High Voltage Engineering – BEE515A

Module-1

Prepared By,

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Course Outline

Course Code	Course Title	Core/Elective	Prerequisite	Contact Hours			Total Hrs/ Sessions
				L	T	P	
BEE515A	High Voltage Engineering	Core	-	4	-	-	40

Objectives of Today's Session

- Time Lag of Breakdown
- Paschen's Law
- Derive an expression for Paschen's Law
- Breakdown in Non-Uniform Fields and Corona Discharges

Time Lag of Breakdown

- Time difference in the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself
- Townsend criterion for breakdown is satisfied only if at least one electron is present in the gap between the electrodes
- With Rapidly varying voltage of short duration (≈10-6 s), the initiatory electron may not be present in the gap
- The breakdown cannot occur due to not available free electron

Classification of Time Lag of Breakdown

- Statistical time-lag(ts)
- Formative time-lag(tf)
- Total time-lag (t)

Classification of Time Lag of Breakdown

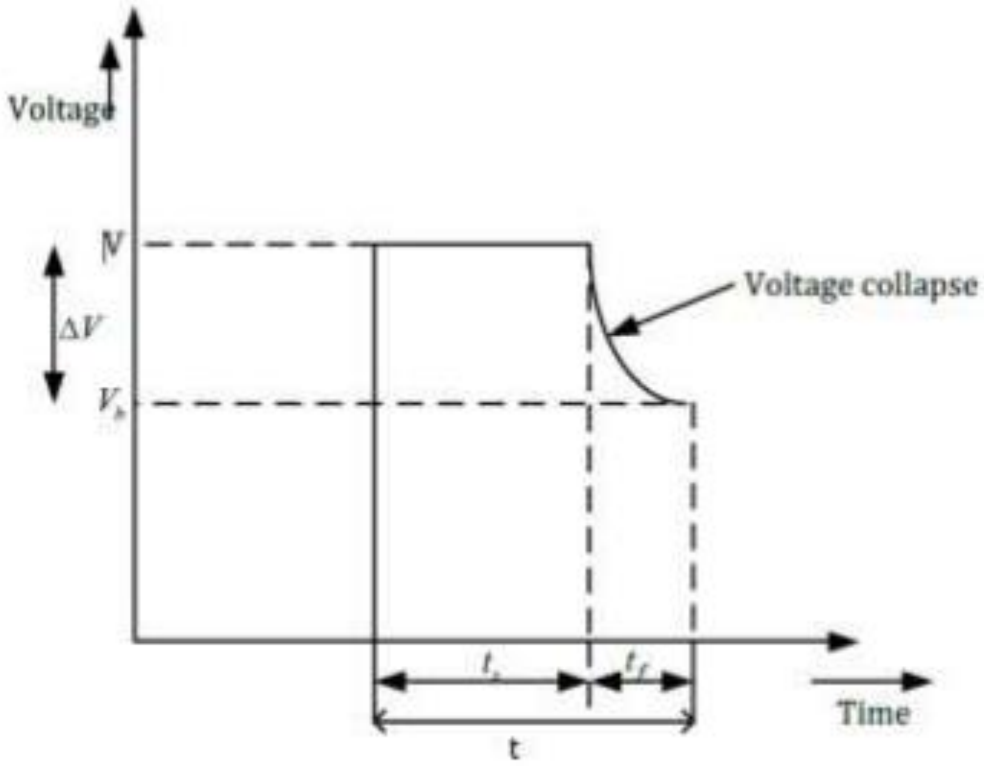
- **Statistical time-lag(ts):**
- It is defined as the time lapsed between the application of voltage sufficient to cause breakdown and the appearance of initiating electron is called as statistical time lag.

1. depends upon the amount of pre-ionization present in the gap.
2. This in turn depends on the size of the gap and the quantity of radiation that produces the primary electrons.
3. The techniques generally used for irradiating the gaps include ultraviolet radiation, radioactive materials and light sources.

