Lecture # 3

Liquid Dielectrics

Liquid dielectrics are widely used in high-voltage equipment such as; cables, capacitors, transformers and circuit breakers. In addition to their function as an insulator, liquid dielectrics have additional function as heat transfer agent in transformers and as arc quenching media in circuit breakers. For transformer, the liquid dielectric is used both for providing insulation between the live elements and the grounded parts besides carrying out the heat from the transformer to the atmosphere thus functioning as coolant. The essential properties of liquid dielectric for most applications are:

1. High dielectric strength
2. Appropriate viscosity
3. Non-flammable
4. Good cooling properties
5. High boiling point
6. Very low freezing point
7. Non-toxic
8. Environmentally friendly and bio-degradable.
9. Non-corrosive

In the past, oils based on polychlorinated biphenyls (PCB) were used, being fire resistant liquids, but PCB's have been found to be very toxic and non-biodegradable. Most of the liquid dielectrics presently used in electrical applications are hydro-carbons, derived from natural mineral or crude oils. Mineral or crude oils based on naphthenic and paraffinic categories are most commonly used as liquid dielectrics in transformers and capacitors. In paraffin carbon atoms that are bonded to each other and arranged in straight or branched chains whereas in naphthenic oil carbon atoms have ring arrangement of five, six, or seven. Naphthenic oils are preferred due to the followings:

1. Paraffinic oils have a tendency to form waxes at low temperature as compared to naphthenic oils.
2. Paraffinic oils have lower thermal stability compared to naphthenic oils.
3. Paraffinic oils have higher viscosity at low temperature compared to that of naphthenic oils.

The refining and processing of crude oil for the production of dielectric fluids is necessary to reduce the poly-aromatic contents in order to enhance the dielectric properties, thermal and chemical stability.

The dielectric strength of liquid dielectric gradually weakens during service due to oxidation, moisture penetration, corona and spark-type discharges at the site of stress concentration. The presence of even 0.01% water in transformer oil reduces the dielectric strength by 20% of the dry oil value. Regular checks on the dielectric strength are therefore necessary as routine maintenance procedures for liquid dielectrics such as transformer oil during service. The routine maintenance usually includes:

1. Measurement of dielectric strength.
2. Filtering to get rid of impurities.
3. Heating to appropriate temperature to reduce/eliminate moisture content.
4. Dissolve Gas Analysis (DGA) for finding mainly the oxygen and CO_2 content.
5. De-gassing to remove oxygen and CO_2 and other un-wanted gases.

The breakdown strength must be routinely checked in the laboratory to ensure reliability of service. Table (1) lists some of the important properties of some dielectrics commonly used in electrical equipments.

Table 1: Some Properties of Commonly used Insulating Oils

S. No	Property	Transformer Oil	Capacitor Oil	Cable Oil	Silicone Oil
1	Dielectric constant at 50Hz	2.2 – 2.3	2.1	2.3 – 2.6	2.7 – 3.0
2	Breakdown strength at 20°C (2.5mm uniform field gap)	15kV/mm	20kV/mm	30kV/mm	35kV/mm
3	Tan δ at 50Hz	10^{-3}	2.5×10^{-3}	2×10^{-3}	10^{-3}
4	Resistivity (Ω-cm)	$10^{12} – 10^{13}$	$10^{13} – 10^{14}$	$10^{12} – 10^{13}$	2.5×10^{14}
5	Specific gravity at 20°C	0.89	0.89	0.93	1.0 – 1.1
6	Maximum permissible moisture content (ppm)	50	50	50	< 40

Example 1: A sample of pure liquid dielectric has a dielectric strength of 0.45MV/cm as measured under standard laboratory conditions (STP with standard uniform field electrodes) is contaminated with 0.03% moisture by volume during service. Find the reduction in its dielectric strength and the dielectric strength.

Solution:

Given that: E = 0.45MV/cm under standard laboratory conditions. A reduction of 20% in dielectric strength is due to 0.01% moisture that will reduce the dielectric strength by 0.09MV/cm. Therefore presence of 0.03% moisture will result in dielectric strength reduction of 0.09 x (0.03/0.01) = **0.27MV/cm**. The dielectric strength will reduce to: E = $(0.45 - 0.27) =$ **0.18MV/cm or 180kV/cm.** Thus it can be noted the dielectric strength reduces by 2.5 times in the presence of 0.03% moisture.

