contents, measured for a wide range of temperatures by Holle [6.6] is shown in Figure 6.9. These measurements were conducted on a standard test cell (guard ring capacitor) applying a constant 50Hz voltage.

Figure 6.10 shows the variation of $\tan \delta$ and ϵ_r of synthetic insulating liquid “Clophen A 50”, with respect to temperature measured at 50Hz constant voltage.

As described earlier, the loss tangent is a function of the applied voltage. Increase in $\tan \delta$ of transformer oil samples, measured at constant temperatures for increasing 50Hz voltage/field intensity magnitudes is shown in Figure 6.11, for two different moisture contents, Bayer et al. [6.5]. These measurements were made at Schering Institute of HV Engineering, University of Hannover. Extra care was taken to design the measuring arrangement, which was developed to be PB free for upto 200kV. As seen from these curves, the increase in temperature as well as moisture content in oil, both result in a premature increase in $\tan \delta$ values with increasing voltage.

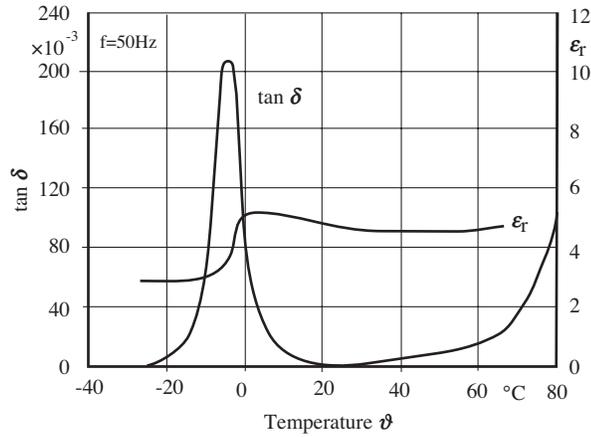


Figure 6.10 Variation in measured values of $\tan \delta$ and ϵ_r with increasing temperature for synthetic insulating liquid, "Clophen A 50" at constant 50Hz ac voltage.

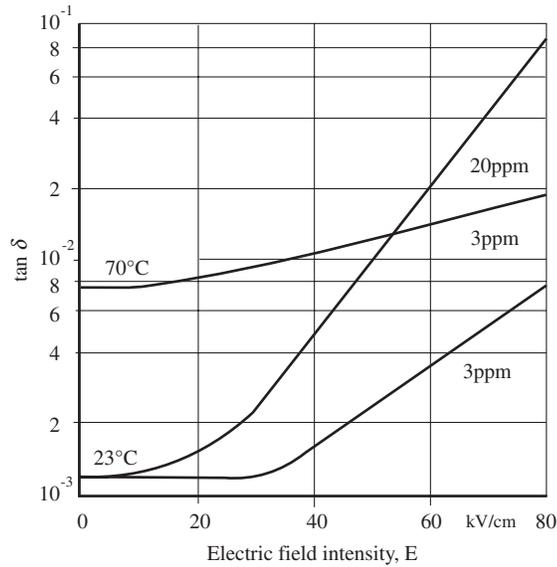


Figure 6.11 Loss tangent ($\tan \delta$) of transformer oil measured with increasing 50 Hz voltage/field intensity at different constant temperatures and moisture contents in oil, Bayer et al. [6.5].

6.3 BREAKDOWN IN LIQUID DIELECTRICS

A very large number of external factors affect the breakdown strength of liquid dielectrics. For example, electrode configuration, their material, size and surface finish; the type of voltage, its period of application and magnitude besides the temperature, pressure, purification of the liquid and its aging condition. Dissolved water, gas or the presence of any other form of contamination considerably affect the breakdown strength. It is, therefore, not possible to describe the breakdown mechanism by a single theoretical analysis, which could take into account all known observed factors affecting the breakdown. Hence, there is no unified physical theory of breakdown in liquids. However, the measured breakdown strength of any dielec-

tric is distinguished into two broad categories known as the “intrinsic” and the “practical” breakdown strengths.

Before describing these, it would be interesting to investigate the mechanisms of pre-breakdown conduction in insulating liquids. The electric conduction primarily determines the dielectric properties. The trend of research in this area has been more practical, involving the commercial liquids used in the industry, Umemura et al. [6.7]. The electric conduction and dielectric properties of insulating liquids used in practice are generally affected by the amount of ionic impurities that they contain.

6.3.1 Electric Conduction in Insulating Liquids

The conduction mechanism in a dielectric liquid is strongly affected by the degree of its purification. A schematic of typical characteristic of conduction current density J versus the applied dc voltage U in a pure liquid is shown in Figure 6.12. At low voltages, the current is directly proportional to the voltage, region 1, representing the ohmic behavior. On raising the applied voltage, and thus the field intensity, the ionic current gets saturated, region 2. At still higher applied voltage, the current density increases rapidly until the breakdown occurs, region 3.

Similar behavior is observed generally in both polar and nonpolar liquids. In some cases the saturation region may be completely missing. This characteristic has an analogy to what has also been commonly observed in gases. In liquids, which have not been highly purified, when subjected to field up to about a few kV/cm the conduction is primarily ionic. The dissociation processes of impurities as well as the injection of charge by the electrodes through electrochemical reactions affect ionic conduction. The electrons do not take part in the passage of current through such liquids. In nonpolar liquids, electrons exhibit a transitory existence. They recombine with positive charges, transfer to surfaces of the vessel or become attached to impurities and form negative ions, Schmidt [6.8].

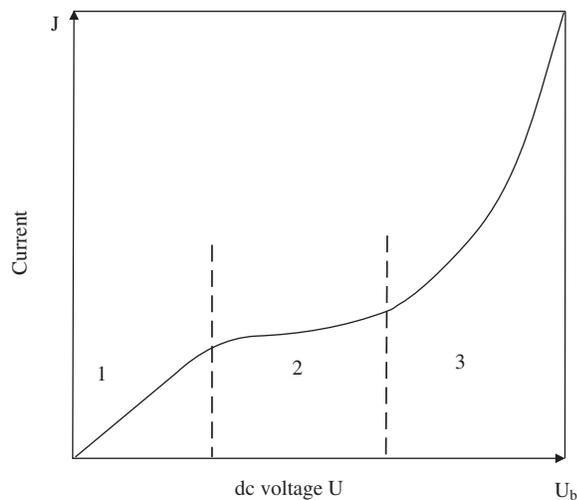


Figure 6.12 Typical voltage—current ($U - J$) characteristic in dielectric liquids.

The concentration of charge carriers and the viscosity of insulating liquids are both strongly affected by the temperature, which in turn influence the conductivity of the liquid. According to Van't Hoffsch law, the conductivity, " κ " within a certain range of temperature follows the relation,

$$\kappa = \kappa_o \exp(-F/kT) \quad (6.29)$$

where k is Boltzmann constant, T absolute temperature, κ_o and F are the material constants. F is known as "activation energy" and is expressed as kcal/mole.

