UNIT-V

Breakdown Mechanism of Gaseous, Liquid and Solid Materials

The electrically live conductors are supported on insulating materials and sufficient air clearances are provided to avoid flashover or short circuits between the live parts of the system and the grounded structures.

In electrical engineering all the three media, viz. the gas, the liquid and the solid are being used

MECHANISM OF BREAKDOWN OF GASES

At normal temperature and pressure, the gases are excellent insulators. The current conduction is of the order of 10–10 A/cm2. This current conduction results from the ionisation of air by the cosmic radiation and the radioactive substances present in the atmosphere and the earth. At higher fields, charged particles may gain sufficient energy between collision to cause ionisation on impact with neutral molecules.
It is known that during an elastic collision, an electron loses little energy and rapidly builds up its kinetic energy which is supplied by an external electric field. On

This ionisation by radiation or photons involves the interaction of radiation with matter. Photoionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionisation energy and is represented as $A + hv \rightarrow A^+ + e$ *where A represents a neutral atom or* molecule in the gas and *hv the photon energy.*

Photoionization is a secondary ionization process and is essential in the streamer breakdown mechanism and in some corona discharges. If the photon energy is less than the ionization energy, it may still be absorbed thus raising the atom to a higher energy level. This is known as *photoexcitation.*

Let *A be the atom to* be ionized and *Bm the metastable, when Bm collides with A, ionization may take place according to the* reaction.

$A + Bm \rightarrow A^{+} + B + e$

Ionization by metastable interactions comes into operation long after excitation and it has been shown that these reactions are responsible for long-time lags observed in some gases.

Thermal Ionisation:

The term thermal ionisation in general applies to the ionizing actions of molecular collisions, radiation and electron collisions occurring in gases at high temperatures. When a gas is heated to high temperature, some of the gas molecules acquire high kinetic energy and these particles after collision with neutral particles ionize them and release electrons.

These electrons and other high-velocity molecules in turn collide with other particles and release more electrons. Thus, the gas gets ionized. In this process, some of the electrons may recombine with positive ions resulting into neutral molecule. Therefore, a situation is reached when under thermodynamic equilibrium condition the rate of new ion formation must be equal to the rate of recombination. Using this assumption, Saha derived an expression for the degree of ionization β in terms of the gas pressure and absolute temperature

as follows:

$$\frac{\beta^2}{1-\beta^2} = \frac{1}{p}\frac{(2\pi m_e)^{3/2}}{h}(KT)^{5/2}\, e^{-W/KT}$$

or

$$\frac{\beta^2}{1-\beta^2} = \frac{2.4\times10^{-4}}{p}\, T^{5/2}\, e^{-W_i/KT}$$

where p is the pressure in Torr, W_i the ionization energy of the gas, K the Boltzmann's constant, β the ratio n_i/n and n_i the number of ionized particles of total n particles.

TOWNSEND SECOND IONISATION COEFFICIENT

$$I = I_0 \, e^{\alpha x}$$

We have, taking log on both the sides.

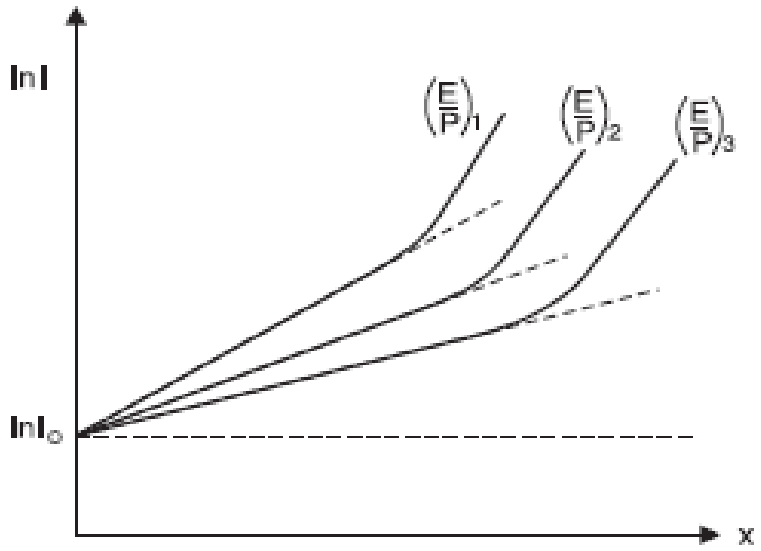


Fig. Variation of gap current with electrode spacing in uniform E

$$\ln I = \ln I_0 + \alpha x$$

This is a straight line equation with slope α and intercept ln *I0 as shown in Figure if for a given* pressure *p, E is kept constant.*

Let us consider the phenomenon of self-sustained discharge where the electrons are released from the cathode by positive ion bombardment.