Testing of Liquid Dielectric

All liquid dielectrics for electrical apparatus must be tested for breakdown prior to their use and must also be routinely checked for any change in its breakdown strength during service. A portable dielectric test set is usually used by power companies for the purpose that is handy and can be conveniently transported. A typical liquid dielectric test set is shown in Fig (2). The range of voltages for most of the portable test sets available are in the range of 30–35kV. Breakdown tests on a sample of liquid dielectric are normally conduced in a test cell that can be connected across the terminals of the test set.

Figure (2) Portable Test Set

A photograph of a typical test cell is shown in Fig (3).

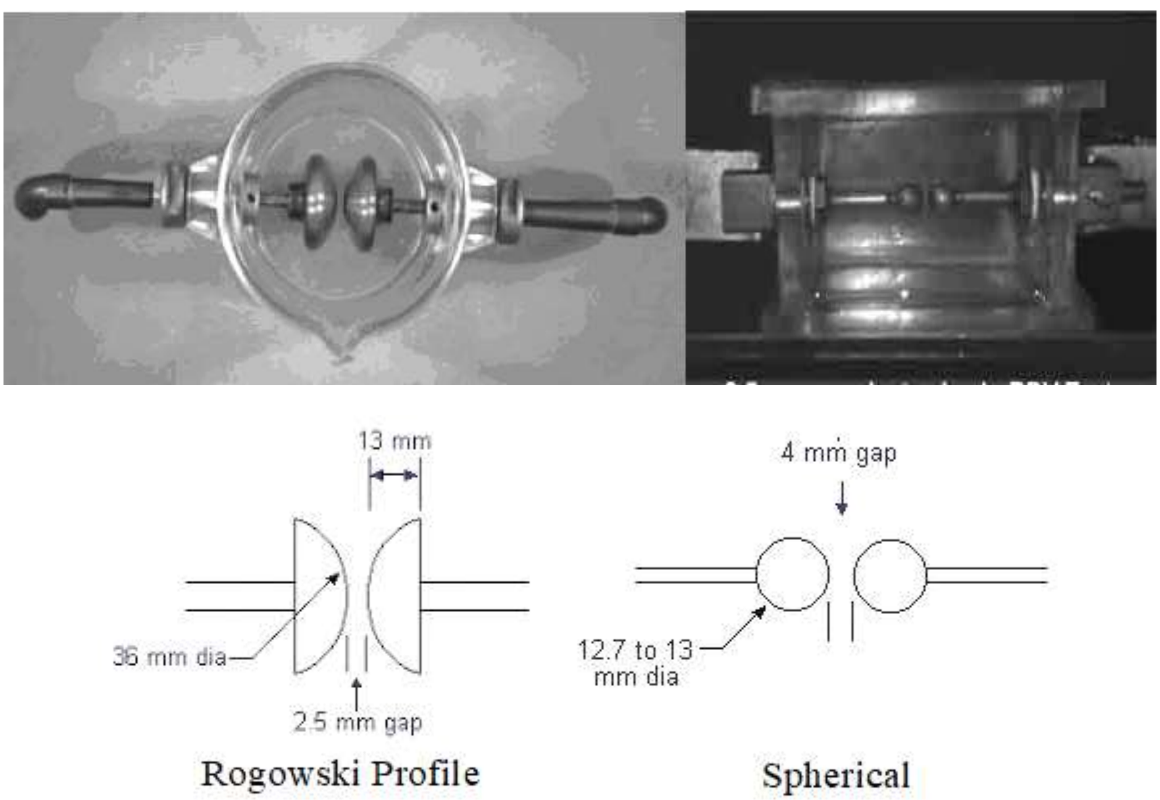

Figure (3): Test Cells

The test cell a simple crucible made of an insulating material implanted in which are two identical electrodes. The electrodes carry external connections, thus allowing the electrodes to be connected to the high voltage test source. AC power frequency voltage is applied to a 2.5 mm gap between two identical electrodes. 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 breakdown.

The dielectric strength E_b is calculated on the basis of uniform field configuration with gap separation between electrodes d (cm) by incorporating the Schwaiger factor (measure of field uniformity) generally about 0.97. Thus:

$$E_b = \frac{V_b}{0.97d} \qquad (1)$$

The test voltages required for these tests are usually of the order of 50-100 kV, because of small electrode spacing.