However, Van't Hoffsch law is valid only in the region where the conduction current follows the ohmic behavior, that is, region 1 in Figure 6.12. It thus depends upon the particular liquid and its impurity contents (for example, moisture content etc). For some aromatic insulating liquids, Umemura et al. [6.7] have discussed the applicability of the above equation at different temperatures and have also estimated the values of the constants. According to them, the conduction phenomenon of the liquids can be divided into two temperature regions. In the low temperature regions, that is, room temperature and lower, the conductivity is governed mainly by ionic carrier mobility. However, in the high temperature region, it is characterized by thermal dissociation of impurities as well as carrier mobility whereas the viscosity of the liquid governs the carrier mobility.

Variation in transformer oil conductivity for a wide range of temperature and different moisture contents measured by Holle [6.6] in near uniform field are illustrated in Figure 6.13. Equation (6.29) is proved to be valid only in the temperature region above the room temperature. The conductivity curve in this region represents a straight line on logarithmic scale (curve 1). It is evident from this figure that the conductivity of oil increases as the water ppm contents rise.

In Figure 6.14 the conduction current characteristics in extremely nonuniform field are shown for negative direct voltage applied to a needle-plane electrode configuration in transformer oil and liquid nitrogen, measured for different radii of curvature, " r_t " of the needle tip by Takashima et al. [6.9]. For these experiments, the needle constituted of a polished platinum wire of radius 0.25 mm and the plane of 50 mm diameter Rogowsky profile curved plate of stainless steel. The current was measured through the plane electrode for a constant gap distance of 4 mm. The sharp bend measured in the curve is supposed to represent the development of a strong space charge around the needle possibly due to inception of PB in extremely non-uniform field.

6.3.1.1 *Liquid Dielectrics in Motion and Electrohydrodynamics (EHD)*

The behavior of transformer oil and other dielectric liquids used for insulation and cooling in power system equipment is significantly influenced by the motion or circulation of the fluid. The motion in fluids could be natural or forced by the action of circulating pumps.

The total conduction current has two distinct contributions: the impurities in the liquid, which may dissociate to produce free ions, and the ions (charge) injected from the electrodes due to electrochemical reactions at the metal-liquid interface. At low electric field, the dissociation current is always larger than or equal to the injected current. However, the charges generated by streaming electrification from

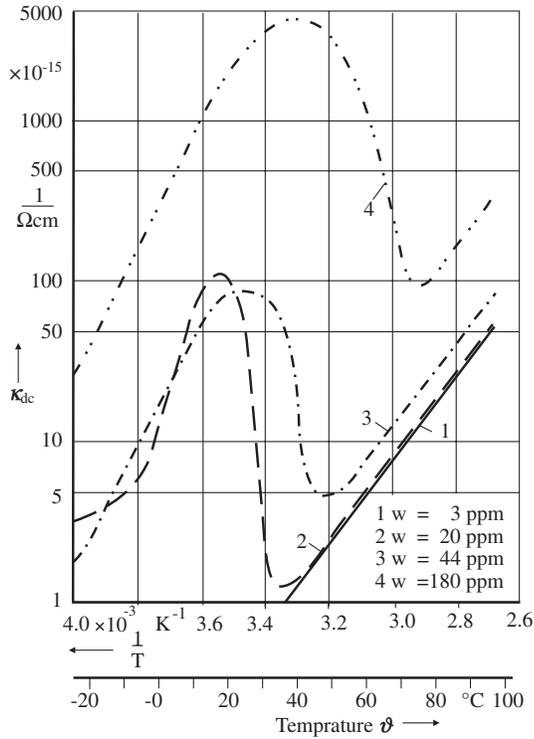


Figure 6.13 Direct current conductivity of transformer oil for different water contents (ppm) with respect to the reciprocal of absolute temperature, Holle [6.6].

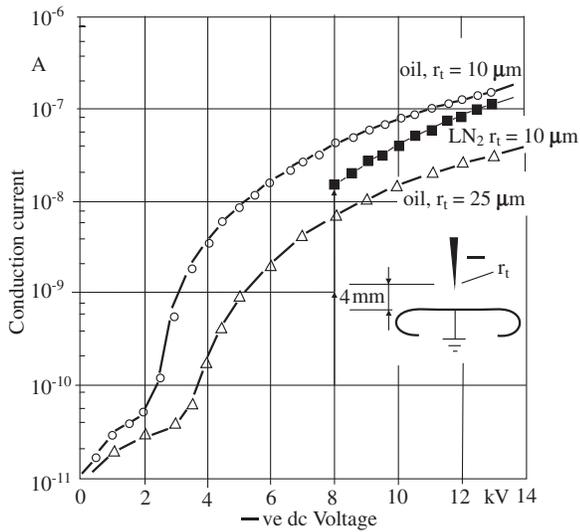


Figure 6.14 Conduction current in oil and liquid nitrogen for negative needle-plane electrode gap of 4 mm with increasing voltage. Oil at 20°C and LN₂ at 77.3 K, Takashima et al. [6.9].

the electrodes are much higher and may, therefore, not uniformly distribute in the liquid. The charges accumulate at critical parts of the hydraulic circuit having high velocity or turbulence. Such an accumulation of charge distorts the electric field at locations where the dielectric integrity is prejudiced. The dielectric strength of the liquid is also altered by the action of the flow in a complex, but predictable, manner, Nelson [6.10]. However, as Nelson reports, there has been very little progress in identifying the trace of contaminants that contribute to the tendency of nonuniform distribution of charge in the liquid dielectric fluids. The most productive engineering approach would be to investigate and identify the conditions under which the large amounts of charge accumulation takes place at locations causing reduction in electric strength of the dielectric. Hence, it would be desirable to have a “continuous contaminant sensing mechanism” in liquid dielectrics to monitor the condition of the equipment.

Since the highly purified liquid dielectrics have very high breakdown strength, a peculiar conduction phenomenon has been observed in these at very high field intensities. On increasing the field intensity to the order of a few hundred kV/cm, the conduction current in both polar and nonpolar liquids is augmented predominantly by large amount of charge carriers injected into the liquid from the electrodes. Beside this, the field aided dissociation process of molecules is intensified. Under certain given conditions, the presence of space charge, say of density q , gives rise to a Coulomb's force of density qE . Due to the action of this force, hydrodynamic instability is caused, developing convection motion in the liquid. Investigations made by many authors, on both polar and nonpolar liquids, have concluded that whenever conduction in an insulating fluid is accompanied with a significant magnitude of charge injection, the convection motions occur. These are known as “electrohydrodynamic” (EHD) motions. The EHD motions augment the passage of current depending upon the charge injection intensity, which in turn is determined by the applied voltage, the nature of liquid and the electrode material, Zahn [6.4], Takashima [6.9] and Atten [6.11].

