Chapter-6

Solid- and Liquid-Insulating Materials, Their Classification, Properties and Breakdown

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Objective

- Classification of solid and liquid dielectrics
- Dielectric properties of insulating solids and liquids
- Pre-breakdown phenomenon in solid and liquid insulating materials
- Partial Breakdown, PB in solid and liquid dielectrics
- Breakdown in solid and liquid dielectrics

Introduction

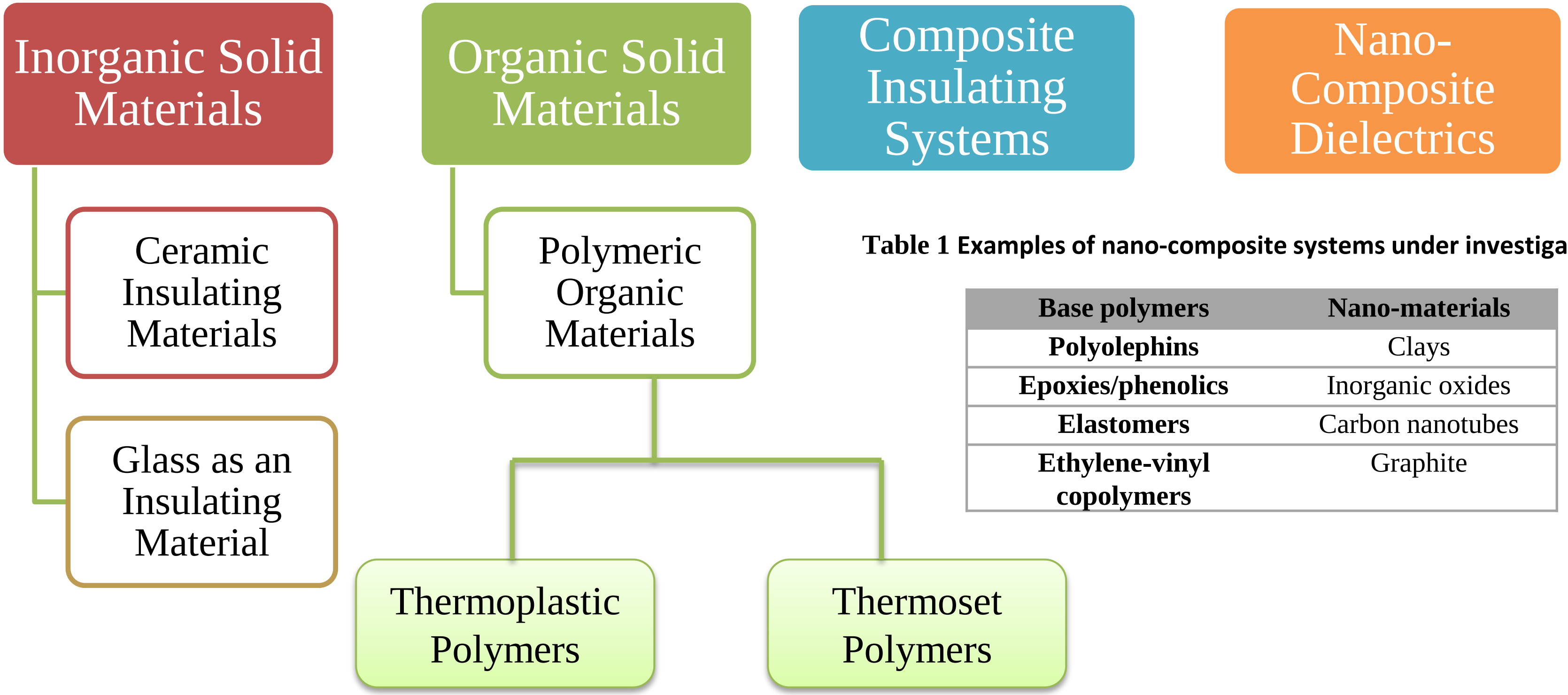
- Solid and liquid dielectric materials are a necessity for supporting the live conductors and augmenting the insulation system in power apparatus.

The functions performed by these insulating materials in the power systems are brought together below:

- Solid dielectrics provide the insulating mechanical support to the live conductors.
- Solid dielectric ‘bushings’ provide passage to the live conductors through the grounded container of transformers.
- Wax-based semi-liquid compounds and low-viscosity oils impregnate the thin paper or other solid material insulation provided in layers over the conductors in power cables, bushings and capacitors.
- As a filler material liquid dielectrics provide or augment the insulation between the parts carrying potential and the grounded containers.
- Liquid dielectrics also perform the cooling action by convection in power transformers and oil filled cables carrying away the heat produced by the live conductors through circulation.
- Rapid injection of liquid oil between circuit breaker contacts helps in the extinction of arcs.
- Thin oils are used for filling the voids formed in ‘composite solid dielectrics’ and also the porosity in some solids, for example, paper.

Classification of Solid and Liquid-Insulating Materials

- **Solid Insulating Materials and their Classification**



Inorganic Solid Materials

- Ceramic Insulating Materials
- Glass as an Insulating Material

Organic Solid Materials

- Polymeric Organic Materials
  - Thermoplastic Polymers
  - Thermoset Polymers

Composite Insulating Systems

Nano-Composite Dielectrics

Table 1 Examples of nano-composite systems under investigations

Base polymers	Nano-materials
Polyolephins	Clays
Epoxies/phenolics	Inorganic oxides
Elastomers	Carbon nanotubes
Ethylene-vinyl copolymers	Graphite

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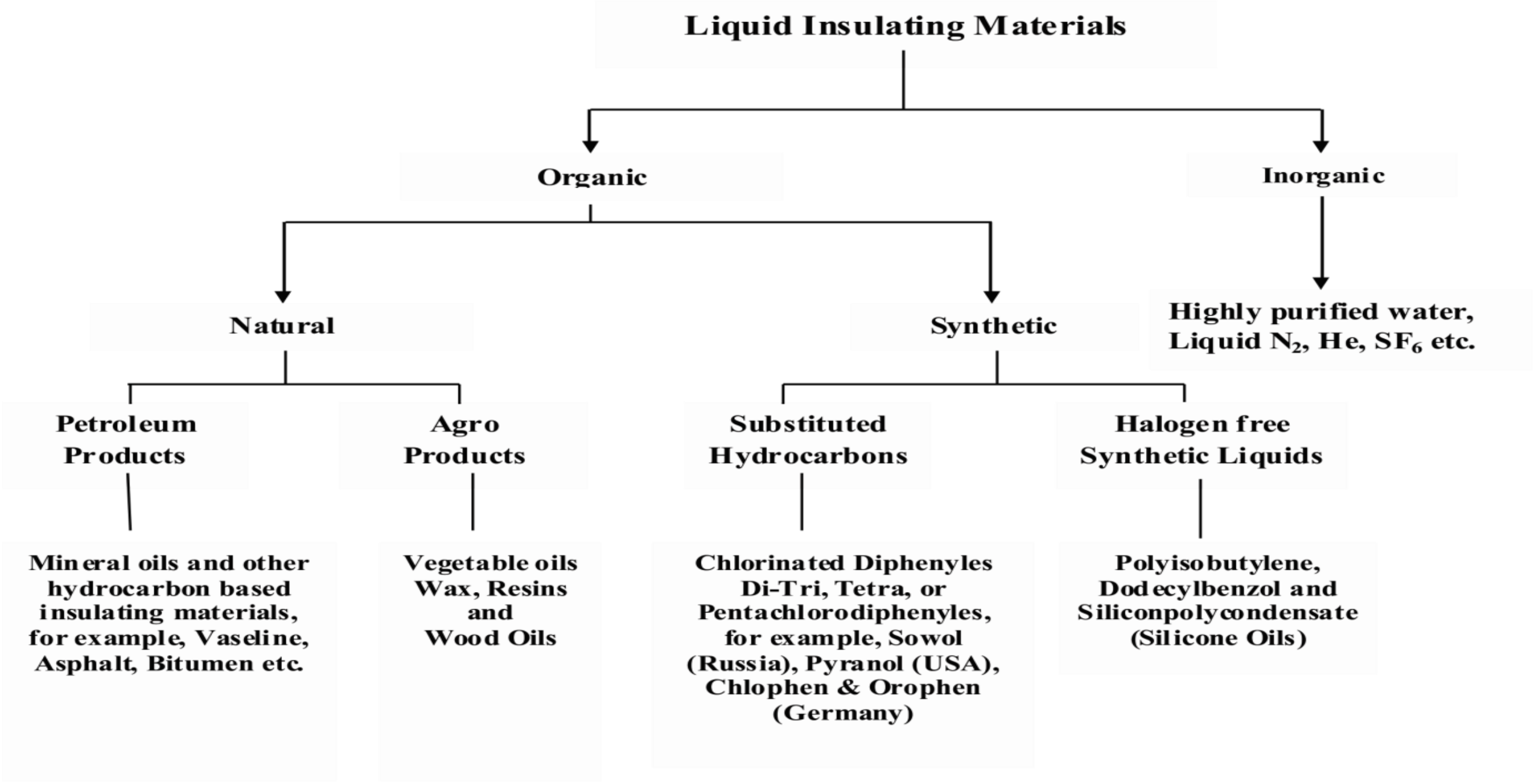
- **Liquid Dielectrics and their Classification**



Liquid Insulating Materials

Organic

Inorganic

Natural

Synthetic

Highly purified water, Liquid N_2, He, SF_6 etc.

Petroleum Products

Agro Products

Substituted Hydrocarbons

Halogen free Synthetic Liquids

Mineral oils and other hydrocarbon based insulating materials, for example, Vaseline, Asphalt, Bitumen etc.