Example 2: A sample of used transformer oil tested between two standard electrodes separated by 2.5mm breaks down at 27.5 kV (50Hz, AC). Find the percentage reduction in its dielectric strength.

Solution:

Given that: V_b = 27.5kV. Using Eq (1)

$$E_b = \frac{V_b}{0.97d} = \frac{27.5}{0.97 \times 2.5} = 11.34\text{kV/mm}$$

From Table (1), the breakdown strength of transformer oil is 15 kV/mm, so that the reduction in its breakdown strength is: 15 – 11.34 = 3.66 kV/mm. Thus the percentage reduction is:

$$\frac{3.66}{15} \times 100 = \mathbf{24.4\%}$$

Breakdown Mechanism in Liquid Dielectrics

Liquid dielectrics are generally classified as pure and commercial. Pure liquids are those that do not contain any other impurity even in traces of 1 in 10^9. Pure liquid dielectrics generally have relatively high dielectric breakdown strength around 1MV/cm. Table (2) lists some of the pure liquids with their dielectric strength.

Table 2: Dielectric Strength of Some Liquids

Liquid Dielectric Type	Maximum breakdown strength (MV/cm)	Liquid Dielectric Type	Maximum breakdown strength (MV/cm)
Hexane	1.1 – 1.3	Liquid Nitrogen	1.6 – 1.9
Benzene	1.1	Liquid Hydrogen	1.0
Silicone	1.0 – 1.2	Liquid Helium	0.7
Liquid Oxygen	2.4	Liquid Argon	1.1 – 1.42

However, due to their inferior properties other than dielectric strength they are seldom used in electrical equipment. On the other hand commercial liquids often contain impurities, such as anti-oxidants and other additives introduced to improve certain properties. Commercial insulating liquids also contain impurities such as gas bubbles, suspended particles (in the form of fibrous and conducting impurities). These impurities are responsible for breakdown of these liquids. The breakdown mechanism in commercial liquids is dependent on several factors, such as the nature and condition of the electrodes, the physical and chemical properties of the liquid, the amount and type of impurities, and dissolved gases present within liquid.

Electronic Mechanism

In case of pure liquids under controlled laboratory conditions and with uniform field, electronic mechanism of breakdown is dominant. The breakdown characteristic follows a trend of gap current similar to that in the case of gases. The electronic mechanism is thus similar to that stated by Townsend for the conduction and breakdown in gases. Electrons injected by field emission from cathode under high electric field contribute significantly to gap current. The breakdown voltage therefore depends on the field, gap separation, cathode work function, and the cathode temperature. 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.

When electrons are injected into liquid dielectric it gains energy from the applied electric field set up by voltage application. It is assumed that electrons are accelerated by the applied electric field until they gain sufficient energy to ionize atoms and molecules on colliding and thereby will result in avalanches. If λ is the mean free path traversed by an electron in electric field E, then the energy gained ξ_g by an electron of charge q is given by:

$$\xi_g = qE\lambda \qquad 2$$

The energy lost ξ_L during collision with atoms or molecules of liquid is given by equivalent quanta of energy as:

$$\xi_L = ch\upsilon \qquad 3$$

Where: c is arbitrary constant that depends on the laboratory conditions. When the applied voltage is low the electrons moves slowly constituting a very small current. The probability of ionization by collision is less or virtually not possible since the energy gained by electrons from the applied field is less and the already presence of electrons contribute nearly all the component of the small current. When the applied voltage is increased, the electrons gain sufficient energies to dissociate the liquid molecules forming ions and atoms. As the field approaches the breakdown field, the process of electron multiplication through collision-ionization triggers and is accompanied by a rapid increase in gap current. In addition, the positive ions produced as a result of collision-ionization reaching the cathode leading to further introduction of electrons by secondary emission leading to further electrons.

The condition for the onset of electron avalanche is obtained by equating the gain in energy gained by an electron over its mean free path, which is necessary for ionization with the energy lost during collision-ionization. That is:

$$qE\lambda = ch\upsilon \qquad (4)$$

The electronic mechanism of breakdown in pure liquids, involves emission and multiplication of electrons at fields greater than 100kV/cm and approaching intrinsic value. It has been observed that the breakdown strength of dielectric liquid is higher if the dissolved gases in the dielectric are electronegative in nature. Similarly, the increase in the hydrostatic pressure of dielectric liquid increases the breakdown strength.