Atten [6.11] explained the effect of the phenomenon of EHD motion on the conduction in liquid dielectrics under two extreme conditions, with and without unipolar injection of charge. For his experimentation, an extremely nonuniform field configuration between a knife and a plane was taken, as shown in Figure 6.15.

Consider first the case of injection of unipolar charge (ions) by the knife, Figure 6.15 (a). The field at the tip of the knife electrode is reduced because of the same polarity space charge being injected, whereas an increase in the field intensity is caused over the basic field towards the plane electrode. The space charge zone is of finite extent when a moderate voltage is applied. Under this condition, the liquid relaxation time is lower than the transit time of the ions from the knife to the plane. The total current is, therefore, higher than the ohmic current because of the enhancement of field intensity near the plane. Moreover, due to the action of the electric field on the same polarity charge close to the knife, a “stream” or “jet” of liquid towards the plane is induced in this region.

In case of pure conduction with no injection of charge, Figure 6.15 (b), an opposite polarity space charge near the knife extends further. Consequently, the space charge field at the tip increases, and is reduced with respect to the basic field

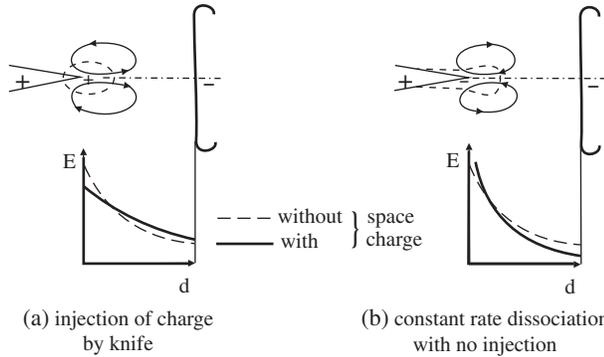


Figure 6.15 Schematic representation of space charge zone and liquid motion streams between knife-plane electrodes and the field distribution along the axis, Atten [6.11].

towards the plane. This results in lower total current than the ohmic current (sub-ohmic behavior). The opposite polarity space charge in the vicinity of the knife gives rise to a liquid motion directed towards the knife.

Takahima et al. [6.9] also observed similar results, when they conducted experiments between a razor blade and the plane in transformer oil and liquid nitrogen. Zahn et al. [6.4] conducted their experiments with highly purified water over a temperature range of 0 to 30°C using parallel plane electrodes. An average field intensity up to 160 kV/cm was achieved on applying a positive impulse voltage. They concluded that for pulse duration times greater than 500 μ s, stainless steel and copper electrodes generally injected positive charge, although under some conditions with mixed electrodes they injected negative charge. Aluminium electrodes injected only negative charge, while brass electrodes could inject either positive or negative charge. Thus by appropriate choice of electrode material combinations and voltage polarity, it is possible to have uncharged, unipolar charged negative or positive, or bipolar charged liquids.

At extremely high field intensities (1000 kV/cm and above) approaching the “intrinsic strength” of liquid dielectrics, the field emission at the electrode surfaces affects the conduction phenomenon. Under these conditions, electrons dominate the conduction current.

6.3.2 Intrinsic Breakdown Strength

The intrinsic breakdown of liquid and solid dielectrics is defined as the highest value of breakdown strength obtained after eliminating all known secondary effects, which may influence the breakdown. The concept of intrinsic breakdown is ideal. It is, however, extremely difficult to ascertain whether an observed breakdown was intrinsic or not. Intrinsic strength can be suitably interpreted as the field intensity at which the particles in the material are accelerated without any limit by the direct electrostatic action of the field.

The mean free path of an electron in insulating oils is very short, of the order of 10^{-6} cm. Extremely high field intensity is therefore required to begin

the elementary process of ionization with free electrons having a very short lifetime. The elementary processes through which energy loss into the liquid takes place, determine the breakdown mechanism. Hence these processes decide the breakdown strength of a dielectric. The elementary processes of ionization are as follows:

- the most likely elementary process in case of hydrocarbon liquids is by excitation or molecular vibration, which is equivalent to thermal vibrations. The vibrational modes of a hydrocarbon are determined by elementary vibration of the C-C and C-H molecular bonds. The frequencies of such vibrations lie in the infra-red region with corresponding energy quanta of about 0.2 to 0.4 eV ($1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$). These may lead to local growth of vapor phase of microbubbles.
- the process of dissociation of molecules in neutral, low molecular, gaseous particles is due to severe molecular vibrations that requires energy levels in the range 1.5 to 7 eV.
- excitation of metastables that may lead to ionization in a few stages, requiring energy levels of the order of 1.5 to 10 eV.
- ionization process involving scintillation of electrons accompanied with weak luminescence, indicating energy quanta of several eV, which is greater than 10 eV in some liquids.

The elementary processes mentioned above depend upon the molecular structure of a dielectric. These may occur spatially and timely together. However, there is no evidence of ionization by electron collision in liquids as in the case of gases. The electrode process may play its usual role as described.

For a mean free path of electrons of the order of 10^{-6} cm and an ionization energy level of about 10 eV, the theoretically estimated field intensity required to cause ionization in insulating liquids is of the order of 10,000 kV/cm, which is an impractical value. On the contrary, a field intensity of about 200 to 400 kV/cm may be sufficient to cause ionization by the elementary process of excitation of molecular vibration.

Electric strengths of some highly purified liquids and liquefied gases as given by Lewis in [5.7] are given in Table 4.2. These breakdown strengths appear to have been measured on very thin liquid films and represent nearest comparative values of intrinsic strengths.

6.3.3 Practical Breakdown Strength Measurement at Near Uniform Fields

The peak *ac* value of electrical breakdown strength of commercially available purified insulating oils is about 350 kV/cm. This is highly contradictory to the measured intrinsic strengths of the order of 1000 kV/cm and above. As mentioned above, it is because of the secondary effects that influence the breakdown strength. If the condition of the liquid is very bad (impure, contaminated, etc.) one may measure an electric strength only as low as 10 kV/cm.

TABLE 6.2 Electric strength of highly purified liquids and liquefied gases, Lewis in [5.7]

Liquids	Breakdown Strength kV/cm
Good oil	1000–4000
Benzene	1100
Silicone	1000–1200
Hexane	1100–1300
Hydrogen	>1000
Oxygen	2400
Nitrogen	1600–1880

In order to compare the electric strengths of different insulating liquids or the same liquid in its different conditions, the methods of measurement of practical breakdown strength have been standardized by various standards. Simple methods are thus evolved to estimate the quality of insulating liquids. The methods laid down by IS-6792 (2003), VDE-0370 and IEC-156 are almost identical. According to these, an *ac* power frequency voltage is applied to a 2.5 mm gap between two identical electrodes, so called “calottes”, of dimensions shown in Figure 6.16 (a). The IS recommends the electrodes to be made of brass having a good surface finish, whereas VDE recommends copper as electrode material. These electrodes are placed in a container of a given size and filled with about 300 cc of the sample of oil as shown in Figure 6.16 (b). The measurement is conducted at room temperature (20°C) increasing the applied sinusoidal waveform alternating voltage at a rate of 2–3 kV/s till upto breakdown. The rms value of the breakdown voltage U_b is measured. The Schwaiger factor or the degree of uniformity, η for the given gap and electrode configuration is 0.97, that is, the field can be considered to be almost uniform.