Let n_0 *be the number of electrons released from the cathode by ultraviolet radiation, n+ the* number of electrons released from the cathode due to positive ion bombardment and *n the number of* electrons reaching the anode. Let ν, known as *Townsend second ionization co-efficient be defined as* the number of electrons released from cathode per incident positive ion, Then

$$n = (n_0 + n+)e^{\alpha d}$$

Now total number of electrons released from the cathode is (*n0 + n+) and those reaching the* anode are *n, therefore, the number of electrons released from the gas = n – (n0 + n+), and corresponding* to each electron released from the gas there will be one positive ion and assuming each positive ion releases ν effective electrons from the cathode then

$$n_+ = \nu\,[n - (n_0 + n_+)]$$

or $$n_+ = \nu n - \nu n_0 - \nu n_+$$

or $$(1 + \nu)\, n_+ = \nu(n - n_0)$$

or $$n_+ = \frac{\nu(n - n_0)}{1 + \nu}$$

Substituting n_+ in the previous expression for n, we have

$$n = \left[n_0 + \frac{\nu(n - n_0)}{1 + \nu} \right] e^{\alpha d} = \frac{(1 + \nu)\, n_0 + \nu n - \nu n_0}{1 + \nu}\, e^{\alpha d}$$

$$= \frac{n_0 + \nu n}{1 + \nu}\, e^{\alpha d}$$

or $$(n + \nu n) = n_0\, e^{\alpha d} + \nu n e^{\alpha d}$$

or $$n + \nu n - \nu n e^{\alpha d} = n_0 e^{\alpha d}$$

or $$n[1 + \nu - \nu e^{\alpha d}] = n_0 e^{\alpha d}$$

or $$n = \frac{n_0 e^{\alpha d}}{1 + \nu n(1 - e^{\alpha d})} = \frac{n_0 e^{\alpha d}}{1 - \nu\,(e^{\alpha d} - 1)}$$

In terms of current

$$I = \frac{I_0\, e^{\alpha d}}{1 - \nu(e^{\alpha d} - 1)}$$

Earlier Townsend derived an expression for current as

$$I = I_0 \frac{(\alpha - \beta)\, e^{(\alpha - \beta)d}}{\alpha - \beta\, e^{(\alpha - \beta)d}}$$

where β represents the number of ion pairs produced by positive ion travelling 1 cm path in the direction of field.

Townsend's original suggestion that the positive ion after collision with gas molecule releases electron does not hold good as ions rapidly lose energy in elastic collision and ordinarily are unable to gain sufficient energy from the electric field to cause ionization on collision with gas molecules
or atoms.

TOWNSEND BREAKDOWN MECHANISM

When voltage between the anode and cathode is increased, the current at the anode is given by

$$I = \frac{I_0 e^{\alpha d}}{1 - \nu (e^{\alpha d} - 1)}$$

The current becomes infinite if

$$1 - \nu(e^{\alpha d} - 1) = 0$$

or $$\nu(e^{\alpha d} - 1) = 1$$

or $$\nu e^{\alpha d} = 1$$

Since normally $$e^{\alpha d} \gg 1$$

the current in the anode equals the current in the external circuit. Theoretically the current becomes infinitely large under the above mentioned condition but practically it is limited by the resistance of the external circuit and partially by the voltage drop in the arc.

The condition $\nu e^{\alpha d} = 1$ *defines the condition* for beginning of spark and is known as the *Townsend criterion for spark formation or Townsend breakdown* criterion. Using the above equations, the following three conditions are possible.