Vegetable oils Wax, Resins and Wood Oils

Chlorinated Diphenyles Di-Tri, Tetra, or Pentachlorodiphenyles, for example, Sowol (Russia), Pyranol (USA), Chlophen & Orophen (Germany)

Polyisobutylene, Dodecylbenzol and Siliconpolycondensate (Silicone Oils)

Fig. 1 Classification of liquid insulating materials

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Dielectric Properties of Insulating Materials

➢ Insulation Resistance of Dielectrics

- The parameter, ‘insulation resistance’ of a dielectric is represented by the dc resistance offered by the insulating material.

$$\rho_{ins} = \frac{1}{\kappa_{dc}} \quad \Omega.m$$

Consider a direct voltage applied across two uniform field electrodes separated by a block of insulating material having an area *A* and length *d* .

$$R_{dc} = \rho_{ins}\frac{d}{A}$$

$$i_{dc} = \frac{U}{R_{dc}} = \frac{U.A}{\rho_{ins}.d}$$

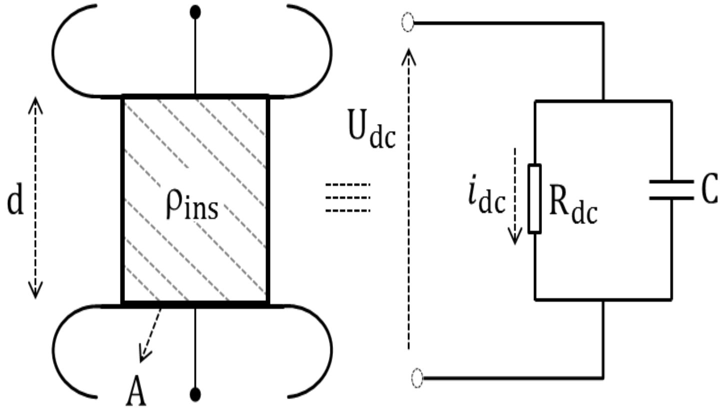

Fig. 2 A block of an insulating material in uniform field and its equivalent circuit diagram

For a uniform field where;

$$E = \frac{U}{d}$$

$$i_{dc} = \frac{E.A.d}{\rho_{ins}.d} = \frac{E.A}{\rho_{ins}} = \kappa_{dc}.A.E$$

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- The specific dc conductivity, κ_{dc} , of low density PE measured by Krohne with increasing field intensity and at different temperatures is shown in Fig. 3. It can be observed that the specific dc conductivity, κ_{dc} increases with increasing temperature as well as increasing intensity of electric field.

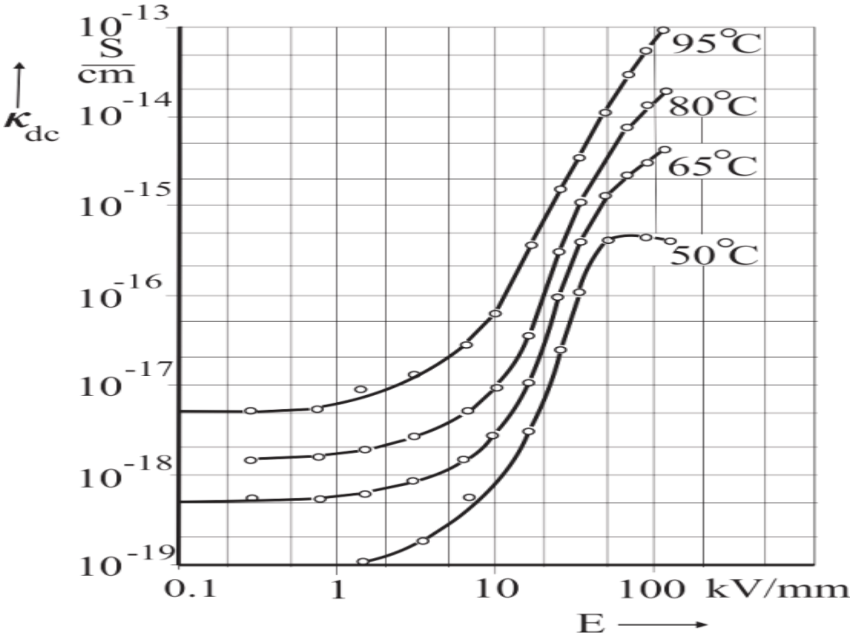

Fig. 3 Specific dc conductivity, κ_{dc} , of LDPE with respect to increasing field intensity at different temperatures.

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- The variation of κ_{dc} with respect to the time of application of the direct voltage, dc, for an insulating oil is shown in Fig. 4. The dc conductivity, which is very high at the instant of the application of the voltage (region-A), is determined by the orientation of dipoles present in the dielectric initially.
- In region-B, the movement of free charge carriers in the material under the influence of applied electric field determine the conduction. The magnitude of conductivity in this region also represents the ac power frequency conductivity κ_{ac}
- The region-C in the figure represents the phenomenon of the development of space charge in front of the electrodes.
- The flow of steady ion current due to dissociation is depicted by region-D, achieved after a considerable time of application of voltage.

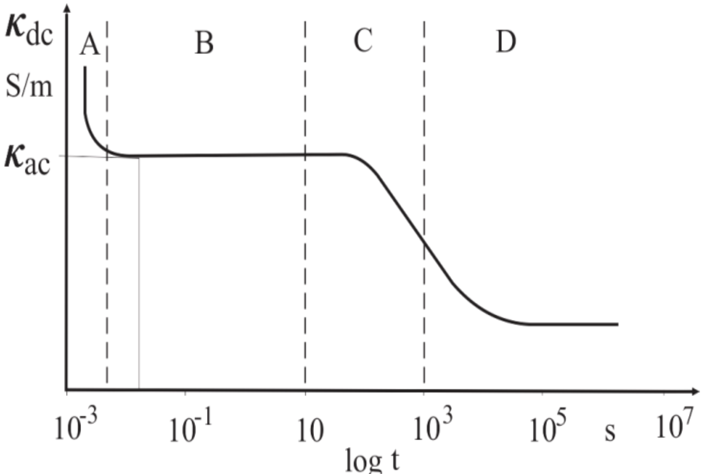

Fig. 4 Schematic of dc conductivity of insulating oils with respect to the time of applied voltage

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Permittivity of Insulating Materials

- Electrical parameter formed by the insulating materials in the network is the capacitance offered by them between given electrode systems.
- The capacitance is always accompanied with some losses determined by the permittivity, 'ε' and the specific insulation resistance, 'ρ_{ins}' of the material.

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

The Relative Permittivity ε_r of a dielectric is defined as

$$\varepsilon_r = \frac{C_x}{C_0}$$

Polarisation in Dielectrics

The phenomenon of interaction between the applied external electric field and the inherent charge carriers present in the form of atoms, ions or molecules is known as 'Polarisation'.

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- The electric flux density is given by,

$$\vec{D}_0 = \varepsilon_0 . \vec{E}$$

- when the vacuum is replaced by an insulating material (solid, liquid or gas) between the electrodes, the electric flux density is given

$$\vec{D}_{ins} = \varepsilon_0 . \varepsilon_r . \vec{E}$$

- The increase in electric flux density, known as $\vec{D}_P$, is caused by polarization in the dielectric
- Hence, $\vec{D}_p = \vec{D}_{ins} - \vec{D}_0 = \varepsilon_0(\varepsilon_r - 1)\vec{E}$

$$\frac{\vec{D}_p}{\vec{D}_0} = (\varepsilon_r - 1)$$

- The polarisation mechanisms are described under the following three main categories.

✓ Displacement polarisation

✓ Space charge or boundary surface polarisation

✓ Orientation polarisation

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- **Dielectric Power Losses in Insulating Materials**

- When a voltage is applied across a dielectric, besides the capacitive charging current real or active currents may also make their passage to flow through.
- These currents not only depend upon the type of applied voltage but also upon the frequency and magnitude of the applied voltage and also the thermal conditions of the dielectric.
- The conductive currents present in an insulating material determine its active as well as reactive 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 Fig. 5 .

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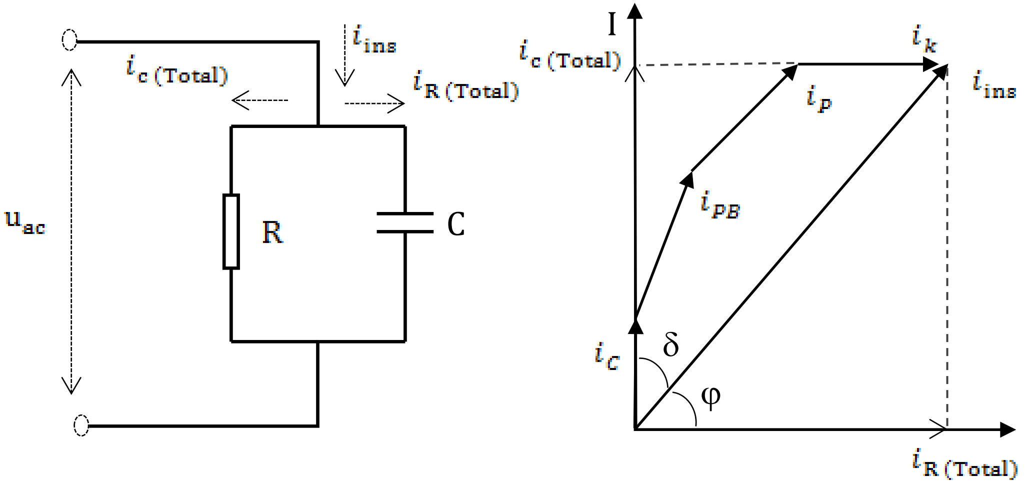