Example 3: A pure liquid dielectric is introduced between uniform field electrodes in a test cell and is subjected to breakdown under carefully controlled laboratory conditions for which $c = 10^4$. Compute the breakdown strength of the liquid for an average mean-free path of 0.01nm with the ionization potential of the liquid atoms to be 8.02eV.

Solution:

Given that: $c = 10^4\ m^{-1}$
Ionization energy = ξ = 8.02eV
Mean-free path = λ = 0.01 x 10^{-9} m

For the electronic process to be cumulative, the kinetic energy (*KE*) of the moving electron must be critically equal to the ionization energy of the liquid atoms, so that:

$$KE = 8.02 \times 1.6 \times 10^{-19} = \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2$$

From which: $v = 1.67 \times 10^6$ m/s. Thus from Eq (4), we have:

$$E = \frac{10^4 \times 6.63 \times 10^{-34} \times 1.67 \times 10^6}{1.6 \times 10^{-19} \times 0.01 \times 10^{-9}} = \mathbf{69.2\ kV/cm}$$

Cavitation or Bubble Mechanism

It was experimentally observed that in many liquids a kind of vapor bubble, formed by some elementary process, is responsible for breakdown. The following processes have also been suggested to be responsible for the formation of the vapor bubbles:

1. Gas pockets formed at the surface of the electrodes due to differential thermal expansion.
2. Sufficient repulsive electrostatic forces between uni-polar space charges that overcomes the surface tension.
3. Gaseous products due to the released energy from the dissociation of liquid molecules by electron collisions.

4. Vaporization of the liquid due to localized corona-type discharges from sharp points and irregularities on the electrode surfaces.

Irrespective of the mechanism of formation of bubble, once a bubble is formed it will be elongated at constant volume in the direction of the electric field. In a bubble with permittivity ε_2, which is assumed to be spherical with radius r, immersed in liquid dielectric having a permittivity ε_1, the electric field E_b inside the bubble is given by:

$$E_b = \frac{3\varepsilon_1}{2\varepsilon_1 + \varepsilon_2} E_0$$

Or

$$E_b = \frac{3}{2 + (\varepsilon_2 / \varepsilon_1)} E_0 \qquad 5$$

Where: E_0 is the electric field in the dielectric liquid in the absence of a bubble. When the field E_b becomes equal to the field required for ionization for gases, a discharge will take place that will result in the decomposition of liquid dielectric followed by breakdown. A more accurate expression for breakdown field of a gas bubble has been developed by Kao, which is:

$$E_o = \frac{1}{\varepsilon_1 - \varepsilon_2} \left\{ \frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r} \left[\frac{\pi}{4} \sqrt{\left(\frac{V_b}{2rE_o} \right) - 1} \right] \right\}^{1/2} \qquad 6$$

Where σ is the surface tension of the liquid, ε_1 is the permittivity of the liquid, ε_2 is the permittivity of the gas bubble, r is the initial radius of the bubble assumed to be spherical and V_b is the voltage drop inside the bubble. Under applied electric field the bubble elongates, the surface tension will keep the bubble intact. The sequence of elongation of bubble inside a dielectric liquid is shown in Fig (4).

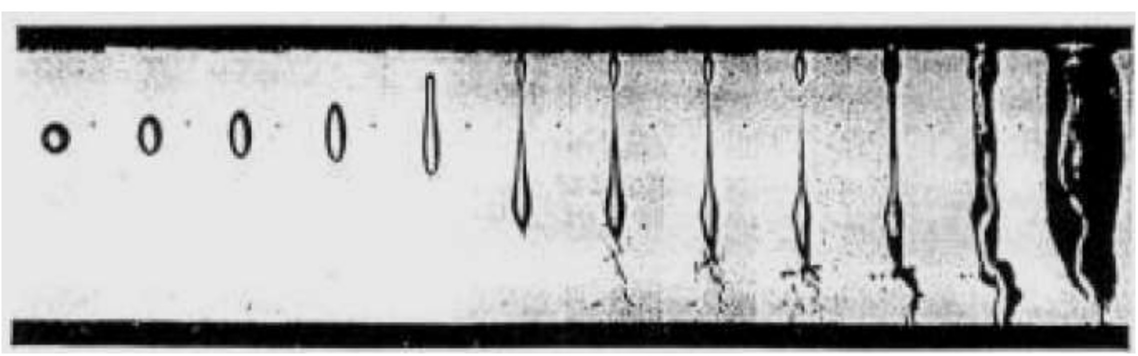

Figure 4: Sequence of Bubble Elongation under Electric Field

The electrostatic forces cause the globule to elongate and take the shape of an elongated spheroid. As the field is increased, the globule elongates and the field exceeds a critical value, with the globule keeps on elongating eventually causing bridging of the electrodes, and breakdown of the gap as shown in Fig (4). When $\varepsilon_2/\varepsilon_1 >> 20$, the critical field E_{crit} at which the globule becomes unstable no longer depends on the ratio, and is given by:

$$E_{crit} = 1.542\sqrt{\frac{\sigma}{r\varepsilon_1}} \text{ V/m} \qquad 7$$

Where, σ is the surface tension of liquid dielectric in N/m, ε_1 is the relative permittivity of the liquid dielectric. The volume of the bubble, however, will remain constant during elongation.

Example 4: Find the critical value of electric field to cause breakdown in the presence of a spherical bubble of air with radius of 1µm in insulation oil having a permittivity of 2.3. Assume the surface tension to be 0.043 N/m.

Solution:

Given that: $r = 1\mu\text{m} = 1\times10^{-6}$ m

$\sigma = 0.043$ N/m

$\varepsilon_1 = \varepsilon_r\varepsilon_0 = 2.3\varepsilon_0$

Using: $E_{crit} = 1.542\sqrt{\frac{\sigma}{r\varepsilon_1}} = 1.542\sqrt{\frac{0.043}{1\times10^{-6}\times8.85\times10^{-12}\times2.3}}$ = **0.71 MV/cm**

Suspended Particle Mechanism

In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present, mostly in the form of fibers or as dispersed solid conducting particles, especially when the liquid dielectric is used in electrical equipment in which the liquid is in contact with solid insulation and metallic parts as in transformers. The fibrous particles are disposed off from bakelite insulation or oil-impregnated paper used as insulation in coils, whereas the conducting particles are introduced from the steel tank structure during service conditions. The permittivity of these particles ε_2 will be different from the permittivity of the liquid ε_1. If these impurities are assumed to be spherical with radius r, and if the applied field is E, then the particles experience of force F given by:

$$F = r^3 E\frac{(\varepsilon_2-\varepsilon_1)}{2\varepsilon_1+\varepsilon_2} gradE \qquad 8$$

This force is directed towards maximum stress regions, 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, then $\varepsilon_2 < \varepsilon_1$, the force will be directed towards the lower stress regions. In case of a conducting particle, $\varepsilon_2 \rightarrow \infty$ and Eq (8) will be rewritten as:

$$F = r^3 E(gradE) \qquad 9$$

If a DC voltage is continuously applied or the cycle of the AC voltage is long enough, a force is exerted on the suspended particles and this force move the particles towards the region of maximum stress against an opposing force of viscous drag. For a particle of radius r, which is slowly moving with a velocity v in dielectric liquid having viscosity η, the drag force F_{drag} experienced by the particle is given by Stokes relation:

$$F_{drag} = 6r\pi\,\eta v \qquad 10$$

If the particles are large in number, they polarize and thereby are aligned due to these forces, and thus form a stable chain bridging the electrode gap causing short-circuit between electrodes resulting in breakdown.

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 be breakdown of the liquid by cavitation mechanism.

Aging and Deterioration

Liquid dielectric used in electrical equipments such as, transformers are prone to contamination from different sources. Contamination can change both physical and chemical nature of the liquid dielectric during service life, which may cause the dielectric to age. Aging deteriorates the dielectric liquid and resulting in lowering its dielectric strength. The two main sources of water in oil used in transformers during service are penetration of moisture from the outside atmosphere and degradation of oil and cellulose. In addition to moisture, solid particles and gas bubbles have considerable effect on the electrical breakdown process. The presence of impurities in the liquid dielectric reduces electric strength. These impurities are created mainly as a by-product of oil oxidation and aging, partial discharge activity and cellulose pieces release due to process of insulation aging.

Before using dielectric liquid such as; transformer oil, care must be taken to eliminate most of the impurity content that can deteriorate its properties. Routine check of dielectric strength during service intervals is necessary to ensure efficiency and reliability. Any discrepancies in its properties to some extent can be overcome by routine purification of the oil in purifiers, where degassing, filtering and dehydration on the oil is performed.