(1) $ve^{\alpha d} = 1$

The number of ion pairs produced in the gap by the passage of arc electron avalanche is sufficiently large and the resulting positive ions on bombarding the cathode are able to release one secondary electron and so cause a repetition of the avalanche process. The discharge is then said to be self-sustained as the discharge will sustain itself even if the source producing *I0 is removed.*

Therefore, the condition $ve^{\alpha d} = 1$ *defines the threshold sparking condition.*

(2) $ve^{\alpha d} > 1$

Here ionization produced by successive avalanche is cumulative. The spark discharge grows more rapidly the more $ve^{\alpha d}$ *exceeds unity.*

(3) $ve^{\alpha d} < 1$

Here the current *I is not self-sustained i.e., on removal of the source the current I0 ceases to flow.*

THE SPARKING POTENTIAL—PASCHEN'S LAW

The Townsend's Criterion

$$\nu(e^{\alpha d} - 1) = 1$$

enables the evaluation of breakdown voltage of the gap by the use of appropriate values of α/p *and* v corresponding to the values E/p *when the current is too low to damage the cathode and also the space* charge distortions are minimum. A close agreement between the calculated and experimentally determined values is obtained when the gaps are short or long and the pressure is relatively low.

An expression for the breakdown voltage for uniform field gaps as a function of gap length and gas pressure can be derived from the threshold equation by expressing the ionization coefficient α/p *as* a function of field strength E *and gas pressure* p *i.e.,*

$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right)$$

Substituting this, we have

$$e^{f(E/p)\,pd} = \frac{1}{\nu} + 1$$

Taking ln both the sides, we have

$$f\left(\frac{E}{p}\right)pd = \ln\left[\frac{1}{\nu} + 1\right] = K \text{ say}$$

For uniform field $E = \frac{V_b}{d}$.

Therefore, $f\left(\frac{V_b}{pd}\right) \cdot pd = K$

or $$f\left(\frac{V_b}{pd}\right) = \frac{K}{pd}$$

or $$V_b = F\,(p.d)$$

This shows that the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and the gap length for a particular gas and electrode material. This relation is known as *Paschen's law.*

This relation does not mean that the breakdown voltage is directly proportional to product *pd even though it is found that for some region of the product pd the relation is linear i.e., the* breakdown voltage varies linearly with the product *pd.*

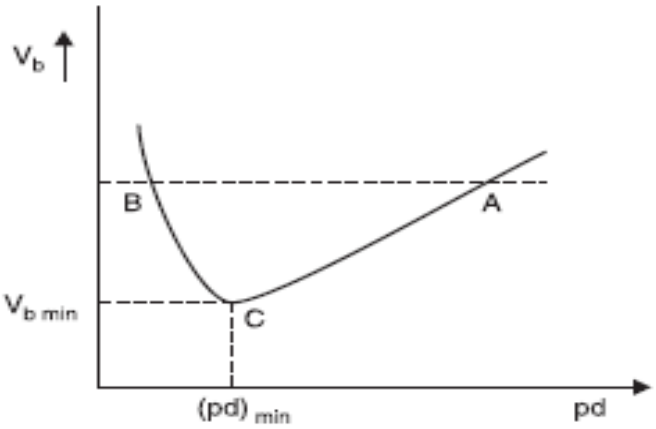


Fig. Paschen's law curve

Let us now compare Paschen's law and the Townsend's criterion for spark potential. We draw the experimentally obtained relation between the ionization coefficient α/p and the field strength $f(E/p)$ for a given gas. Fig. Here point $\left(\frac{E_b}{p}\right)_c$ represents the onset of ionization.