For each sample of insulating liquid, at least 10 minutes after pouring the fluid in to the cell six measurements of breakdown voltages are recommended to be performed stirring the liquid thoroughly after every breakdown and a minimum wait of 2 minutes (VDE), 1–5 minutes (IEC) or 5 minutes (IS) in between the measurements. VDE and IS recommend mean of all the six values to be taken into account. If the mean rms breakdown voltage is U_b in kV, the peak value of electric strength of the liquid is given as follows,

$$\hat{E}_b = \frac{\sqrt{2}U_b}{\eta \cdot d} = \frac{\sqrt{2}U_b}{0.97 \times 0.25} \text{ kV/cm} \approx 5.8U_b \text{ kV/cm} \quad (6.30)$$

According to the method described above, the required values of electric strengths of various pure insulating liquids available commercially, are given in Table 6.1.

The standard test procedures are the quality control tests since the breakdown strengths thus measured are primarily determined by the contaminants in the sample.

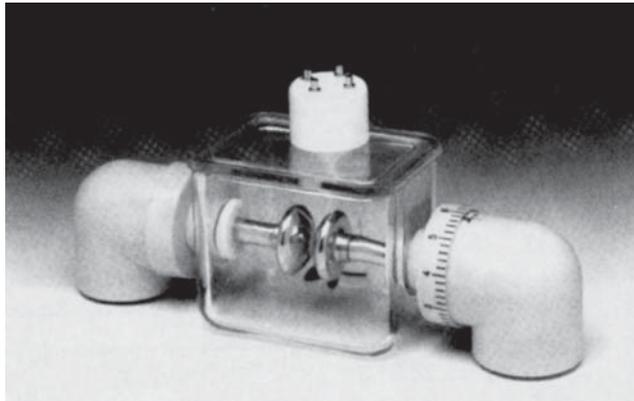
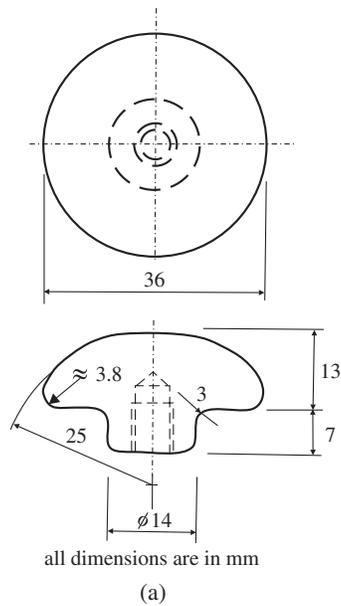


Figure 6.16 (a) Electrode design having $\eta = 0.97$ for the measurement of electric strength of commercial liquid dielectrics according to VDE-0370/IS-6792. (b) An oil test cell with PB free leads, Musil et al. [6.11].

The effects of various contaminants and the measuring conditions such as moisture, dissolved gases, types of particles, their size and quantity, temperature, sampling methods, pressure, and so on have been investigated extensively. However, Musil et al. [6.12] concluded that in spite of standard procedures, *ac* breakdown voltage of insulating liquids thus measured are valid for certain conditions of measurement. Considerable effect of the design of test apparatus and the test procedure has been found. The parameters, which influence the measurements, are:

- shape of the standardized electrodes
- electrical test circuit characteristics, e.g., trip current level setting, voltage measurement system, current limiting series resistance in the circuit etc.
- construction of the test cell, level of oil sample above the electrodes, formation of stray capacitances
- the method of circulation of liquid during the test
- liquid collection/sampling and storage practices

It is recommended to set a minimum trip current of 5 to 6 mA to avoid any false tripping. It is also desirable that the level of liquid filled in the test cell is at least 40 mm above the electrodes. A continuous, slow circulation of the liquid sample throughout the test is also desirable, Musil et al. [6.12].

Laboratory measurements may give different results for samples of the same oil collected and stored in glass and plastic bottles.

6.3.3.1 Effect of Moisture and Temperature on Breakdown Strength

Power frequency *ac* breakdown voltage/field intensity with increasing temperature measured by Holle [6.6] according to the standard method described above for transformer oil having different moisture contents are shown in Figure 6.17. These curves illustrate the effect of moisture content in oil on breakdown voltage. At very low moisture contents (less than 20 ppm) the breakdown strength is more or less independent of the temperature. For moisture contents above 20 and up to 100 ppm,

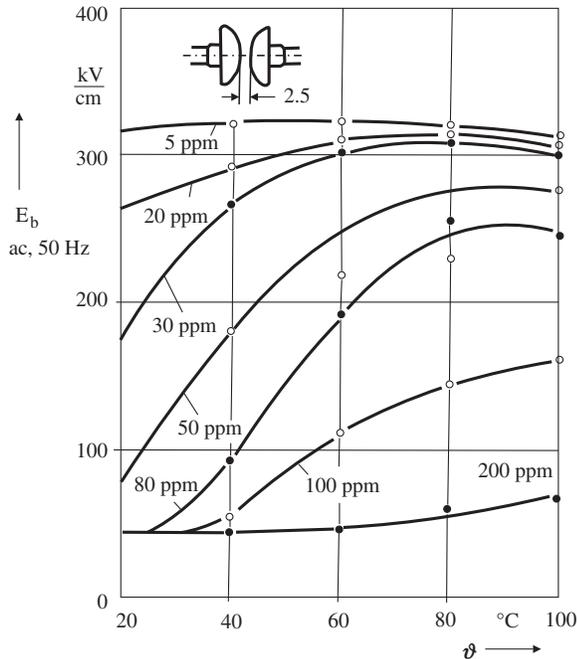


Figure 6.17 Power frequency ac breakdown field intensity (rms) with increasing temperature of a transformer oil having different water contents in ppm, Holle [6.6].