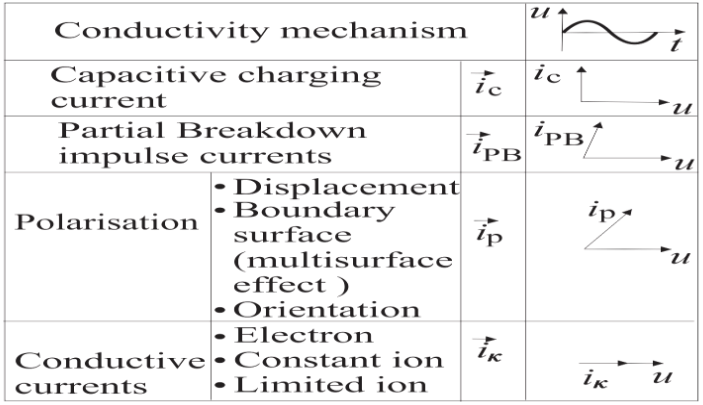

Conductivity mechanism			u t
Capacitive charging current		$\vec{i}_c$	i_c u
Partial Breakdown impulse currents		$\vec{i}_{PB}$	i_{PB} u
Polarisation	• Displacement • Boundary surface (multisurface effect) • Orientation	$\vec{i}_p$	i_p u
Conductive currents	• Electron • Constant ion • Limited ion	$\vec{i}_\kappa$	i_κ u

Fig. 5 Conductive current mechanisms in insulating materials for alternating voltage with equivalent circuit and vector diagrams.

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- The dielectric loss tangent 'tanδ' is defined as

$$tan\delta = \frac{Active\ Power}{Reactive\ Power} = \frac{u.i_{ins}cos\varphi}{u.i_{ins}sin\varphi} = \frac{i_{R(Total)}}{i_{c(Total)}} \quad \text{.....(1)}$$

- The total capacitive conductive current I_c is given as

$$I_{c(Total)} = \frac{U}{1/\omega C} = \omega.C.U \quad \text{......(2)}$$

- The active power loss $'P_{ac}'$ is given by

$$P_{ac} = \omega.C.U^2.tan\delta \quad \text{.....(3)}$$

$$P_{ac} = \omega.\varepsilon_0.\varepsilon_r\frac{A}{d}(E.d)^2tan\delta \quad \text{or} \quad P_{ac} = \varepsilon_0.\omega.E^2.V.\varepsilon_r.tan\delta \quad \text{.....(4)}$$

The dc power losses are determined by (3) and (4) is given as:

$$P_{dc} = \frac{U_{dc}^2}{R_{dc}} \quad \text{or} \quad P_{dc} = E^2.V.\kappa_{dc} \quad \text{.....(5)}$$

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- Variation in loss tangent, *tanδ*, of transformer oil samples having different moisture contents, measured for a wide range of temperature is shown in Fig. 6.
- The increase in *tanδ* measured on transformer oil samples at constant temperatures and moisture contents with increasing voltage/field intensity magnitudes at 50 Hz is shown in Fig. 7.

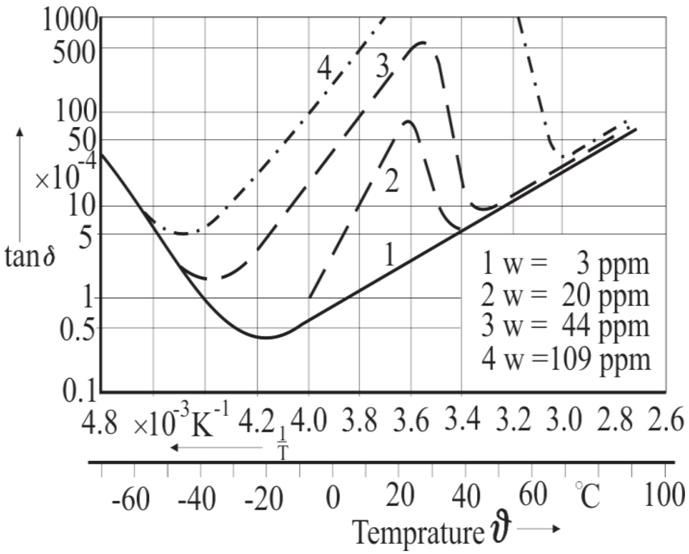

Fig. 6 Loss tangent 'tan δ' of transformer oil having different ppm moisture contents with varying temperature at 50 Hz constant voltage.

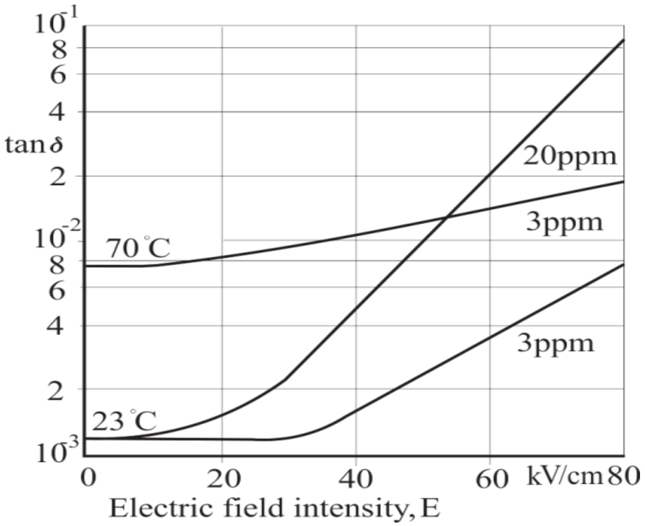

Fig. 7 Loss tangent (tan δ) of a transformer oil measured with increasing voltage/field intensity (50 Hz) at different constant temperatures and for different moisture contents in oil.

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Table 2 Standard values of electrical properties of some solid insulating materials

Material and their Classification		Relative Permittivity	Loss tangent	Specific Insulation Resistance	Specific Thermal Resistance
		ε_r (50Hz, 20°C)	tanδ (50Hz, 20°C)	ρ Ω.cm (20°C)	Σ °C *cm/W*
Ceramics	Porcelain	5-6.5	20.10^{-3}	10^{11}-10^{12}	70-125
	Steatite		2.10^{-3}		40-50
Glass	Non alkaline and E-Glass	3.8-10	$<1.10^{-3}$	10^{13}	85-135
Thermoplastic Polymers	Polyvinyl Chloride (PVC) (Cable insulation compound)	5.0-5.3	$30\text{-}100.\ 10^{-3}$	10^{16}	600-700
	Polyethylene (PE)	2.3	$0.1\text{-}0.2.10^{-3}$	10^{17}	350
Thermoset Polymer	Bisphenol-A Epoxyresin Silicon Rubber (SiR)	Pure 3.5 with filler 5.8 2.8-6.0	5.5 $33.\ 10^{-3}$ $5\text{-}10.\ 10^{-3}$	$>>10^{17}$ - 10^{13}-10^{15}	- - 500
Composite Dielectrics	Oil Impregnated Cable paper	3.5-3.9	$(2.6\text{-}3.0)\ 10^{-3}$	10^{15}	550

Table 3 Nominal/standard values of some properties of pure insulating liquids in high voltage applications

Insulating Liquid	**Relative Permittivity**	**Loss tangent**	**Dynamic Viscosity***	**Density at20°C**	**Electric Strength**	
	ε_r	tanδ	$P_{a.s}$	g/((kg/m^3*10^{-3})	E_b kV/cm	Applications
Mineral insulating oils (transformer oil)	At 20°C 50Hz≈20	At 50Hz 20°C≤10^{-3} 90°C≤4 >10^3	At 40°C 0.0067-0.0143 Tr oil at 20°C 0.0243 (IS-335)	<0.895	350 to 500 Minimum value for transformers ≥ 300 For circuit breaker ≥ 175	Power transformers CTs, PTs CircuitBreaker Bushings Cables and Condensers
Linseed oil	At 20°C 50Hz ≈ 3.2	At 50Hz 20°C>10^{-3} At 50Hz 20°C< 10^{-2}	At 40°C ≈ 0.00260 At 100°C ≈ 0.0067	0.930	-	-
Castor oil	At 20°C 50Hz between 4.2 and 4.5	At 50Hz 20°C<10^{-2}	At 40°C ≈ 0.2684 At 100°C ≈ 0.0192	0.96-0.97	175-250	Condensers
Chlorinated Diphenyles	At 20°C 50 Hz between 4- 6	At20°C, 50 Hz between 10^{-4} - 10^{-3}	At 20°C ≈ 0.0600 At 90°C ≈ 0.0040	1.400-1.550	250-500	Transformers condensers (prohibited in some countries)
Silicone oils	At 20°C 50Hz ≈ 2.6	At 20°C 50Hz<10^{-4}	At 20°C 0.0096-0.9700	0.960-0.970	300-400	Cable Condensers Bushings

Pre-Breadown Phenomena in Solid and Liquid-Insulating Materials

Electric Conduction in Insulating Liquid and Solid Dielectrics

- A perfect dielectric is a material with zero electrical conductivity, counterpart of a perfect conductor, thus exhibiting only a displacement current; therefore it stores and returns electrical energy as if it were an ideal capacitor.
- Every dielectric has some conduction of charge or current, it can be said that there is no dielectric which is “dia-electric”.
- Conduction currents through dielectrics mainly depend upon their relative permittivity number, ε_r and the type and amplitude of the electric field intensity/voltage applied.
- The conduction mechanism in both, solid and liquid dielectrics is strongly affected by the degree of their purity.
- In the liquids, which have not been highly purified, when subjected to fields up to about a few kV/cm the conduction is primarily ionic.
- Ionic conduction is affected by the dissociation process of impurities as well as the injection of charge by the electrodes through electrochemical reactions.