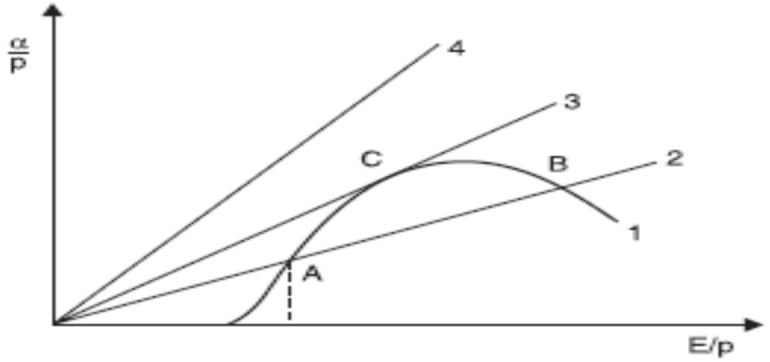


Fig. The relation between Townsend's criterion for spark = k and Paschen's criterion

Now the Townsend's criterion $\alpha d = K$ can be re-written as

$$\frac{\alpha}{p}\cdot\frac{V}{E}=\frac{K}{p} \quad \text{or} \quad \frac{\alpha}{p}=\frac{K}{V}\cdot\frac{E}{P}$$

This is equation to a straight line with slope equal to *K/V depending upon the value of K. The* higher the voltage the smaller the slope and therefore, this line will intersect the ionization curve at two points *e.g., A and B in Fig.*

Therefore, there must exist two breakdown voltages at a constant pressure (*p = constant), one corresponding to the small value of gap length i.e., higher E (E = V/d) i.e.,* point *B and the other to the longer gap length i.e., smaller E or smaller E/p i.e., the point A. At low* values of voltage *V the slope of the straight line is large and, therefore, there is no intersection between* the line and the curve 1.

This means no breakdown occurs with small voltages below Paschen's minimum irrespective of the value of *pd. The point C on the curve indicates the lowest breakdown voltage* or the minimum sparking potential. The spark over voltages corresponding to points *A, B, C.*

BREAKDOWN IN SOLID DIELECTRICS

Solid insulating materials are used almost in all electrical equipments, be it an electric heater or a 500 MW generator or a circuit breaker, solid insulation forms an integral part of all electrical equipments especially when the operating voltages are high.

The solid insulation not only provides insulation to the live parts of the equipment from the grounded structures, it sometimes provides mechanical support to the equipment.

The breakdown of solid dielectrics not only depends upon the magnitude of voltage applied but also it is a function of time for which the voltage is applied. Roughly speaking, the product of the breakdown voltage and the log of the time required for breakdown is almost a constant *i.e.,*

$$V_b = 1n\ t_b = constant$$

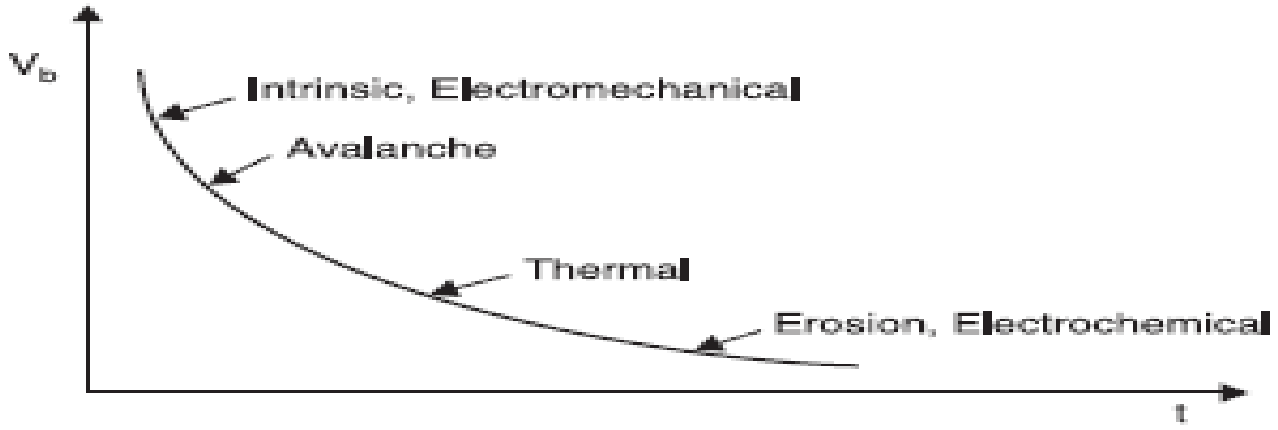


Fig. Variation of V_b with time of application

The dielectric strength of solid materials is affected by many factors viz. ambient temperature, humidity, duration of test, impurities or structural defects whether a.c., d.c. or impulse voltages are being used, pressure applied to these electrodes etc