Classification of Time Lag of Breakdown

- **Formative time-lag(tf):**
- After the appearance of electron, the time tf required for the ionization process to develop fully to cause to the breakdown of gap is called as formative time-lag.
- depend mostly on the mechanism of the avalanche growth in the gap.
- Total time-lag (t): is define as the sum total of Statistical time-lag and formative time-lag T= ts + tf

Breakdown with a step function voltage pulse



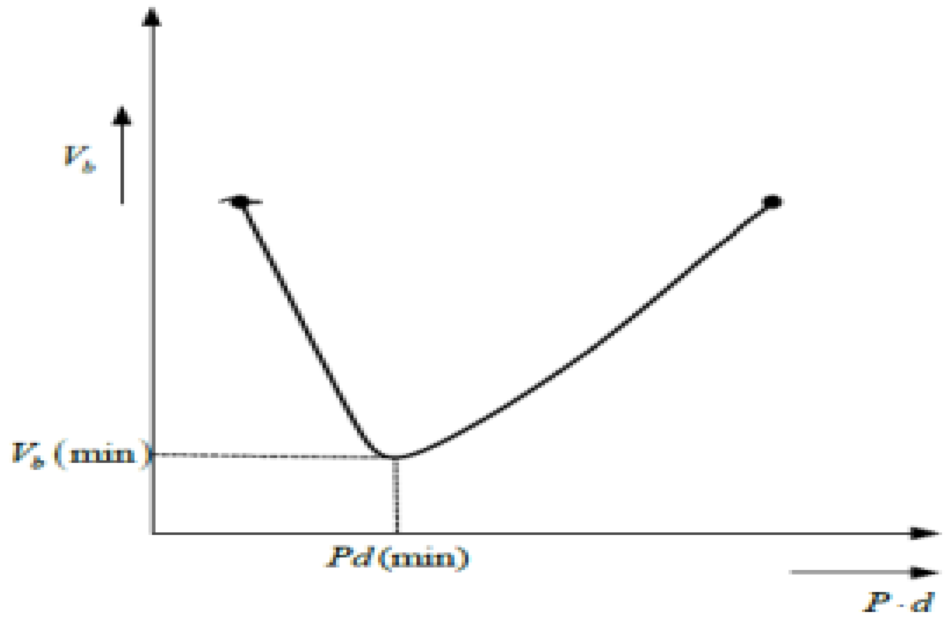
Paschen’s Law

- Paschen’s theory is one of the most important theories related to breakdown of gaseous insulating material.
- It is widely used in the design of extra high voltage equipments.
- The gas to be used in the apparatus is matched and studied with operating voltage of the system.
- The breakdown voltage must be greater than the operating voltage of the system.

Paschen's Law

- Paschen's Law: The law essentially states that,

At higher pressures (above a few torr) the breakdown characteristics of a gap are function (generally not linear) of the product of the gas pressure(p) and gap length(d), usually written as V= f(P.d)



Observations of Paschen's Law

1. Paschen, a scientist studied the breakdown voltage of various gases between the parallel metal plates as the pressure & distance where varied.

2. Paschen found that Voltage is a function only of the product of the pressure & gap length(distance).

3. The equation V= f(pd) is called as Paschen's law

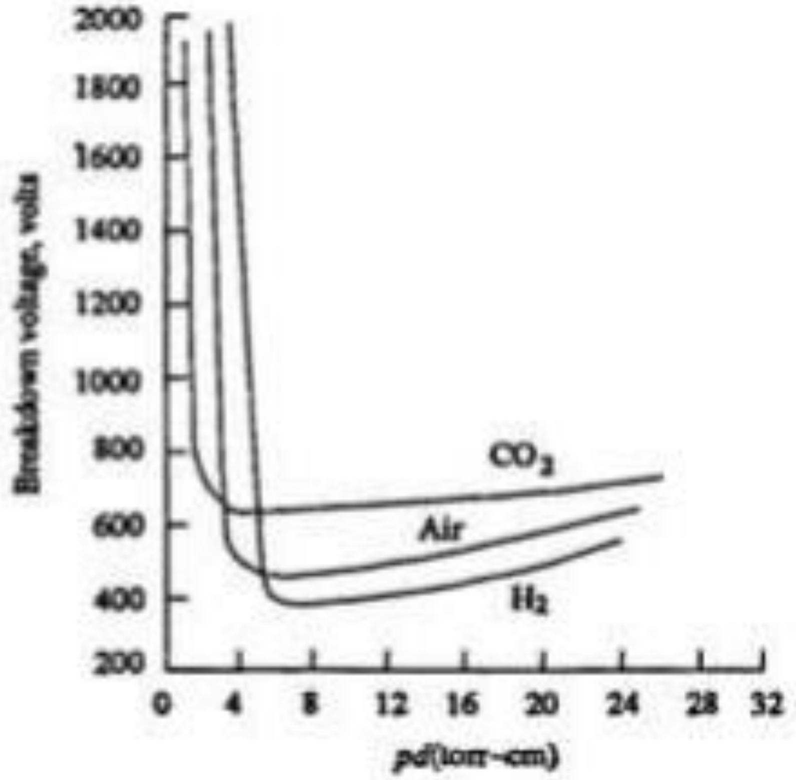
4. At higher pressure and air gap length, the breakdown voltage is approximately proportional to product of pressure & air gap.