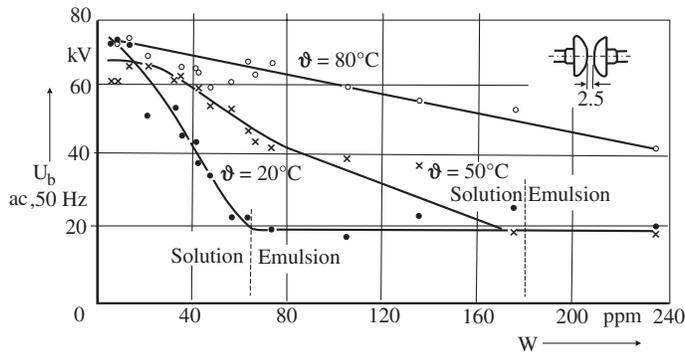


Figure 6.18 Power frequency ac breakdown voltage of a transformer oil at different constant temperature with increasing water content in ppm, Holle [6.6].

the breakdown strength is lowest at room temperature, but it increases considerably with increasing temperature. For 200 ppm again, the temperature does not appreciably affect the breakdown strength but it is quite low.

The breakdown strength is in fact strongly affected by the state of moisture in the insulating oils. As soon as the moisture content in oils acquires the emulsion state, that is tiny water droplets are unevenly distributed instead of a solution state of moisture in the oil, the lowest breakdown strengths are measured, irrespective of an increase in *ppm* water content. Holle [6.6] also measured this phenomenon, clearly illustrated in Figure 6.18, on another transformer oil sample at different constant temperatures for increasing water contents in *ppm*. When the moisture in the oil acquired emulsion state, a constant lowest breakdown voltage was measured.

In his dissertation, Haushild [6.13] made a comparison between breakdown strengths of transformer oil for different types of voltages in weakly nonuniform fields. These are illustrated in Figure 6.19, measured on a sphere-plane electrode configuration with increasing gap distance. The Schwaiger factor, or degree of uniformity of the field η , was estimated to have a value of 0.57 for the 100 mm diameter sphere and the longest gap distance of 50 mm.

Except for very small gap lengths (up to about 5 mm), the breakdown curves show linear characteristics. As in case of gaseous, in liquid dielectrics the highest mean potential gradient of the order of 360 kV/cm was also required for breakdown in the gap with *li*. The mean potential gradient in the gap for breakdown with *si* was measured lower (185 kV/cm) and it was lowest (50 kV/cm) with power frequency *ac* peak voltage.

Although in weakly nonuniform fields no stable PB takes place, still it is the propagation of an unstable streamer that leads to breakdown with an arc. In Figure 6.20 photographs taken by Fiebig [6.14] in 1968 show the breakdown in transformer oil between plane and spheres of different sizes. They represent different degrees of uniformity of the field. Because of fairly high mean field intensity at the instant of breakdown, a very dense bunch of streamer discharge is produced, as seen

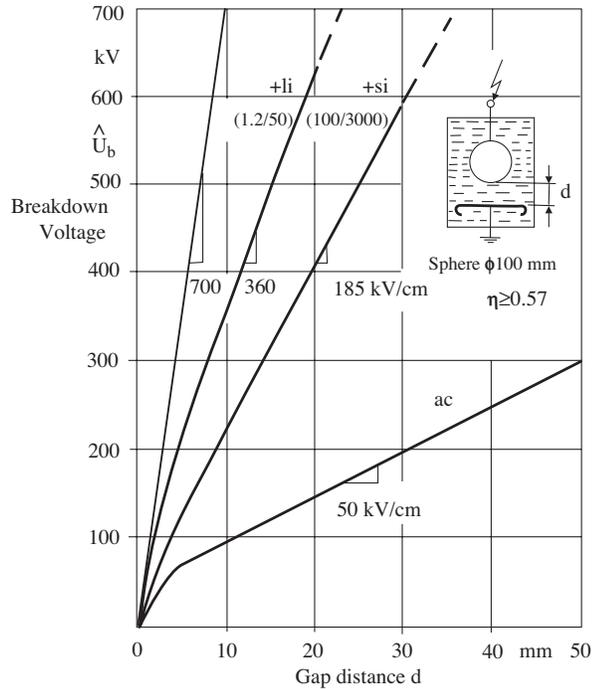


Figure 6.19 Power frequency ac, si and li breakdown voltages of transformer oil measured on sphere-plane weakly nonuniform electrode configuration with increasing gap distance, Hauschild [6.13].

in these photographs. On applying an *ac* power frequency voltage to the spheres, the breakdown always occurred at positive half cycle. Hence, a positive streamer is seen developing in all directions followed by a bright, luminous arc in the middle accomplishing the breakdown.

Figure 6.21 shows the two similar photographs taken by Torshin [6.15] in the year 2003. These Schlieren photographs, a special technique of photography, show the development of prebreakdown unstable streamer at the tip of the electrodes in weakly and extremely nonuniform fields without complete breakdown on applying positive polarity lightning impulse voltages in transformer oil. Similar work published by Top et al. [6.16] in 2002 concluded that the development and propagation of streamer in weakly and extremely nonuniform fields are different.

6.3.4 Breakdown in Extremely Nonuniform Fields and the Development of Streamer

As in gaseous dielectrics, in insulating liquids stable PB occurs in extremely nonuniform fields before the breakdown. The phenomenon of electrical breakdown in insulating liquids has been investigated extensively since the 1960s. The advent of very high speed electro-optical cameras has made it possible to study this process

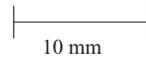
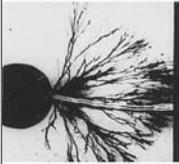
	η	D (mm)	d (mm)	\hat{U}_b kV/cm
	0.1	2	10	52
	0.2	5	10	73
	0.4	10	10	120
	0.7	20	5	224

Figure 6.20 Photographs of electrical breakdown of transformer oil in weakly and changing nonuniform fields with alternating voltage for increasing degree of uniformity, Fiebig [6.14].

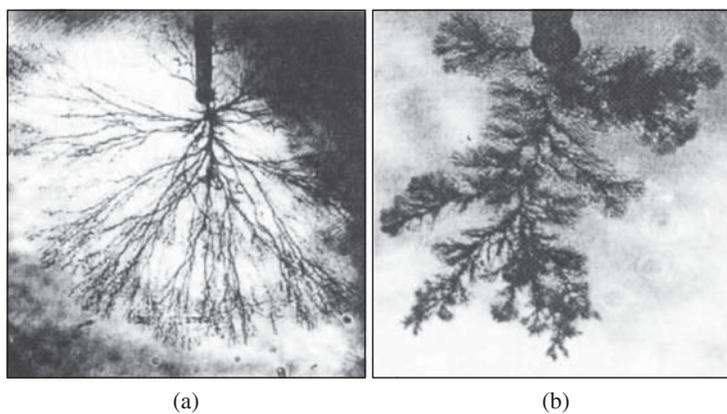


Figure 6.21 Photographs of development of typical tree and bush type streamers at the tip of the electrodes in weakly and extremely nonuniform fields taken by Schlieren photographic technique, Torshin [6.15].

in more detail. The mechanism of breakdown in insulating liquids is more or less similar to that in gases, but the causes and the sources of charge carriers are different.