The various mechanisms are:

(*i) Intrinsic Breakdown*
(*ii) Electromechanical Breakdown*
(*iii) Breakdown Due to Treeing and Tracking*
(*iv) Thermal Breakdown*
(*v) Electrochemical Breakdown*

Intrinsic Breakdown

Fig. Specimen designed for intrinsic breakdown

If the dielectric material is pure and homogeneous, the temperature and environmental conditions suitably controlled and if the voltage is applied for a very short time of the order of 10–8 second, the dielectric strength of the specimen increases rapidly to an upper limit known as *intrinsic dielectric strength.*

The intrinsic strength, therefore, depends mainly upon the structural design of the material *i.e., the* material itself and is affected by the ambient temperature as the structure itself might change slightly by temperature condition. In order to obtain the intrinsic dielectric strength of a material, the samples are so prepared that there is high stress in the centre of the specimen and much low stress at the corners

The intrinsic breakdown is obtained in times of the order of 10–8 sec. and, therefore, has been considered to be electronic in nature. The stresses required are of the order of one million volt/cm.

The intrinsic strength is generally assumed to have been reached when electrons in the valance band gain sufficient energy from the electric field to cross the forbidden energy band to the conduction band.
In pure and homogenous materials, the valence and the conduction bands are separated by a large energy gap at room temperature, no electron can jump from valance band to the conduction band.

The conductivity of pure dielectrics at room temperature is, therfore, zero.

In an amorphous dielectric the energy gained by electrons from the electric field is much more than they can transfer it to the lattice. Therefore, the temperature of electrons will exceed the lattice temperature and this will result into increase in the number of trapped electrons reaching the conduction band and finally leading to complete breakdown.

Electromechanical Breakdown

When a dielectric material is subjected to an electric field, charges of opposite nature are induced on the two opposite surfaces of the material and hence a force of attraction is developed and the specimen is subjected to electrostatic compressive forces and when these forces exceed the mechanical withstand strength of the material, the material collapses.

If the initial thickness of the material is *d0 and is* compressed to a thickness *d under the applied voltage V then the compressive stress developed due to* electric field is

$$F = \frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2}$$

where ε_r is the relative permittivity of the specimen. If γ is the Young's modulus, the mechanical compressive strength is

$$\gamma \ln \frac{d_0}{d}$$

Equating the two under equilibrium condition, we have

$$\frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2} = \gamma \ln \frac{d_0}{d}$$

or

$$V^2 = d^2 \cdot \frac{2\gamma}{\varepsilon_0\varepsilon_r} \ln \frac{d_0}{d} = Kd^2 \ln \frac{d_0}{d}$$

Differentiating with respect to d, we have

$$2V\frac{dV}{dd} = K\left[2d \ln \frac{d_0}{d} - d^2 \cdot \frac{d}{d_0} \cdot \frac{d_0}{d^2}\right] = 0$$

or $$2d \ln \frac{d_0}{d} = d$$

or $$\ln \frac{d_0}{d} = \frac{1}{2}$$

or $$\frac{d}{d_0} = 0.6$$

For any real value of voltage V, the reduction in thickness of the specimen can not be more than 40%. If the ratio V/d at this value of V is less than the intrinsic strength of the specimen, a further increase in V shall make the thickness unstable and the specimen collapses. The highest apparent strength is then obtained by substituting $d = 0.6\, d_0$ in the above expressions.

$$\frac{V}{d} = \sqrt{\frac{2\gamma}{\varepsilon_0 \varepsilon_r} \ln 1.67} \quad \text{or} \quad \frac{V}{d_0} = E_a = 0.6 \left[\frac{\gamma}{\varepsilon_0 \varepsilon_r} \right]^{1/2}$$

The above equation is approximate only as γ depends upon the mechanical stress. The possibility of instability occuring for lower average field is ignored *i.e.*, the effect of stress concentration at irregularities is not taken into account.

Breakdown due to Treeing and Tracking

whenever a solid material has some impurities in terms of some gas pockets or liquid pockets in it the dielectric strength of the solid will be more or less equal to the strength of the weakest impurities.