5. The curve which shows the voltage versus the pressure gap length is called Paschen's curve.

6. Paschen law will be helpful for finding the minimum breakdown voltage of a gas.
7. The minimum pd value for air is 0.567 and 367V.

Observations of Paschen's Law

Paschen's Curve:



Observations of Paschen's Law

- Application – based on Paschen's law, we can find the minimum sparking voltage (Breakdown voltage)of various gas

Minimum Sparking Potential For Various Gases

Gas	V_s min (V)	pd at V_s min (torr-cm)
Air	327	0.567
Argon	137	0.9
H_2	273	1.15
Helium	156	4.0
CO_2	420	0.51
N_2	251	0.67
N_2O	418	0.5
O_2	450	0.7
SO_2	457	0.33
H_2S	414	0.6

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Mathematical Analysis

- From Townsends first Ionization Constant,

That is $$\frac{\alpha}{p} = f[E/p]$$

$$\therefore \alpha = f[E/p] \times p$$

And Townsend's criterion for Breakdown is

$$\gamma\left[e^{\alpha d} - 1\right] = 1$$

$$\gamma e^{\alpha d} - \gamma = 1$$

$$\gamma e^{\alpha d} = 1 + \gamma$$

$$e^{\alpha d} = \frac{1+\gamma}{\gamma} = \left(1 + \frac{1}{\gamma}\right)$$

$$\ln\left(e^{\alpha d}\right) = \ln\left(1 + \frac{1}{\gamma}\right)$$

$$\alpha \cdot d = \ln\left(1 + \frac{1}{\gamma}\right)$$

$$f\left[\frac{E}{p}\right] \cdot p \cdot d = \ln\left(1 + \frac{1}{\gamma}\right) = K$$

$$f\left(\frac{V_b}{p \cdot d}\right) \cdot p \cdot d = K \quad \left(\because E = \frac{V_b}{d}\right)$$

$$f\left(\frac{V_b}{p \cdot d}\right) = \frac{K}{p \cdot d}$$

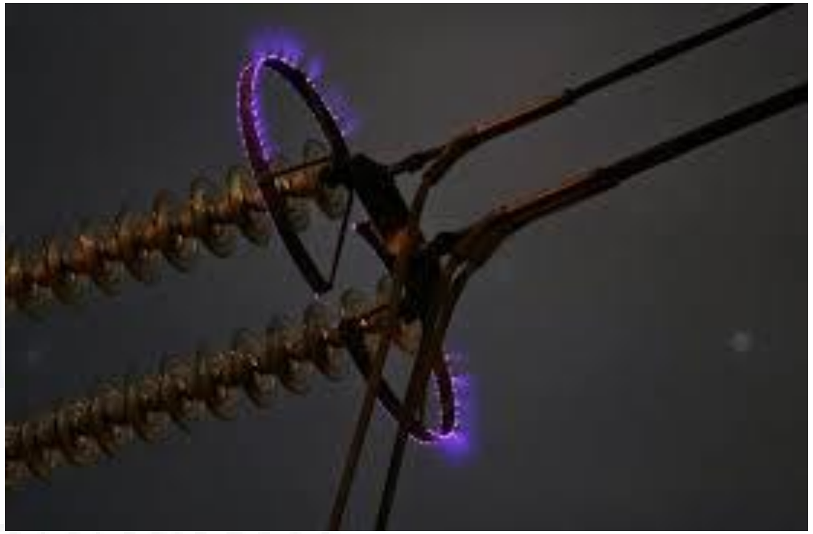
$$V_b = f(p \cdot d)$$

Penning Effect

- Paschen's law does not hold good for many gaseous mixtures.
- A typical example is that of mixture of Argon in neon.
- A small percentage of Argon in Neon reduces the dielectric strength of pure Neon.
- The dielectric strength is smaller than the dielectric strengths of either pure Neon or Argon.
- The lowering of dielectric strength is due to the fact that the lowest excited stage of neon is meta-stable and its excitation potential (16eV) is about 0.9eV greater than the ionization potential of Argon
- The meta-stable atoms have a long life in neon gas, and on hitting Argon atoms there is a very high probability of ionizing them.
- This phenomenon is known as **Penning Effect**.