Fiebig (1968) and Hauschild (1969) [6.13 and 6.14] performed two excellent studies on the breakdown phenomenon in extremely nonuniform fields at TU Dresden in their dissertations. Similar investigation results have been published in IEEE ever since by a number of authors all over the world [6.15 to 6.22]. With the development in measurement techniques a little more detailed information could be obtained by the later work. A considerable amount of information regarding the positive and negative streamer propagation in liquids is thus available. This has helped in a better understanding of the breakdown mechanism in liquid dielectrics.

The streamer discharge propagates in liquids in a manner analogous to the propagation of discharge in gases. However, in liquids, electron avalanches contribute to the local discharge bursts, providing a means for sufficient initial charge to facilitate the propagation of streamer. Such a discharge may be caused due to particle impurity or the abrupt failure of a negatively charged oxide layer on the anode surface. In the absence of such accidental occurrence, breakdown does not take place unless the field is sufficiently high to extract electrons directly from the liquid or the electrodes.

Both the negative and the positive streamers in liquid dielectrics have been recognized to appear at low-density regions within the fluid. Thermal electrons surround them as well as the fragments produced by electron impact ionization and local/partial discharges (PB) due to enhanced electric field. Consequently, the local field dominated by the space charge intensifies the process of the growth of streamer.

Optical investigations of pre-breakdown events in insulating liquids conducted by Watson and Chadband [6.17] showed that the initial stage of the breakdown of needle-plane gaps involved growth of a vapor cavity from the needle tip. This was followed by the propagation of streamer from the cavity due to electro-hydrodynamic (EHD) instability of the vapor-fluid interface.

A schematic explanation of the process of development of positive streamer as given by Fiebig [6.14] is shown in Figure 6.22. Due to high field intensity at the tip of the needle electrode, a positive space charge is developed that expands the vapor cavity in the form of a channel. This vapor channel is described as a low density region. According to Fiebig, the avalanche process within this vapor channel is due to the production of photons (photoelectrons) by local breakdown (PB) process giving rise to light emission and current pulses. The positive space charge developed due to dissociation leaves behind a bipolar space charge. The bipolar space charge results in a field equalization effect in the region between the tip of the electrode and the extent of vapour channel, as shown in Figure 6.22.

However, within the vapour channel, displacement of the positive and negative charge carriers takes place due to the interface effect. This causes an enhancement of field intensity at the tip giving rise to new avalanche processes. Although impractical, field intensities of the order 5–50 MV/cm have been estimated at the streamer tip by Felici [6.20]. Felici has also given a similar explanation for the development of negative streamer in liquids.

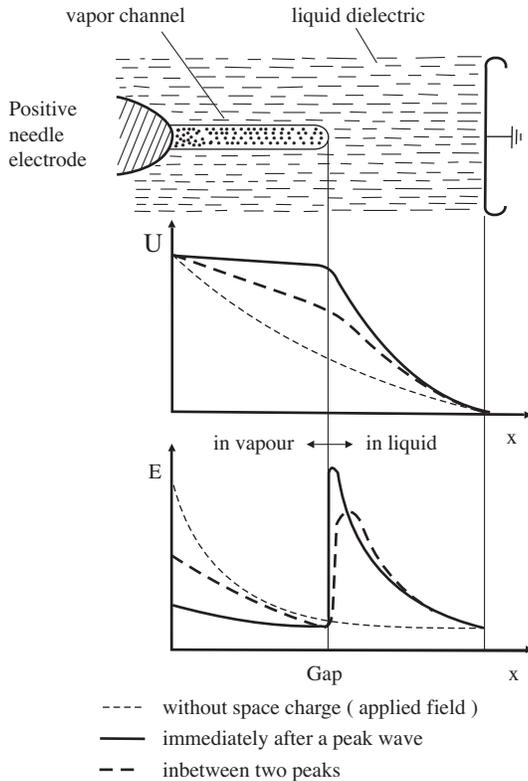


Figure 6.22 A schematic showing the development of positive streamer in liquid dielectrics, Fiebig [6.14].

Lewis [6.23] made investigations on breakdown initiating mechanisms at electrode interfaces in 2003 and also concluded that the cavity production in the fluids depends strongly upon the field intensity and the local surface/interface compositions. The cavities are likely to be filled with vapor at pressures at which impact ionization would readily take place.

The dynamics of the development of pre-breakdown cavities/channels have been widely studied using photographic techniques of pulsed Schlieren and shadowgraph, [6.17, 6.20]. The inception of prebreakdown current is associated with light emission, which precedes the first appearance of a streamer. Both bush and tree type streamer developments, along with light emission have been observed in various liquids. A tree type streamer development is generally observed for positive streamer but the negative streamer appears invariably to be a bush type. In Figure 6.23, photographs of positive and negative pre-breakdown streamers taken by Fiebig [6.14] in transformer oil at a needle electrode are shown. The typical tree and bush type appearances of streamer are easily distinguishable in these photographs. Similar results were measured by Top et al. [6.16].

In organic liquids Felici [6.20] also identified two distinct forms of streamers. A bush like slow propagating streamer at subsonic speed occurs mostly at the negative polarity electrodes. The other, observed typically at positive polarity electrodes, is filamentary, elongated and propagates faster at supersonic speeds. Since it has