Suppose some gas pockets are trapped in a solid material during manufacture, the gas has a relative permittivity of unity and the solid material ε*r, the electric field in the gas will be εr times the field in the* solid material. As a result, the gas breaks down at a relatively lower voltage.

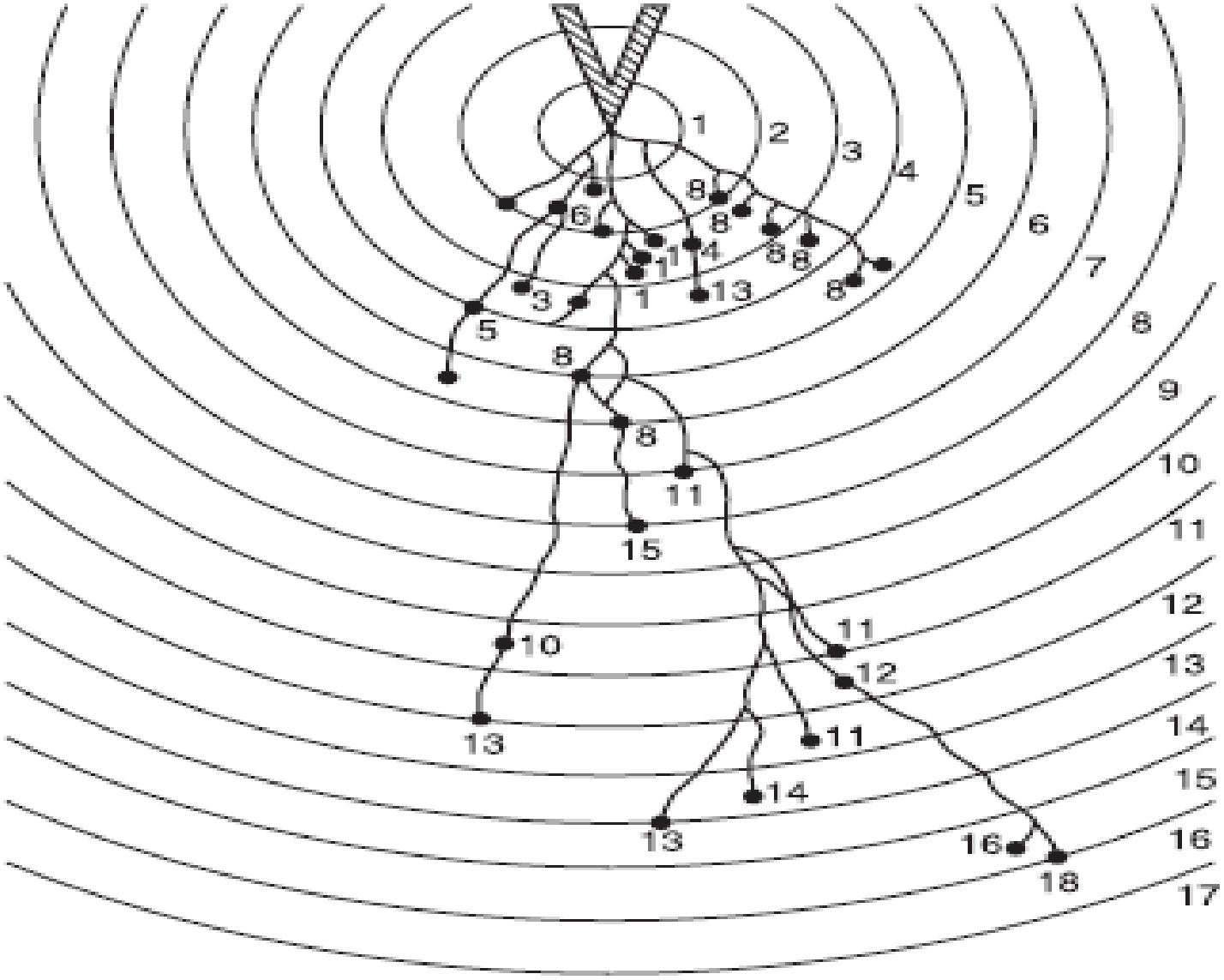
The charge concentration here in the void will make the field more non-uniform. The charge concentration in such voids is found to be quite large to give fields of the order of 10 MV/cm which is higher than even the intrinsic breakdown.