Breakdown in Non-Uniform Fields and Corona Discharges

- Visual and audible discharge
- The corona will occur when the strength of the electric field around a conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects.
- It is often seen as a bluish (or other color) glow in the air adjacent to pointed metal conductors carrying high voltages, and emits light.
- Potential difference between two electrodes should be greater than threshold value (30kV).



Breakdown in Non-Uniform Fields and Corona Discharges

- This phenomenon is always accompanied by a hissing noise, and the air surrounding.
- Corona is responsible for considerable loss of power from high voltage transmission lines,
- it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges.
- Corona also gives rise to radio interference.

Breakdown in Non-Uniform Fields and Corona Discharges

- The voltage gradient required to produce visual a.c. corona in air at a conductor surface, called the corona inception field, can be approximately given for the case of parallel wires of radius r as

$$E_w = 30md\left[1+\frac{0.301}{\sqrt{dr}}\right].$$

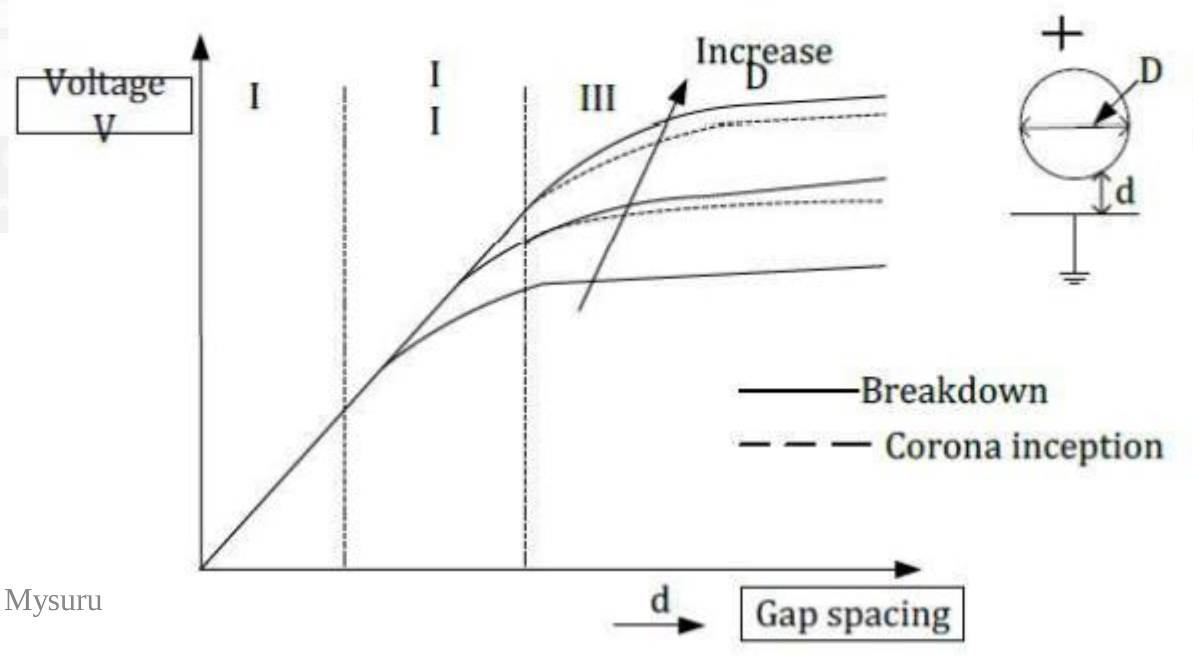
- For a coaxial cylinders, the inner cylinder of radius r

$$E_c = 31md\left[1+\frac{0.308}{\sqrt{dr}}\right].$$

- m → Surface irregularity factor = 1 for highly polished smooth wires
- d → relative air density correction factor given by $d = \frac{0.392b}{(273+T)}$