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- Fig. 8 shows at low voltages, the current varies proportionally to the voltage (region-1), representing the ohmic behaviour of the material. On raising the applied voltage, hence the field intensity, the ionic conduction current gets saturated, (region-2). At still higher applied voltage the current density increases rapidly until the breakdown occurs, (region-3).

- In Fig. 9 the conduction current characteristics are shown for negative direct voltage applied to a needle-plane electrode configuration in transformer oil and liquid nitrogen, measured by Takashima et al. for different radii of curvature 'r_t' of the needle tip. The sharp bend measured on the curve is supposed to represent the development of a strong space charge around the needle.

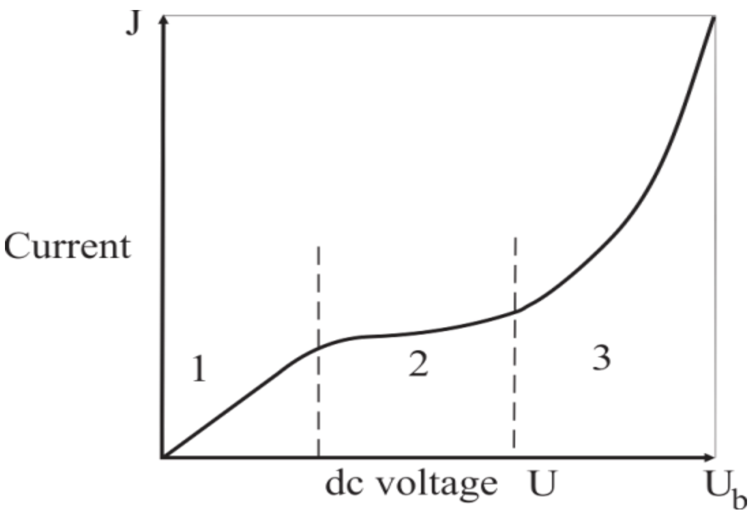

Fig. 8 Typical voltage-current (*U-J*) characteristic in dielectric liquids.

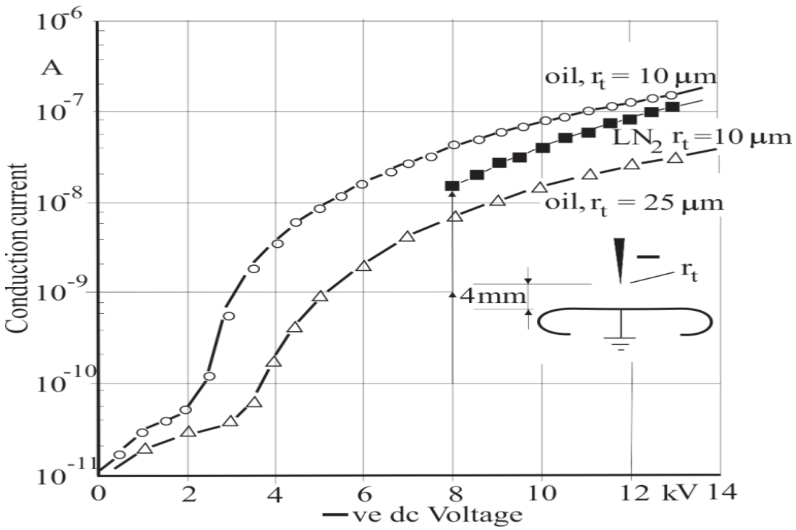

Fig. 9 Conduction current in transformer oil and liquid nitrogen for negative needle-plane electrode gap of 4mm with increasing voltage. Oil at 20°C and LN_2 at 77.3 K

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- According to Van'tHoffsch law, the conductivity 'κ' within a certain range of temperature follows the relation:

$$\kappa = \kappa_0 \exp\left(-\frac{F}{kT}\right)$$

- Where k is Boltzmann constant, T absolute temperature, κ_o and F are material constants. F is known as 'activation energy' of the material and it is expressed in kcal/mole.
- Van'tHoffsch law is valid only in the region where the conduction current follows the ohmic behaviour, that is, region-1 in Fig. 8.
- Variation in transformer oil conductivity was measured with dc positive polarity voltage for a wide range of temperature for different moisture contents as illustrated in Fig. 10.
- It is evident from this figure that the conductivity of oil increases as the water ppm content rises. Van'tHoffsch law is valid only in the temperature region above the room temperature.

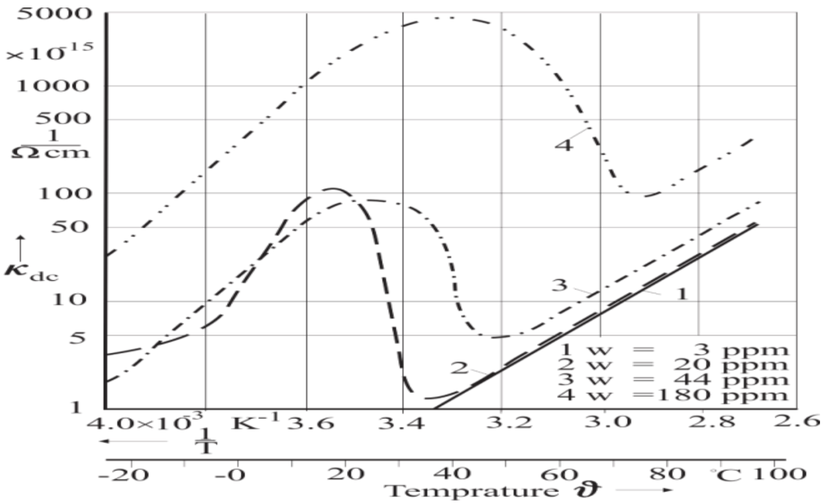

Fig. 10 Direct current conductivity of transformer oil for different water contents w (ppm) with respect to the reciprocal of absolute temperature

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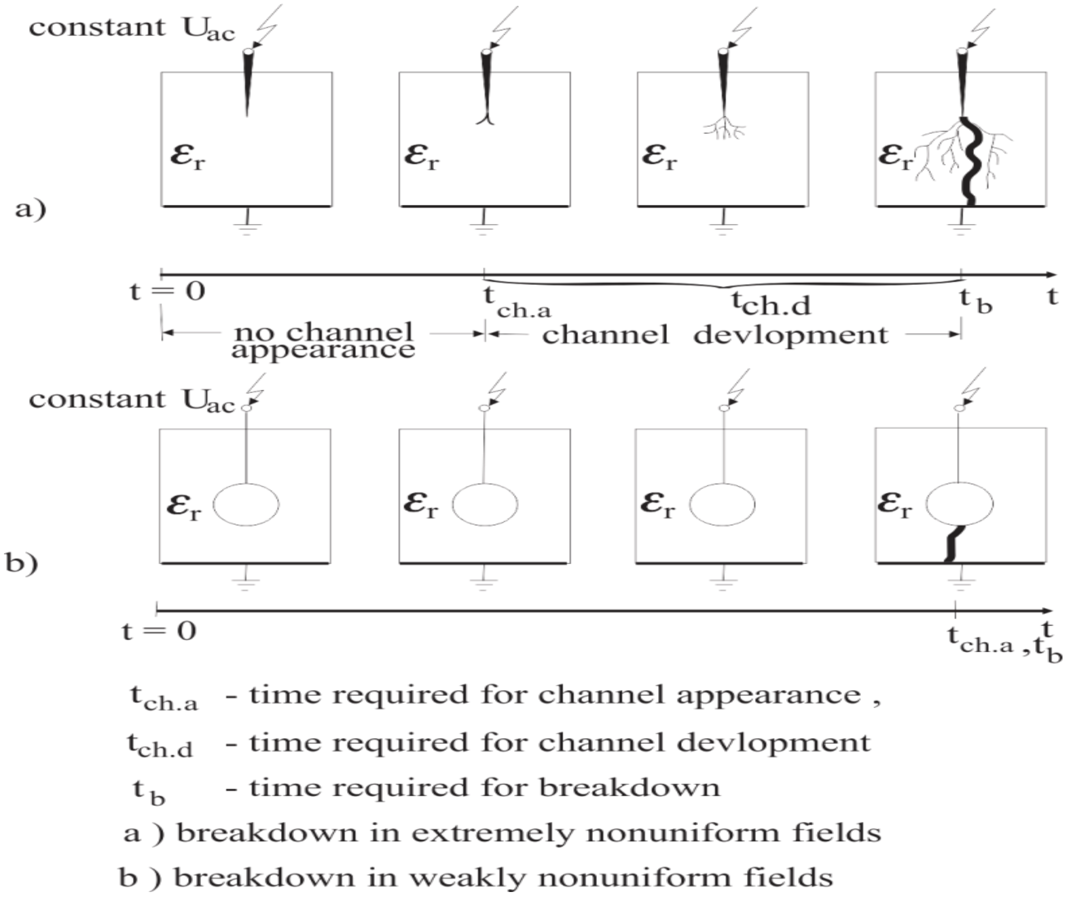
➢ Requirement of Time for Breakdown



$t_{ch.a}$ - time required for channel appearance ,

$t_{ch.d}$ - time required for channel devlopment

t_b - time required for breakdown

a) breakdown in extremely nonuniform fields

b) breakdown in weakly nonuniform fields

Fig. 11 Development of breakdown in extremely and weakly nonuniform fields with time