The treeing phenomenon can be readily demonstrated in a laboratory by applying an impulse voltage between point plane electrodes with the point embedded in a transparent solid dielectric such as perspex.

The treeing phenomenon can be observed in all dielectric wherever non-uniform fields prevail.

Suppose we have two electrodes separated by an insulating material and the assembly is placed in an outdoor environment. Some contaminants in the form of moisture or dust particles will get deposited on the surface of the insulation and leakage current starts between the electrode through the contaminants say moisture. The current heats the moisture and causes breaks in the moisture films.

Therefore, tracking is the formation of a permanent conducting path usually carbon across the surface of insulation. For tracking to occur, the insulating material must contain organic substances.
For this reason, for outdoor equipment, tracking severely limits the use of insulation having organic substances. The rate of tracking can be slowed down by adding filters to the polymers which inhibit carbonization.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Electrochemical Breakdown

Whenever cavities are formed in solid dielectrics, the dielectric strength in these solid specimen decreases. When the gas in the cavity breaks down, the surfaces of the specimen provide instantaneous anode and cathode.

Some of the electrons dashing against the anode with sufficient energy shall break the chemical bonds of the insulation surface. Similarly, positive ions bombarding against the cathode may increase the surface temperature and produce local thermal instability. Similarly, chemical degradation may also occur from the active discharge products *e.g., O3, NO2 etc. formed in air.*

The net effect of all these processes is a slow erosion of the material and a consequent reduction in the thickness of the specimen.

Normally, it is desired that with ageing, the dielectric strength of the specimen should not decrease. However, because of defects in manufacturing processes and/or design, the dielectric strength decreases with time of voltage application or even without voltage application and in many cases; the decrease in dielectric strength (*Eb) with time follows the following empirical relation.*

$$t\, Eb^{n} = constant$$

where the exponent *n depends upon the dielectric material, the ambient temperature humidity and the* quality of manufacture. This is the main reason why high a.c. voltage testing is not recommended.

Solid Dielectrics Used in Power Apparatus

The main requirements of the insulating materials used for power apparatus are:

1. High insulation resistance
2. High dielectric strength
3. Good mechanical properties *i.e., tenacity and elasticity*
4. It should not be affected by chemicals around it
5. It should be non-hygroscopic because the dielectric strength of any material goes very much down with moisture content

BREAKDOWN IN LIQUID DIELECTRICS

Liquid dielectrics are used for filling transformers, circuit breakers and as impregnates in high voltage cables and capacitors.

For transformer, the liquid dielectric is used both for providing insulation between the live parts of the transformer and the grounded parts besides carrying out the heat from the transformer to the atmosphere thus providing cooling effect.

For circuit breaker, again besides providing insulation between the live parts and the grounded parts, the liquid dielectric is used to quench the arc developed between the breaker contacts. The liquid dielectrics mostly used are petroleum oils.

The three most important properties of liquid dielectric are
(*i) The dielectric strength (ii) The* dielectric constant and (*iii) The electrical conductivity.*
Other important properties are viscosity, thermal
stability, specific gravity, flash point etc.

The most important factors which affect the dielectric strength of oil are the, presence of fine water droplets and the fibrous impurities. The presence of even 0.01% water in oil brings down the dielectric strength to 20% of the dry oil value and the presence of fibrous impurities brings down the dielectric strength much sharply.

The main consideration in the selection of a liquid dielectric is its chemical stability. The use of liquid dielectric has brought down the size of equipment tremendously.