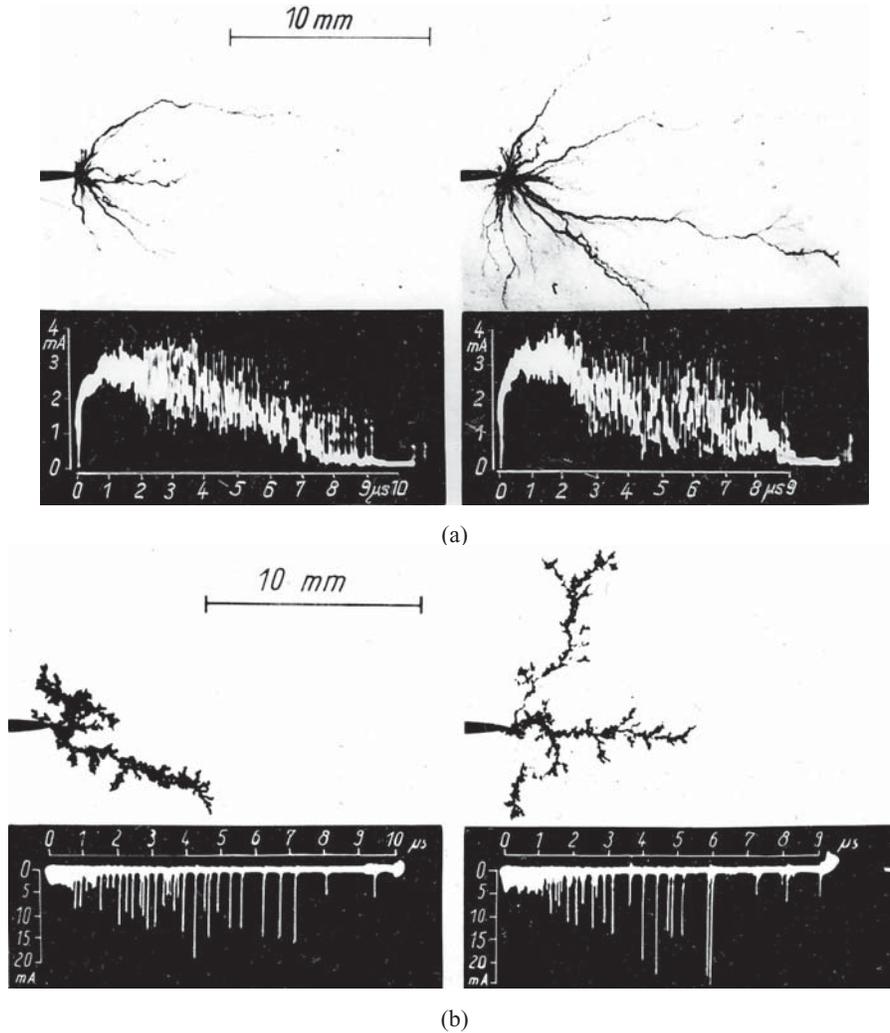


Figure 6.23 Development of streamer in transformer oil between needle-plane gaps, Fiebig [6.14]. (a) Tree type positive streamer in a gap length of 50 mm at 60kV ac (peak). (b) Bush type negative streamer in a gap length of 50 mm at 60kV ac (peak).

branches like a tree, it is described as tree type streamer by some authors. Felici further discovered that the fast and filamentary ones replace the slow negative streamers when an electron scavenger is added to the liquid. It has been concluded in general that streamers in liquid dielectrics travel slowly and at a very broad range of speed (0.05 to 20 mm/μs). Further, the light emitted by streamers has been correlated with the instantaneous current. Fiebig and Hauschild had also earlier discovered the above-mentioned properties of streamer development.

The ultimate breakdown is achieved when an unstable leader bridges the gap. Hauschild [6.13] investigated the breakdown mechanism in insulating oils in

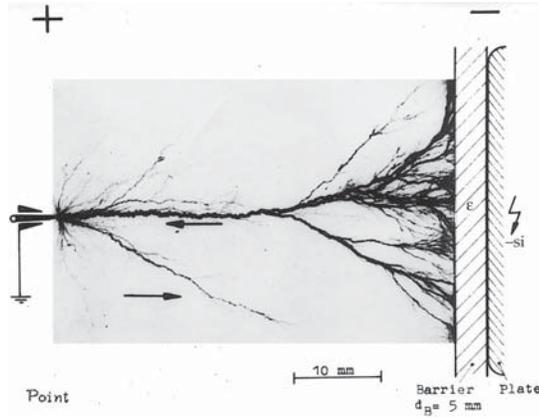


Figure 6.24 Discharge in transformer oil in extremely nonuniform field with an insulating barrier at the plane for si of negative polarity, showing stable leader developing in backward direction, Hauschild [6.13].

extremely nonuniform field between needle-plane gap of 50 mm applying switching impulse of 50/5000 μs . In order to prevent a complete breakdown with an arc between the electrodes, yet achieve a stable leader discharge through the gap, Hauschild covered the plane electrode with an “insulating barrier” having a thickness of 5 mm. The discharge extending up to the barrier in transformer oil is shown in Figure 6.24. This photograph was also taken by the Schlieren photographic technique suitable for taking photographs in liquids. The plane electrode was applied a negative polarity si while the needle electrode was earthed. From these investigations it could be concluded that the growth of the main leader is in the direction from negative plane (cathode) towards positive needle (anode), as shown by the arrow on the photograph. He proposed the name “backward leader” for this kind of discharge, as it develops in the opposite direction of the field intensity. This phenomenon is similar to the propagation of “negative leader” described in Section 3.3.3.2.

Experiments were performed to investigate the development of positive and negative streamers in bulk oil and also along pressboard surface in transformer oil on a 150 mm gap between 190 μm tip needle and plane electrodes by Lundgaard et al. [6.24]. Figure 6.25 shows schematic and actual tracks of positive streamer development on pressboard surface between needle and plane. It could be observed that the velocity of propagation of initial streamer development was faster (about twice) with pressboard than without the board. In this case the velocity of streamer propagation of the order of 800 mm/ μs was recorded. In the presence of pressboard, faster propagation could be attributed to the surface resistivity of the dielectric, which is always lower than the volume resistivity. As observed in gaseous dielectrics, in liquid dielectrics the stable PB streamer channels are also highly conductive. Potential gradient of the order of 2 kV/mm has been estimated along the positive streamer channels in transformer oils, Lundgaard [6.24]. It is approximately four times greater than the estimated potential gradient required for positive streamer in atmospheric air, Section 3.3.2.1. This is an expected phenomenon since the dielectric strength of oils is much higher.

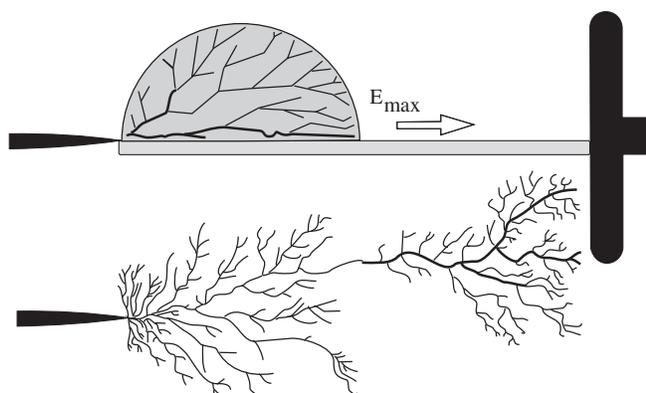


Figure 6.25 Development of positive streamer along a pressboard surface in oil. Upper: The positive streamer schematic, Lower: Actual track observed on the pressboard surface, Lundgaard [6.24].

A comparison between breakdown voltage characteristics of a sample of commercial transformer oil in extremely nonuniform field between needle and plane with *ac* power frequency, positive polarity *si* and *li* voltages is shown in Figure 6.26, also measured by Hauschild [6.13]. Up to a gap distance of about 100 mm, the *li* breakdown voltage is measured to be lower than *si*. However, above a gap distance of 100 mm the *li* breakdown voltage is much higher. A similar trend is seen in the breakdown characteristics with all the three types of voltages at a gap distance between 25 and 40 mm. As in case of gaseous dielectrics, in transformer oils too, it represents stable PB activity above a certain gap distance between given electrode systems. Compared to air, the PB inception voltages are much higher in oils.

