

## LIQUIDS AS INSULATORS

Liquid dielectrics, because of their inherent properties, appear as though they would be more useful as insulating materials than either solids or gases. This is because both liquids and solids are usually  $10^3$  times denser than gases and hence, from Paschen's law it should follow that they possess much higher dielectric strength of the order of  $10^7$  V/cm. Also, liquids, like gases, fill the complete volume to be insulated and simultaneously will dissipate heat by convection. Oil is about 10 times more efficient than air or nitrogen in its heat transfer capability when used in transformers. Although liquids are expected to give very high dielectric strength of the order of 10 MV/cm, in actual practice the strengths obtained are only of the order of 100 kV/cm. Liquid dielectrics are used mainly as impregnants in high voltage cables and capacitors, and for filling up of transformers, circuit breakers etc. Liquid dielectrics also act as heat transfer agents in transformers and as arc quenching media in circuit breakers. Petroleum oils (Transformer oil) are the most commonly used liquid dielectrics.

Synthetic hydrocarbons and halogenated hydrocarbons are also used for certain applications. For very high temperature application, silicone oils and fluorinated hydrocarbons are also employed. In recent times, certain vegetable oils and esters are also being tried. However, it may be mentioned that some of the isomers of poly-chlorinated diphenyls (generally called askerels) have been found to be very toxic and poisonous, and hence, their use has been almost stopped. In recent years, a synthetic ester fluid with the trade name 'Midel' has been developed as a replacement for askerels. Liquid dielectrics normally are mixtures of hydrocarbons and are weakly polarised. When used for electrical insulation purposes they should be free from moisture, products of oxidation and other contaminants. The most important factor that affects the electrical strength of insulating oil is the presence of water in the form of fine droplets suspended in the oil. The presence of even 0.01% water in transformer oil reduces its electrical strength to 20% of the dry oil value. The dielectric strength of oil reduces more sharply, if it contains fibrous impurities in addition to water.

### Transformer Oil

As already mentioned, transformer oil is the most commonly used liquid dielectric in power apparatus. It is an almost colour less liquid consisting a mixture of hydrocarbons which include paraffins, iso-paraffins, naphthalenes and aromatics. When in service, the liquid in a transformer is subjected to prolonged heating at high temperatures of about 950C, and consequently it undergoes a gradual ageing process. With time the oil becomes darker due to the formation of acids and resins, or sludge in the liquid. Some of the acids are corrosive to the solid insulating materials and metal parts in the transformer. Deposits of sludge on the transformer core, on the coils and inside the oil ducts reduce circulation of oil and thus its heat transfer capability gets considerably reduced. Complete specifications for the testing of transformer oils are given in IS 1866 (1983), IEC 296 (1969) and IEC 474 (1974).

### Electrical Properties

The electrical properties that are essential in determining the dielectric performance of a liquid dielectric are

- (a) its capacitance per unit volume or its relative permittivity
- (b) its resistivity
- (c) its loss tangent ( $\tan \delta$ ) or its power factor which is an indication of the power loss under a.c. voltage application
- (d) its ability to withstand high electric stresses.

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

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

**Power Factor** of a liquid dielectric under a.c. voltage will determine its performance under load conditions. Power factor is a measure of the power loss and is an important parameter in cable and capacitor systems. However, in the case of transformers, the dielectric loss in the oil is negligible when compared to copper and iron losses. Pure and dry transformer oil will have a very low power factor varying between  $10^{-4}$  at  $20^{\circ}\text{C}$  and  $10^{-3}$  at  $90^{\circ}\text{C}$  at a frequency of 50 Hz.

**Dielectric Strength** is the most important parameter in the choice of a given liquid dielectric for a given application. The dielectric strength depends on the atomic and molecular properties of the liquid itself. However, under practical conditions the dielectric strength depends on the material of the electrodes, temperature, type of applied voltage, gas content in the liquid etc., which change the dielectric strength by changing the molecular properties of the liquid. The above factors which control the breakdown strength and lead to electrical breakdown of the liquid dielectrics are discussed in subsequent sections.

## PURE LIQUIDS AND COMMERCIAL LIQUIDS

Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in  $10^9$ , and are structurally simple. Examples of such simple pure liquids are n-hexane ( $\text{C}_6\text{H}_{14}$ ), n-heptane ( $\text{C}_7\text{H}_{16}$ ) and other paraffin hydrocarbons. By using simple and pure liquids, it is easier to separate out the various factors that influence conduction and breakdown in them. On the other hand, the commercial liquids which are insulating liquids like oils which are not chemically pure, normally consist of mixtures of complex organic molecules which cannot be easily specified or reproduced in a series of experiments.