Table . Dielectric properties of some liquids

S.No.	*Property*	*Transformer Oil*	*Capacitor Oil*	*Cable Oil*	*Silicone Oil*
1.	Relative permittivity 50 Hz	2.2 – 2.3	2.1	2.3 – 2.6	2.7 – 3.0
2.	Breakdown strength at 20°C 2.5 mm 1 min	12 kV/mm	18 kV/mm	25 kV/mm	35 kV/mm
3.	(*a*) Tan δ 50 Hz	10^{-3}	2.5×10^{-4}	2×10^{-3}	10^{-3}
	(*b*) 1 kHz	5×10^{-4}	10^{-4}	10^{-4}	10^{-4}
4.	Resistivity ohm-cm	$10^{12} – 10^{13}$	$10^{13} – 10^{14}$	$10^{12} – 10^{13}$	2.5×10^{14}
5.	Maximum permissible water content (ppm)	50	50	50	< 40
6.	Acid value mg/gm of KOH	NIL	NIL	NIL	NIL
7.	Sponification mg of KOH/gm of oil	0.01	0.01	0.01	< 0.01
8.	Specific gravity at 20°C	0.89	0.89	0.93	1.0–1.1

Electronic Breakdown

Once an electron is injected into the liquid, it gains energy from the electric field applied between the electrodes. It is presumed that some electrons will gain more energy due to field than they would lose during collision.

These electrons are accelerated under the electric field and would gain sufficient energy to knock out an electron and thus initiate the process of avalanche.

The threshold condition for the beginning of avalanche is achieved when the energy gained by the electron equals the energy lost during ionization (electron emission) and is given by

$$e \lambda E = Chv$$

where λ is the mean free path, *hv is the energy of ionization and C is a constant.*

Cavity Breakdown

It has been observed experimentally that the dielectric strength of liquid depnds upon the hydrostatic pressure above the gap length. The higher the hydrostatic pressure, the higher the electric strength, which suggests that a change in phase of the liquid is involved in the breakdown process. In fact,smaller the head of liquid, the more are the chances of partially ionized gases coming out of the gap and higher the chances of breakdown. This means a kind of vapour bubble formed is responsible for the breakdown.

The following processes might lead to formation of bubbles in the liquids:
(*i) Gas pockets on the surface of electrodes.*
(*ii) Due to irregular surface of electrodes, point charge concentration may lead to corona discharge,*
thus vapourizing the liquid.
(*iii) Changes in temperature and pressure.*
(*iv) Dissociation of products by electron collisions giving rise to gaseous products.*

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

Where E_0 is the field in the liquid in absence of the bubble. The bubble under the influence of the electric field E_0 elongates keeping its volume constant. When the field E_b equals the gaseous ionization field, discharge takes place which will lead to decomposition of liquid and breakdown may follow.

A more accurate expression for the bubble breakdown strength is given as

$$E_b = \frac{1}{\varepsilon_2 - \varepsilon_1}\left\{\frac{2\pi\sigma(2\varepsilon_2 + \varepsilon_1)}{r}\left[\frac{\pi}{4}\sqrt{\frac{V_b}{2rE_0} - 1}\right]\right\}^{1/2}$$

where σ is the surface tension of the liquid, ε_2 and ε_1 are the permittivities of the liquid and bubble, respectively, r the initial radius of the bubble and V_b the voltage drop in the bubble. From the expression it can be seen that the breakdown strength depends on the initial size of the bubble which of course depends upon the hydrostatic pressure above the bubble and temperature of the liquid.

Electroconvection Breakdown

When a highly pure insulating liquid is subjected to high voltage, electrical conduction results from charge carriers injected into the liquid from the electrode surface.
The resulting space charge gives rise to coulombic forces which under certain conditions causes hydrodynamic instability, yielding convecting current. It has been shown that the onset of instability is associated with a critical voltage. As the applied voltage approaches the critical voltage, the motion at first exhibits a structure of hexagonal cells and as the voltage is increased further the motion becomes turbulent. Thus, interaction between the space charge and the electric field gives rise to forces creating an eddy motion of liquid. It has been shown that when the voltage applied is near to breakdown value,

the speed of the eddy motion is given by $v_e = \sqrt{\varepsilon_2 / \rho}$ where ρ is the density of liquid. In liquids, the ionic drift velocity is given by

$$v_d = KE$$

where K is the mobility of ions.

Let $$M \frac{v_e}{v_d} = \sqrt{\frac{\varepsilon_2}{\rho}} / KE$$

The ratio M is usually greater than unity and sometimes much greater than unity (Table 1.4).