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- Consider a solid dielectric in extremely nonuniform field between needle and plane.
- The field intensity at the needle tip will be maximum in this electrode configuration if there is no other cause of field distortion present elsewhere in the dielectric volume.
- On increasing the applied voltage when this process acquires certain intensity, the development of a gas filled channel may begin after certain time lag.
- Let the time required for the first appearance of such a channel be called 'channel appearance' time, . This is the beginning of the degradation process by the so called “treeing” phenomenon in the dielectric.
- The time required for the tree to grow up to the opposite electrode, may vary considerably in different dielectrics from location to location, depending upon the favourable local conditions.
- The time required for breakdown can be given as the sum of the time required for the appearance of the first channel and its development up to the opposite electrode

$$t_b = t_{ch.a} + t_{ch.d}$$

$t_{ch.d} \gg t_{ch.a}$ (In extremely nonuniform fields)

$t_{ch.d} \ll t_{ch.a}$ (In weakly nonuniform fields)

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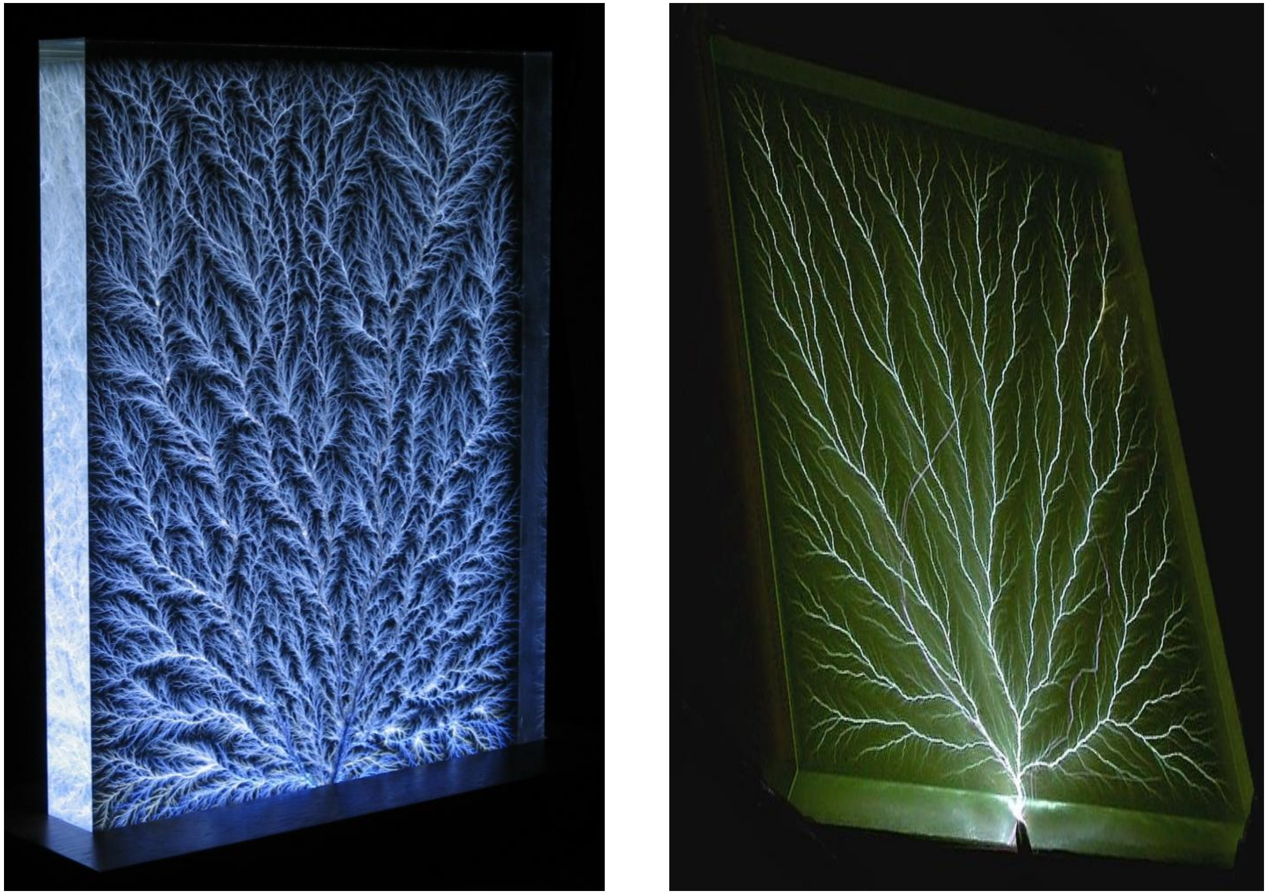

Fig. 12 (a) Photographs of the full grown conductive channels due to PB in Acrylic solid dielectric blocks in extremely nonuniform field, used with permission from Bert Hickman, Stoneridge Engineering, LLC, http://capturedlightning.com , Hickman [6.6].

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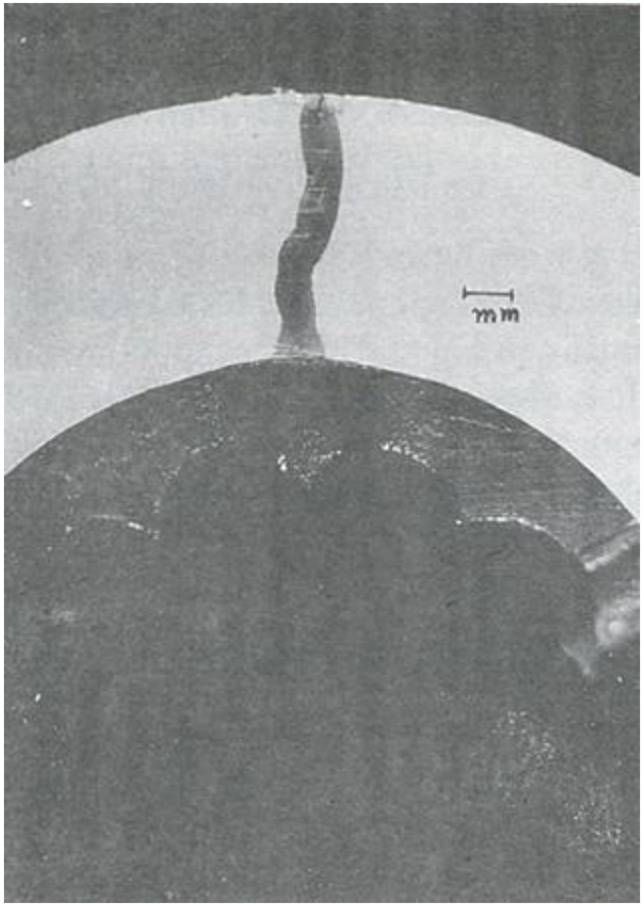

Fig. 12 (b) Breakdown channel in coaxial PE cable in a weakly nonuniform field.

The above photograph of a breakdown channel in weakly nonuniform field in a 20 kV, coaxial PE cable taken by Arora [6.7]. A clean breakdown channel appears to have developed abruptly in the dielectric between the two semi-conductive layers without any PB or treeing process as explained in the schematic in Fig. 11 (b).

Partial Breakdown in Solid and Liquid Dielectrics

Internal Partial Breakdown

- Partial Breakdown in solid dielectrics may take place at the defects, the so called weak points.
- These weak points may be voids, cuts and cavities, foreign particles or conductive protrusions in the dielectric, as shown in Fig. 13.

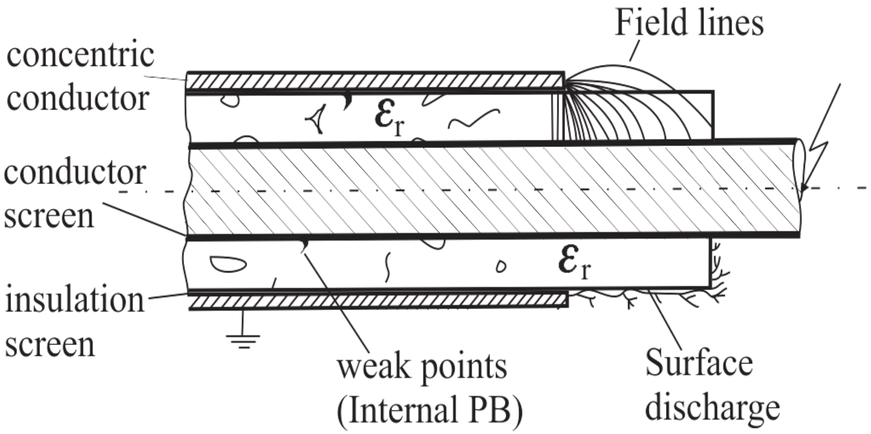

Fig. 13 A cable cross section showing possibilities of internal and surface discharges