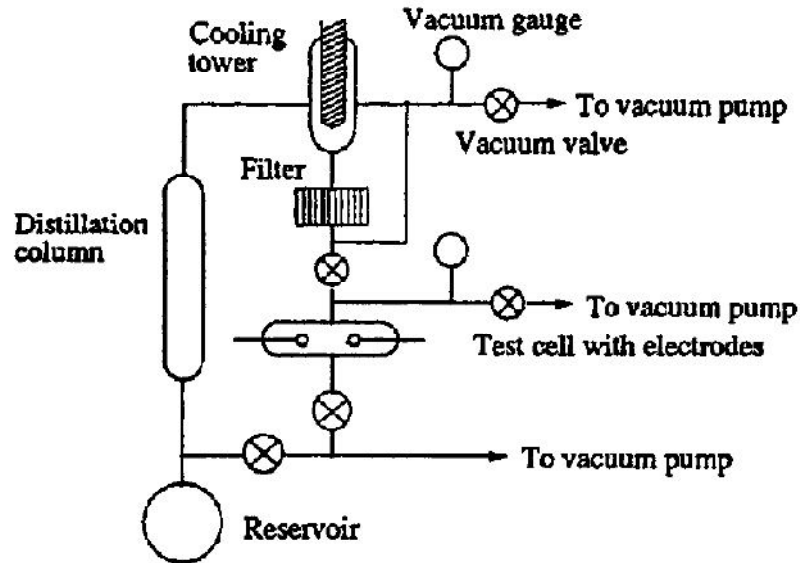
## Purification

The main impurities in liquid dielectrics are dust, moisture, dissolved gases and ionic impurities. Various methods employed for purification are filtration (through mechanical filters, spray filters, and electrostatic filters), centrifuging, degassing and distillation, and chemical treatment (adding ion exchange materials such as alumina, fuller's earth, etc. and filtering). Dust particles when present become charged and reduce the breakdown strength of the liquid dielectrics, and they can be removed by careful filtration. Liquid will normally contain moisture and dissolved gases in small quantities. Gases like oxygen and carbon dioxide significantly affect the breakdown strength of the liquids, and hence it is necessary to control the amount of gas present. This is done by distillation and degassing. Ionic impurity in liquids, like water vapour which easily dissociates, leads to very high conductivity and heating of the liquid depending on the applied electric field. Water is removed using drying agents or by vacuum drying. Sometimes, liquids are shaken with concentrated sulphuric acid to remove wax and residue and washed with caustic soda and distilled water. A commonly used closed-cycle liquid purification system to prepare liquids as per the above requirements is shown in below diagram. This system provides for cycling the liquid. The liquid from the reservoir flows through the distillation column where ionic impurities are removed. Water is removed by drying agents or frozen out in the low-temperature bath. The gases dissolved in the liquid are removed by passing them through the cooling tower and/or pumped out by the vacuum pumps. The liquid then passes through the filter where dust particles are removed. The liquid thus purified is then used in the test cell. The used liquid then flows back into the reservoir. The vacuum system thus helps to remove the moisture and other gaseous impurities.

## Breakdown Tests

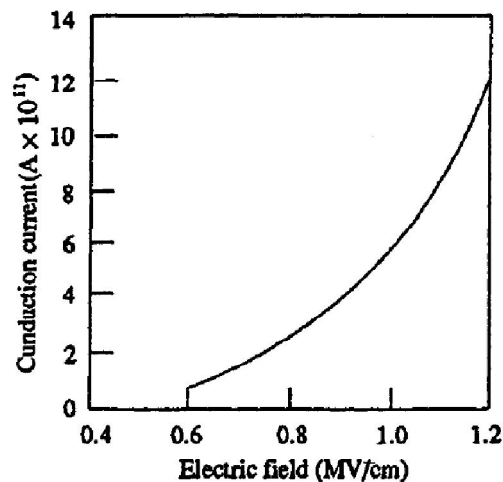
Breakdown tests are normally conducted using test cells. For testing pure liquids, the test cells used are small so that less quantity of liquid is used during testing. Also, test cells are usually an integral part of the purification system as shown in Diagram. The electrodes used for breakdown voltage measurements are usually spheres of 0.5 to 1 cm in diameter with gap spacings of about 100-200nm. The

gap is accurately controlled by using a micrometer. Sometimes parallel plane uniform-field electrode systems are also used. Electrode separation is very critical in measurements with liquids, and also the electrode surface smoothness and the presence of oxide films have a marked influence on the breakdown strength. The test voltages required for these tests are usually low, of the order of 50-100 kV, because of small electrode spacings. The breakdown strengths and d.c. conductivities obtained in pure liquids are very high, of the order of 1 MV/cm and  $10^{-18} - 10^{-20}$  mho/cm respectively, the conductivity being measured at electric fields of the order of 1 kV/cm.