6.4 AGING IN MINERAL INSULATING OILS

Aging of mineral oils is a continuous process in oil filled equipment. Ingress of moisture and oxygen from the atmosphere may take place in storage, handling and in service. In the presence of metallic parts in apparatus, for example, copper, lead, aluminium and others, the catalytic effects of metal ions accelerate the oxidation reactions in oils at high working temperatures. As a result, this gives rise to various oxidative products, such as peroxides, alcohols, ketones, esters and acids. These products may ultimately combine together to form higher molecular-weight compounds, both soluble and insoluble in oils. Insoluble oxidative products not only darken the oil color but in the advanced stage of oxidation lead to sludge formation. The degradation of physical as well as electrical properties of oils with time in electrical equipment is an unavoidable process.

Aging of oils leads to deterioration of their insulating properties. The electric strength of oils as well as their loss tangents and specific resistances are greatly affected by the presence of water content, contaminants and oil-soluble compounds. Resulting from oxidation, the oil soluble compounds are also known as polar

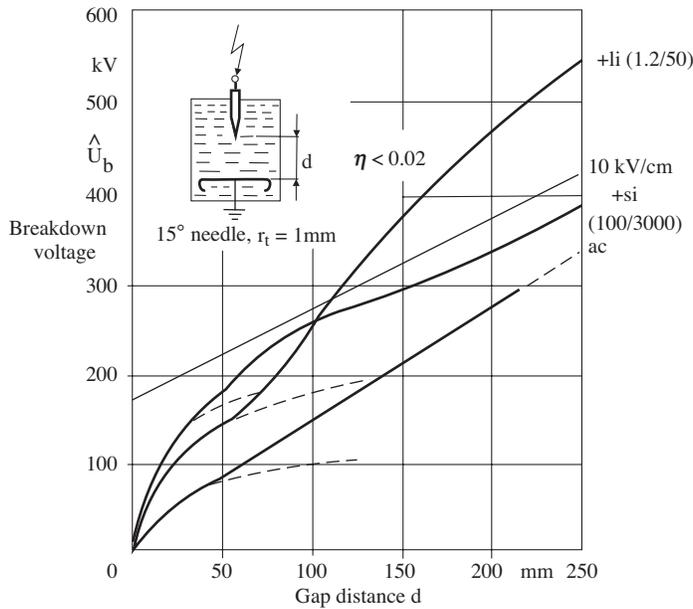


Figure 6.26 Power frequency ac, positive polarity si and li breakdown voltages of transformer oil in extremely nonuniform field between needle-plane with increasing gap distances, Hauschild [6.13].

substances [6.25]. It has been observed that the interfacial tension and viscosity of oils also change fairly rapidly during the early stages of aging. However, the rate of their change decreases with time. An interesting correlation is mentioned in [6.25] that the formation of sludge in the mineral insulating oils is possible if the interfacial tension value falls below 0.018 N/m. Deterioration in viscosity and interfacial tension of oil may also affect the cooling action in the equipment.

Fournie et al. [6.26] studied the aging process on fresh mineral insulating oils, subjecting them to photochemical, electrical and thermal stresses. During their investigations they found the evidence of increase in corrosive sulphur-index of the mineral oils when subjected to sunlight. The action of light on insulating oils caused the formation of abundant sludge, containing sulphur compounds. Infrared spectra of the sludge revealed that these were various stages of sulphur oxidations. These photo-oxidized oils showed a very poor electric strength property.

Studies made by Fournie et al. further revealed that in darkness and at room temperature, application of an electric field on fresh oils caused smaller quantity of sludge formation. However, the combined action of light and the electric field led to the formation of sludge that settled down on the conducting parts and the solid dielectrics.

The thermal aging alone does not result in oxidation of sulphur compounds, although sometimes it leads to abundant sludge formation. The degradation of electrical properties of oils is found to be much slower by thermal aging than under

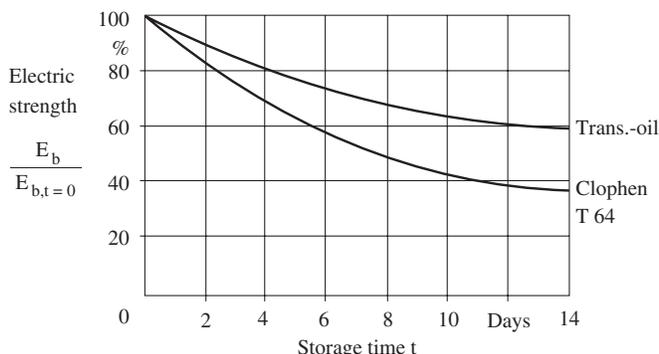


Figure 6.27 Degradation of electric strength of liquid dielectrics due to aging.

ultraviolet radiation. In worst cases, there are evidences of the presence of solid sludge in transformers and circuit breakers with sulphur contents of the order of 4 to 6%.

Degradation in electric strength of transformer oil and Clophen T-64, with respect to the storage time in air at 20°C and 63% relative humidity, are shown in Figure 6.27. Just in two weeks, the electric strength almost reduced to half when the oil was exposed to the atmosphere.

Investigation of radiation-induced chemical degradation phenomena in mineral and synthetic electrical insulating oils by Yasufuku [6.27] revealed that γ -irradiation accelerates the corrosive action of the oils in the presence of copper strips. The sulphur compounds in oil change rapidly to corrosive sulphur under irradiation and accelerate corrosion on the copper surface. Similar investigations by Krishnamoorthy et al. [6.28] revealed that the copper/oil ratio is the most significant factor in accelerating the thermo-aging process. Whereas copper has negligible effect on the rate of oxidation at 70°C, it increases with the increase in copper/oil ratio above 85°C.

The general principles and maintenance rules that can be applied for handling, reconditioning and replacement of insulating oils are found in various standards for a given type of equipment. The physical means used for removing solid particles and insoluble contaminants in suspension from the oils and to decrease their water contents to acceptable level include several types of filters, centrifuges and vacuum dehydrators. However, these cannot be effectively removed when the foreign substances are in dissolved or in colloidal form. The treatment devices do not remove air; on the contrary, they tend to aerate the oil. The water removing ability of a filter is dependent upon the dryness of the filter media. A centrifuge can handle much greater concentration of contamination than a conventional filter but cannot remove some of the contaminants as effectively as a filter. Consequently, a centrifuge is generally used for rough and bulk cleaning where a large amount of contaminated oil is to be handled. The output of the centrifuge is put through a filter for the final clean up. Apart from removing water, the vacuum dehydrators de-gas the oil and remove more volatile acids. For more details, the reader may refer to IS-1866 (2000) [6.25].

It is suggested in various specifications and also recommended by the manufacturers that the quality of oils in use should be periodically checked. The frequency of such examination of oils in service depends upon the power rating, loading, construction and other service conditions of the equipment.

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