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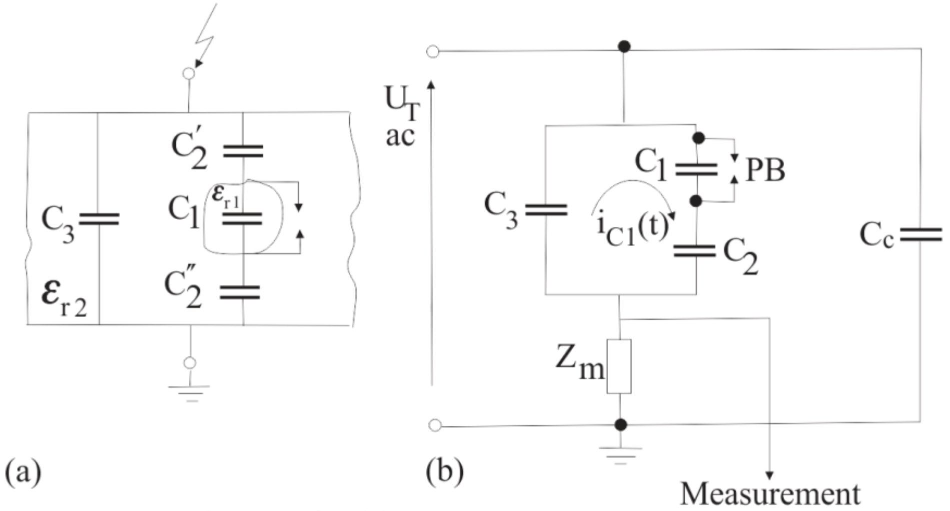
- Weak points or the defects in the solid dielectrics have lower electric strength in general than the dielectric itself. Still worse is that they acquire higher electric fields due to distortion in the existing field pattern and lower relative permittivity. Such weak points can be simulated by a capacitance C_1 within the main dielectric system having capacitance C_3, as shown below:



C_1 - capacitance of void
C_2' and C_2'' - capacitance between void and electrodes
C_3 - capacitance of the test objects , C_c - coupling capacitor
C_2 - is equivalent of C_2' and C_2'' in series
Z_m - measuring impedance

Fig. 14 Simulation of internal Partial Breakdown (a) Schematic showing a simulated capacitance formed by the void (b) Equivalent circuit diagram for measurement

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- Let the magnitude of the voltage at which PB at C_1 incept to be U_{C1i}, and the voltage at which PB extinguish U_{C1e} is shown below:

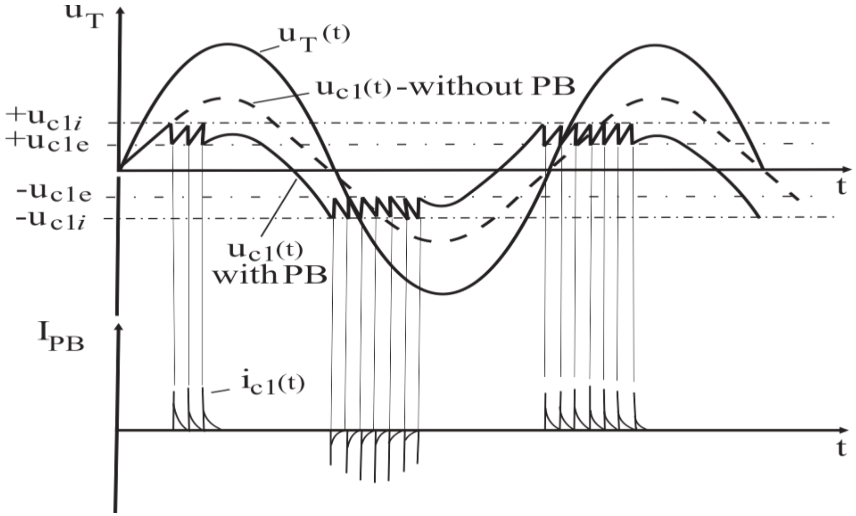

Fig. 15 PB voltages and pulse currents at a void or cavity in the dielectric

- The inception voltage U_{C1i} can be given in terms of the applied voltage and capacitances shown in the equivalent circuit diagram as:

$$U_{C1i} = U_T \frac{C_2}{C_1 + C_2}$$

- Considering no change at C_1 initially, ΔU_{C1} is given by,

$$\Delta U_{C1} = U_{C1} \frac{C_2}{C_3 + C_2}$$

Cont…

- If the voltage drop at C_1 is assumed to be equal to the corresponding drop in applied voltage at the test object ΔU_T, it can be given by,

$$\Delta U_T = U_T \frac{C_2^2}{(C_3 + C_2)(C_1 + C_2)}$$

- The actual charge q_{c1}, transposed to the weak point (void) in this process from the circuit, is given by,

$$q_{c1} = \Delta U_{C1} \left[C_1 + \frac{C_2 . C_3}{C_2 + C_3} \right]$$

- The charge delivered at the power input terminals can be approximated using fig. 14 as:

$$q \approx \Delta U_T \left(C_3 + \frac{C_1 C_2}{C_1 + C_2} + C_c \right) = q_a$$

- The sum total of discharge 'q_s' takes into account all the individual PB processes occurring in the test object within a certain time frame of the applied voltage.

- A more comprehensive investigation of PB phenomenon in an object is made possible by measuring q_s. In Fig. 16, variation of measured values of q_i and q_s with increasing voltage are illustrated.

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•PB inception voltage 'U_i'

It is the lowest terminal voltage at which a discharge due to partial breakdown exceeding a specified intensity is observed under specified conditions, when the voltage applied to the test object is gradually increased from a lower value at which no such discharges are observed.

•PB extinction voltage 'Ue'

It is the voltage at which PB exceeding a specified intensity cease under specified conditions when the voltage is gradually decreased from a value exceeding the inception voltage.

•Repetition rate 'n'

The PB pulse repetition rate 'n' is the average number of pulses produced per second.

•Energy of an individual PB, 'w'

The energy involved in PB, 'w' is the energy dissipated during one individual discharge. It is expressed in joules.

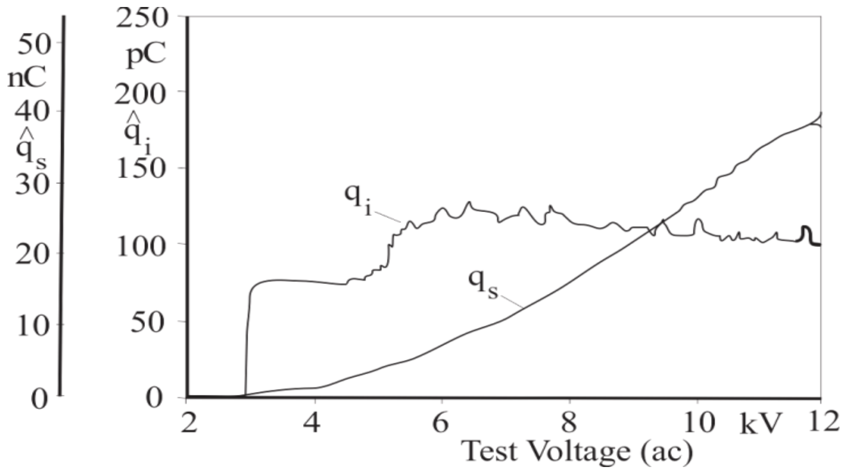

Fig. 16 Variation of impulse 'q_i' and cumulative 'q_s' discharge magnitudes with increasing voltage.

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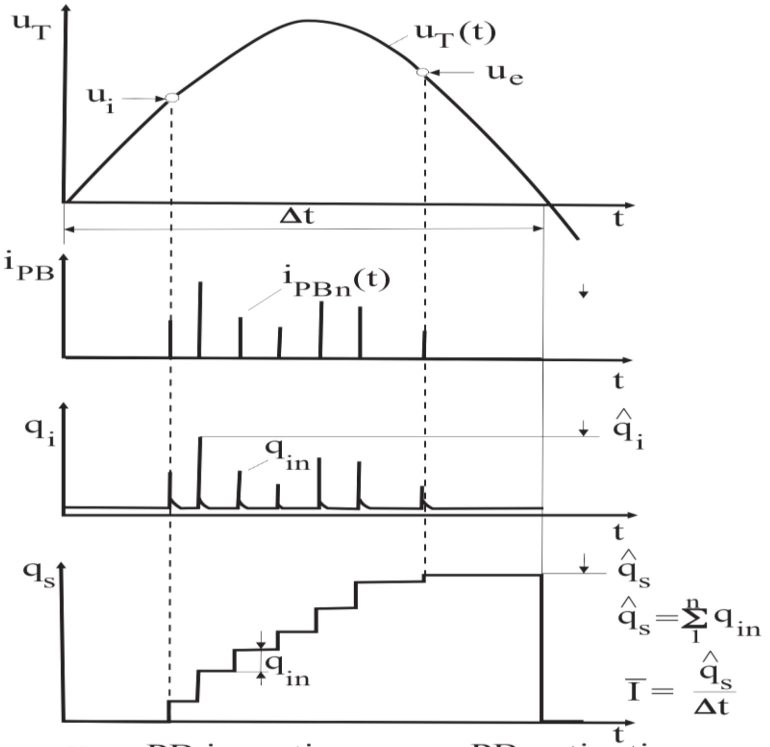

$$\hat{q}_s = \sum_{1}^{n} q_{in}$$

$$\bar{I} = \frac{\hat{q}_s}{\Delta t}$$

u_i - PB inception , u_e - PB extinction

Δt - time interval of measurment ,

q_i - apparent impulse discharge , q_s - apparent cumulative discharge,

$\hat{q}_i$ - impulse discharge of maximum intensity,

$\hat{q}_s$ - sum total of individual discharges in a time interval of Δt,

$\bar{I}$ - average discharge current

Fig. 17 Measurable quantities of PB

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➢ Partial Breakdown Phenomenon on the Surfaces of Solid and Liquid Dielectrics

- **Surface Discharge (Tracking)**

- Surface discharges are caused when an interruption in the flow of creepage current across the surface of the dielectric takes place and the tangential field component at the location exceeds the electric strength of the medium.
- Surface Discharge or tracking is also a PB phenomenon.

$$\frac{T_c}{T_m} = \frac{\begin{array}{c}\text{Dissociation energy of all the bonds which}\\ \text{on breaking produce free carbon (kcal/mole)}\end{array}}{\text{Total bond energy of the molecules (kcal/mole)}}$$