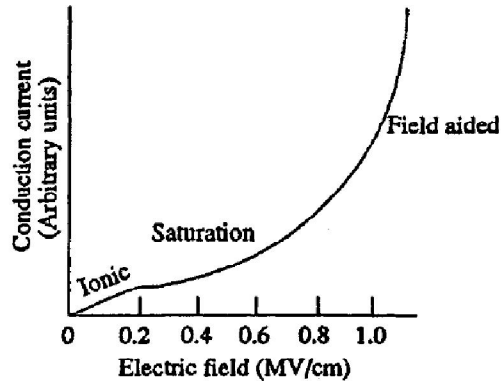
### CONDUCTION AND BREAKDOWN IN PURE LIQUIDS

When low electric fields less than 1 kV/cm are applied, conductivities of  $10^{-18} - 10^{-20}$  mho/cm are obtained. These are probably due to the impurities remaining after purification. However, when the fields are high ( $> 100$  kV/cm) the currents not only increase rapidly, but also undergo violent fluctuations which will die down after some time. A typical mean value of the conduction current in hexane is shown in Diagram.



This is the condition nearer to breakdown. However, if this figure is redrawn starting from very small currents, a current-electric field characteristics shown in diagram, can be obtained. This curve will have three distinct regions as shown. At very low fields the current is due to the dissociation of ions. With

intermediate fields the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from the cathode gets multiplied in the liquid medium by a Townsend type of mechanism. The current multiplication also occurs from the electrons generated at the liquid and impurities. The increase in current by these processes continues till breakdown occurs.



The exact mechanism of current growth is not known; however, it appears that the electrons are generated from the cathode by field emission of electrons. The electrons so liberated get multiplied by a process similar to Townsend's primary and secondary ionization in gases. As the breakdown field is approached, the current increases rapidly due to a process similar to the primary ionization process and also the positive ions reaching the cathode generate secondary electrons, leading to breakdown. The breakdown voltage depends on the field, gap separation, cathode work-function, and the temperature of the cathode. In addition, the liquid viscosity, the liquid temperature, the density, and the molecular structure of the liquid also influence the breakdown strength of the liquid.

### CONDUCTION AND BREAKDOWN IN COMMERCIAL LIQUIDS

As already mentioned, commercial insulating liquids are not chemically pure and have impurities like gas bubbles, suspended particles, etc. These impurities reduce the breakdown strength of these liquids considerably. The breakdown mechanisms are also considerably influenced by the presence of these impurities. In addition, when breakdown occurs in these liquids, additional gases and gas bubbles are evolved and solid decomposition products are formed. The electrode surfaces become rough, and at times explosive sounds are heard due to the generation of impulsive pressure through the liquid. The breakdown mechanism in commercial liquids is dependent, as seen above, on several factors, such as, the nature and condition of the electrodes, the physical properties of the liquid, and the impurities and gases present in the liquid. Several theories have been proposed to explain the breakdown in liquids, and they are classified as follows:

- (a) Suspended Particle Mechanism
- (b) Cavitation and Bubble Mechanism
- (c) Stressed Oil Volume Mechanism

These are explained briefly below.

#### Suspended Particle Theory

In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres or as dispersed solid particles. The permittivity of these particles ( $\epsilon_2$ ) will be different from the permittivity of the liquid ( $\epsilon_1$ ). If we consider these impurities to be spherical particles of radius  $r$ , and if the applied field is  $E$  then the particles experience a force  $F$ , where

$$F = \frac{1}{2r^3} \frac{(\epsilon_2 - \epsilon_1)}{2\epsilon_1 + \epsilon_2} \text{grad } E^2$$

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

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

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

### Cavitation and the Bubble Theory

It was experimentally observed that in many liquids, the breakdown strength depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of vapour bubble formed is responsible for breakdown. The following processes have been suggested to be responsible for the formation of the vapour bubbles:

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

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

$$E_0 = \frac{1}{(\epsilon_1 - \epsilon_2)} \left[ \frac{2\pi\sigma(2\epsilon_1 + \epsilon_2)}{r} \left\{ \frac{\pi}{4} \sqrt{\left( \frac{V_b}{2rE_0} \right) - 1} \right\} \right]^{\frac{1}{2}}$$

where  $\sigma$  is the surface tension of the liquid,  $\epsilon_1$  is the permittivity of the liquid,  $\epsilon_2$  is the permittivity of the gas bubble,  $r$  is the initial radius of the bubble assumed as a sphere and  $V_b$  is the voltage drop in the bubble (corresponding to minimum on the Paschen's curve). From this equation, it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid. This theory does not take into account the production of the initial bubble and hence the results given by this theory do not agree well with the experimental results. This is shown in the below diagram.

### Thermal Mechanism of Breakdown

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

### Stressed Oil Volume Theory

In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the "largest possible impurity" or "weak link". On a statistical basis it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region. In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress ( $E_{\text{max}}$ ) contour and  $0.9 E_{\text{max}}$  contour. According to this theory the breakdown strength is inversely proportional to the stressed oil volume.

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

