Conduction and Breakdown in Commercial Liquids

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

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

(a) Electronic breakdown

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

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

**b) Suspended Particle Theory**

Solid impurities may be present in the liquid either as fibres or as dispersed solid particles and their presence of solid impurities cannot be avoided. The permittivity of these particles \( \varepsilon_1 \) will be different from the permittivity of the liquid \( \varepsilon_2 \). If we consider these impurities to be spherical particles of radius \( r \), and if the applied field is \( E \), then the particles experience of force \( F \), where

\[
F = r^3 \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} E \frac{dE}{dX} \tag{1}
\]

This force is directed towards areas of maximum stress, if \( \varepsilon_2 > \varepsilon_1 \), 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. \( \varepsilon_2 < \varepsilon_1 \), the force will be in the direction of areas of lower stress (opposite direction). If the voltage is continuously applied (d.c) or the duration of the voltage is long (a.c), then this force drives the particles towards the area of maximum stress. If the number of particles is large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes. The force given by eqn (1) increases as the permittivity of the suspended particle (\( \varepsilon \)) increases, and for a conducting particle for which \( \varepsilon_1 \rightarrow \infty \) the force becomes

\[
F = F_\infty = r^3 E \text{ grad } E
\]

Thus the force will urge the particle to move to the strongest region of the field. In a uniform field gap or sphere gap of small spacing the strongest field is in the uniform region. In this region \( \text{grad } E \) is equal to zero so that the particle will remain in equilibrium there. Accordingly, particles will be dragged into the uniform field region. If the permittivity of the particle is higher than that of the medium, then its presence in the uniform field region will cause flux concentration at its surface. Other particles will be attracted into the region of higher flux concentration and in time will become aligned head to tail to form a bridge across the gap. The field in the liquid between the particles will be enhanced, and if it reaches critical value breakdown will follow. The movement of particles by electrical force is
opposed by viscous drag, and since the particles are moving into the region of high stress, diffusion must also be taken into account. If there is only a single conducting particle between the electrodes, it will give rise to local field enhancement depending on its shape. If this field exceeds the breakdown strength of the liquid, local breakdown will occur near the particle, and this will result in the formation of gas bubbles which may lead to the breakdown of the liquid. The value of the breakdown strength of the liquids containing solid impurities was found to be much less than the values for pure liquids. The impurity particles reduce the breakdown strength, and it was also observed that the larger the size of the particles the lower were the breakdown strengths.

(c) Cavitation and the Bubble Theory

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

a) Gas pockets at the surface of the electrodes;

b) electrostatic repulsive forces between space charges which may be sufficient to overcome the surface tension;

c) gaseous products due to the dissociation of liquid molecules by electron collisions; and

d) Vaporization of the liquid by corona type discharges from sharp points and irregularities on the electrode surfaces.

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

The electric field in a spherical gas bubble which is immersed in a liquid of permittivity $\varepsilon_2$ is given by $E_b = \frac{3E_0}{(\varepsilon_2+2)}$; where $E_0$ is the field in the liquid in the absence of the bubble. When the field $E_b$ becomes equal to the gaseous ionization field, discharge takes place which will lead to decomposition of the liquid and breakdown may follow. Kao has developed more accurate expression for the breakdown field as
\[ E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)} \left[ \frac{2\pi \sigma (2 \varepsilon_1 \varepsilon_2)}{r} \sqrt{\frac{V_h}{(2rE_0)}} - 1 \right]^{\frac{1}{2}} \]

where \( \sigma \) is the surface tension of the liquid, \( \varepsilon_1 \) is the permittivity of the liquid, \( \varepsilon_2 \) is the permittivity of the gas bubble, \( r \) is the initial radius of the bubble assumed as a sphere and \( V_h \) is the voltage drop in the bubble (corresponding to minimum on the Paschen’s curve).

From this equation it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid. But this theory does not take into account the production of the initial bubble and hence the results given by this theory do not agree well with the experimental results. In general, the cavitation and bubble theories try to explain the highest breakdown strengths obtainable, considering the cavities or bubbles formed in the liquid dielectrics.

**d) Stressed Oil Volume Theory**

In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the “largest possible impurity” or “weak link”. On a statistical basis it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region. In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress \( E_{max} \) contour and 0.9 \( E_{max} \) contour. According to this theory the breakdown strength is inversely proportional to the stressed oil volume. The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage. The variation of the breakdown voltage stress with the stressed oil volume is shown in Fig.
CONCLUSIONS

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

\[ V_b = A d^n \]

where, \( A \) = constant, and \( n \) = constant, always less than 1.

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