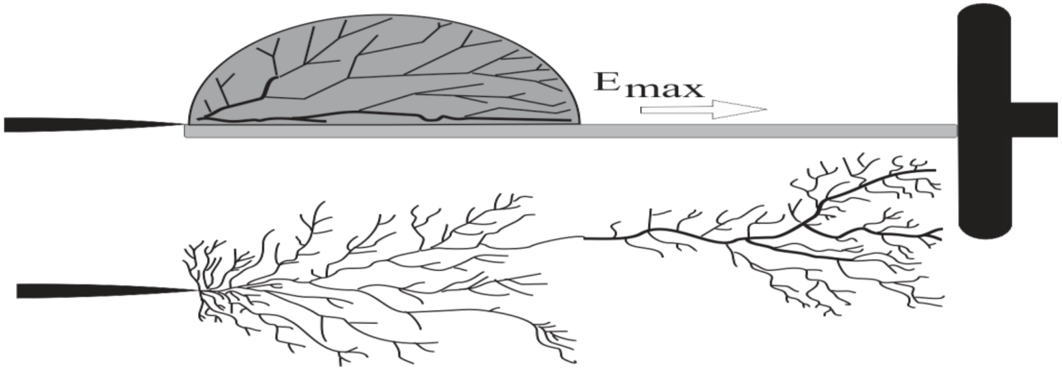

Fig. 18 Development of positive streamer along a pressboard surface in oil. Upper: The positive streamer schematic, Lower: Actual track observed on the pressboard surface

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- **Degradation of Solid Dielectrics Caused by PB**
- **Treeing, a pre-breakdown degradation process due to PB**
- If the PB intensity is unusually high, the degradation and erosion mechanism may proceed at sufficiently fast rate.
- Conductive channels in different shapes and sizes are formed within the solid dielectrics, known as ' Tree' formation. The phenomenon is known as ‘Treeing Process’.
- It grows towards the opposite electrode with time.
- It may lead to complete failure of the insulating properties of the dielectric taking different amounts of time which depends upon the material and its condition, the field intensity and its configuration.
- Treeing process normally begins at a very sharp, pointed electrode tip due to internal partial breakdown which takes place under extremely nonuniform field conditions.
- Extreme field distortions at protrusions in the dielectrics may also give rise to the development of treeing process.
- Treeing may occur and develop slowly due to PB. In the presence of moisture it may develop slowly even without any measurable quantity of PB. However, treeing develops rapidly when very high impulse voltage is applied.

Cont…

- Treeing process developed in solidified resin is shown in Fig. 19. A needle electrode imbedded inside the resin block produces an extremely nonuniform field at the tip of the needle. This gives rise to PB within the solid dielectric on applying a voltage greater than *Ui*, the PB inception voltage. The PB causes formation of conductive channels due to degradation of the dielectric under heat. These develop in the form of a tree extending towards the opposite electrode, the ground electrode.

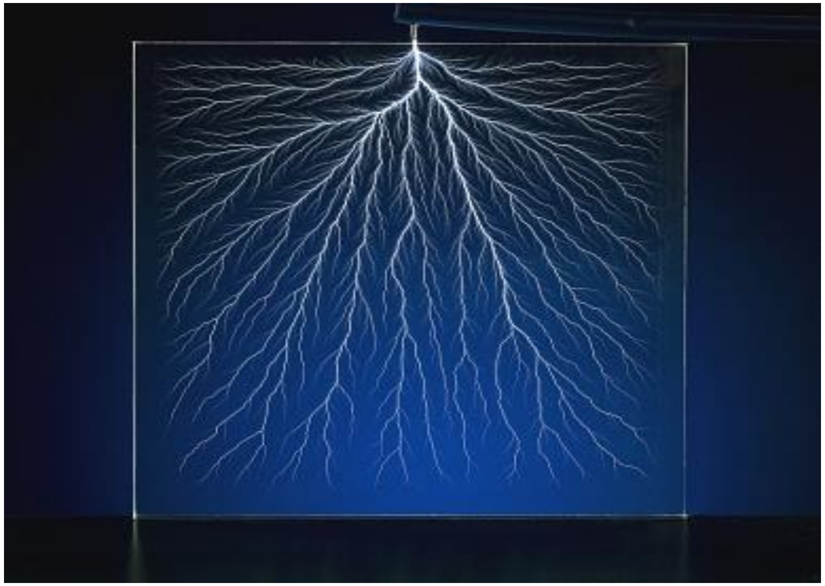

Fig. 19 Development of Treeing Process in Epoxy Resin, used with permission from Bert Hickman, Stoneridge Engineering, LLC, http://capturedlightning.com , Hickman [6.6].

Breakdown in Solid and Liquid Dielectrics

- The breakdown mechanisms is similar to those described for gaseous dielectrics.
- The phenomenon of partial breakdown takes place only in extremely nonuniform fields before the complete breakdown.
- The PB leads to the treeing process and ultimately complete breakdown.
- The breakdown strength also depends strongly upon the type of voltage, ac, dc, impulse; li or si with which it is measured.
- The breakdown strength of these dielectrics is distinguished into two broad categories known as the ‘intrinsic’ and the ‘practical’ breakdown strengths measured in uniform or near uniform fields.

➢ Intrinsic strength of liquid dielectrics

1. The most likely elementary process of ionisation in hydrocarbon liquids is by excitation or molecular vibration, which is equivalent to thermal vibrations.
2. The process of dissociation of molecules in neutral, low molecular, gaseous particles takes place due to severe molecular vibrations, which requires energy levels in the range 1.5 to 7 eV.
3. Excitation of metastables, which may lead to ionization in a few stages, requires energy levels of the order of 1.5 to 10 eV.
4. Scintillation of electrons accompanied with weak luminescence, indicating high energy quanta of several eV; which is greater than 10 eV in some liquids leads to ionization process.

Cont…

➢ Partial breakdown strength of liquid dielectrics

- The practical breakdown strength of insulating liquids is measured with help of standard electrodes having weakly nonuniform field between them.
- It is because of the secondary effects, which influence the breakdown strength of liquid dielectrics considerably.
- The BIS recommends the electrodes to be made of brass with a good surface finish, whereas VDE recommends copper as electrode material
- These electrodes are placed in a container of given dimensions and filled with about 300 cc of the sample of oil to be tested.

$$\hat{E}_b = \frac{\sqrt{2}U_b}{\eta . d} = \frac{\sqrt{2}U_b}{0.97 \times 0.25}\ kV/cm \approx 5.8U_b$$

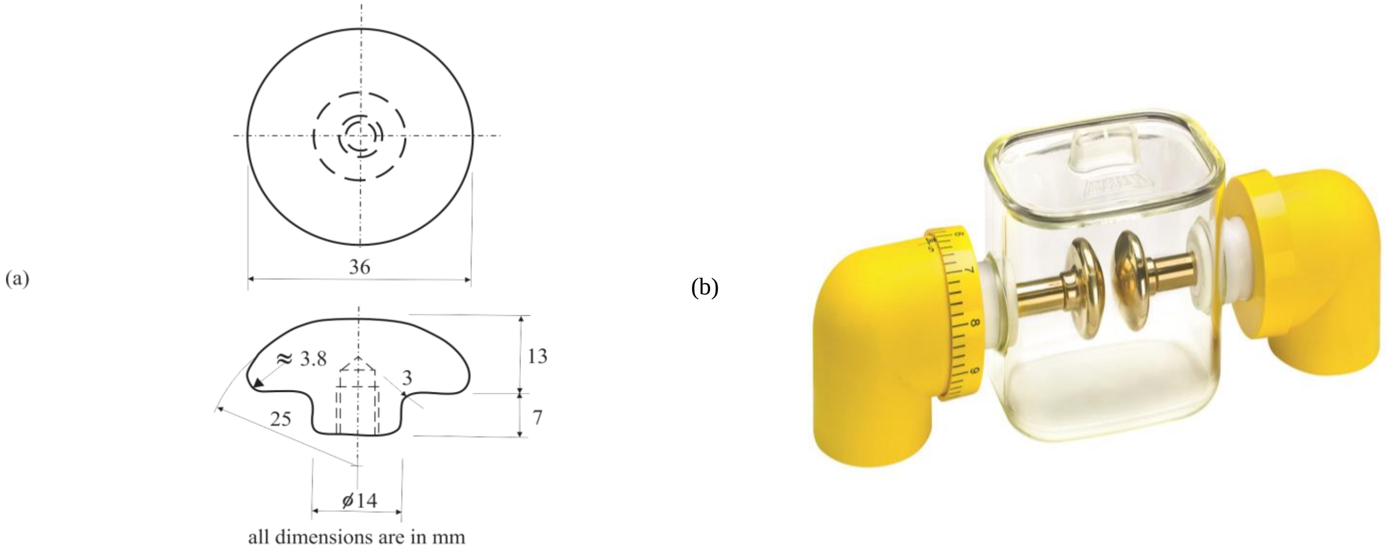

Fig. 20 (a) Electrode design having η = 0.97 for the measurement of electric strength of commercial liquid dielectrics according to VDE-0370. (b) An oil test cell, Courtesy BAUR GmbH

Cont…

- Power frequency ac breakdown voltage/field intensity of transformer oil samples having different moisture content were measured by Holle with increasing temperature according to the standard method of measurement.
- These measurement curves illustrate the effect of moisture content in oil samples on their breakdown strengths.

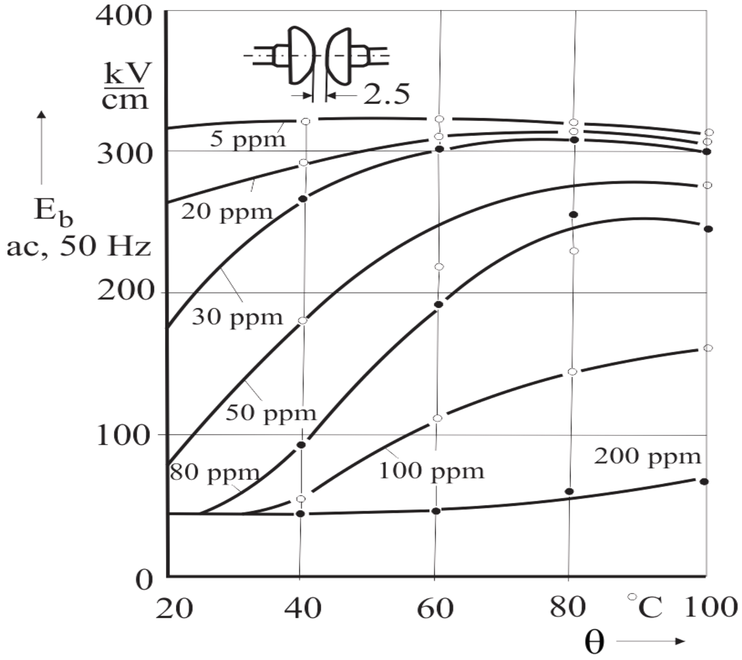

Fig. 21 ac power frequency breakdown field intensity (rms) with increasing temperature of a transformer oil having different water contents in ppm

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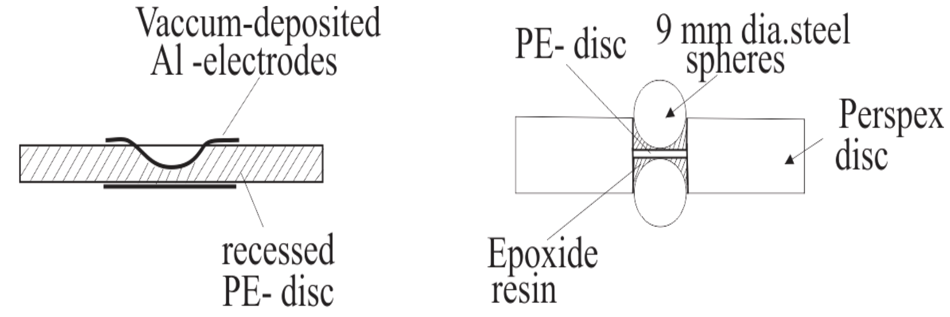
➢ Intrinsic strength of solid dielectrics

- In order to measure intrinsic strength, preparation of the test samples is the utmost sensitive part involving a considerable amount of precision techniques.
- Only two methods of preparation of samples for the measurement of intrinsic strength of solid dielectrics are seriously considered, the 'Recessed specimen' and the 'McKeown's technique' .
- The actual thickness of the specimen sample is reduced to about 50 µm.
- Extremely satisfactory at room temperatures for measuring the intrinsic strength of low-loss polymers.



a) Recessed specimen

b) Mc keown specimen

Fig. 21 Specimens for the measurements of intrinsic strength of solid dielectrics

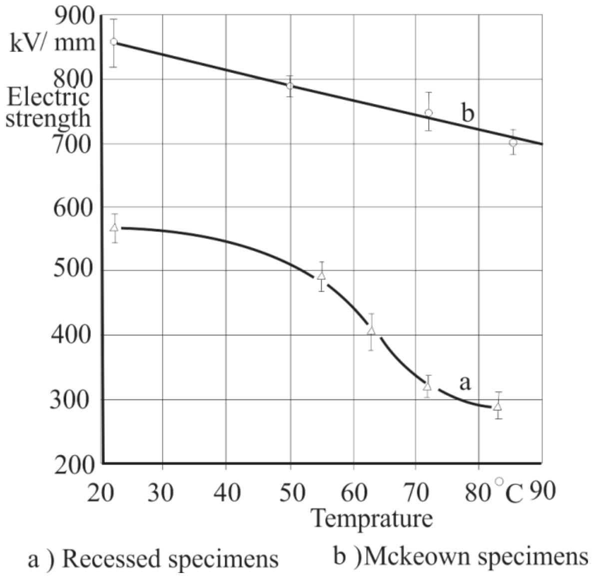


Fig. 22 Variation of intrinsic electric strength of PE specimens with temperature

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➢ Mechanism of breakdown in extremely non-uniform fields

- The mechanism of breakdown is more or less similar to that in gases, but the causes and sources of charge carriers are different.
- In case of solid dielectrics, a weakly nonuniform field is preferred by design .
- But, the pre-breakdown process generally begins at an extreme intensity or distortion of local field at the so called ‘weak point’.
- Under the action of these high local electric fields, the solid and liquid dielectrics may either lose their electrical insulating property locally leading to partial or complete disintegration.
- At field intensities closer to breakdown, massive ‘space charge’ injection in to the dielectric takes place by the electrodes causing considerable increase in ‘electric stress’ in the dielectric.
- Development of ‘electromechanical’ force under such conditions may also cause dielectric instability.
- It gives rise to the initiation and growth of conducting paths in solids and the phenomenon of ‘electro-hydrodynamic’ EHD motions in the liquid dielectrics.
- Such developments affect the breakdown strength adversely to a great extent.

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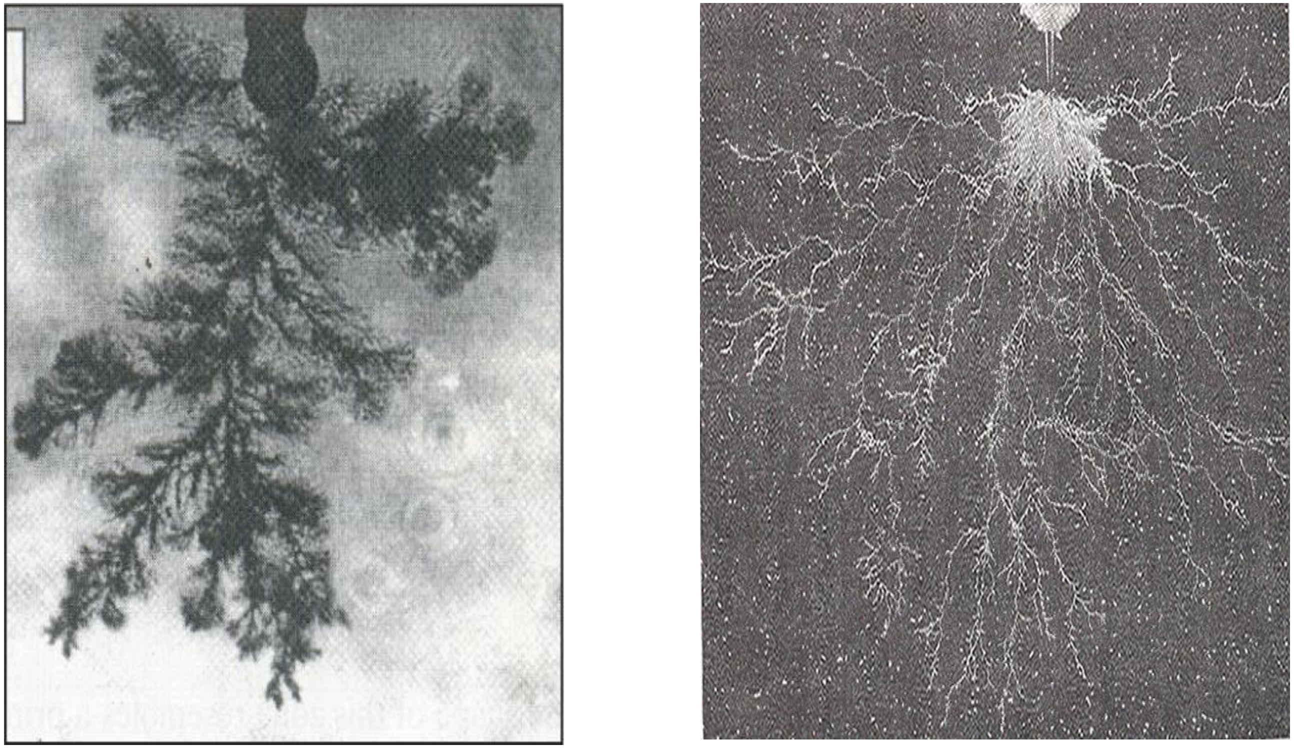

Fig. 23 (a) Development of a typical tree in transformer oil, Courtesy Dr. Torshin, (b) A bush type tree in Piacryl solid dielectric.

Summary

- Besides the electrical insulation, solid insulating materials provide mechanical support as a base for the live conductors carrying high voltage.
- The role of liquid dielectrics is basically to fill the porosity in the solid insulating materials and also conduct heat, generated in the conductors due to I^2R losses, towards the atmosphere by their movement.
- The knowledge of electric field dependent performance of insulating materials helps in designing a more economic, dependable and reliable insulation system in an apparatus.
- Unlike in the case of gaseous dielectrics, PB in solid dielectrics cause permanent damage to the insulation system, which could lead to its premature breakdown.
- Although the ‘intrinsic strength’ of solid and liquid dielectrics is found to be very high by researchers, their practical breakdown strengths are much lower.
- With the development in material manufacture technology, methods of application of insulating materials and equipment production techniques, the in-service maximum electric field intensity in high voltage apparatus equipment could be increased four folds in the past five decades.
- In this chapter, classification and dielectric properties of solid and liquid dielectrics have been presented.
- Partial breakdown and breakdown mechanism in solid and liquid dielectrics are discussed.

Thank You
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