Breakdown in Non-Uniform Fields and Corona Discharges

- Zone-I : Field is Uniform, Breakdown depends on gap spacing
- Zone-II: Field is non Uniform, the breakdown voltage depends on both the sphere diameter and the spacing
- Zone -III: Field is non-uniform and the breakdown is preceded by corona and is controlled only by the spacing and corona inception voltage depends on sphere diameter



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Results:

- Power loss
- Hissing noise
- Chemical activities

Factors affecting corona :

- Air density & Humidity are inversely proportional to corona discharge.
- Surface conduction is proportional to corona.

Problems associated with corona:

- Nitric acid & Nitrogen oxide (NOx) production
- Electromagnetic interference
- Audible noise
- Insulation losses

Solid Dielectrics

Solid dielectrics are commonly used in all kinds of electric circuit and devices.

• Provide insulation for current carrying conductors.

Properties of good solid dielectric material

1. Good mechanical strength
2. Free from gaseous inclusion
3. Free from moisture
4. Resistant to thermal and chemical deterioration
5. Low dielectric loss

Types of breakdown mechanism in Solid Dielectrics

1. Intrinsic or ionic breakdown
   - Electronic breakdown
   - Avalanche breakdown

2. Electromechanical breakdown

3. Failure due to treeing and tracking

4. Thermal breakdown

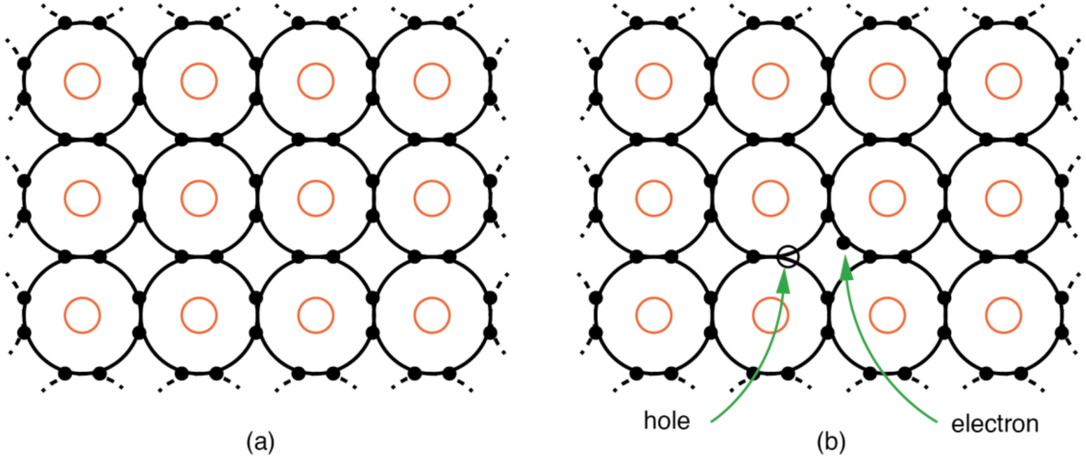
5. Electrochemical breakdown

6. Breakdown due to internal discharges

Types of breakdown mechanism in Solid Dielectrics

1. Intrinsic or ionic breakdown:

- Small number of conduction electrons (free electrons) present in the solid dielectrics
- Small number of impurities & Structural imperfection of dielectric material are responsible for intrinsic breakdown.
- Presence of free electrons which are capable of migration through the lattice of the dielectrics participate in the conduction process.



Types of Intrinsic breakdown

- 1. Electronic breakdown
- 2. Avalanche breakdown

Types of breakdown mechanism in Solid Dielectrics

i) Electronic breakdown

- Due to the presence of large density free electrons in a solid dielectrics
- Whenever a high voltage is applied, collision between large free electrons will take place.
- As a result, electrons gain energy from the electric field and cross the forbidden energy gap from the valance to the conduction band.

ii) Avalanche breakdown:

- Similar to breakdown in gaseous dielectric
- It is a Form of electric current multiplication that can allow very large currents within materials & causes dielectric breakdown

Types of breakdown mechanism in Solid Dielectrics

Steps involved in Avalanche breakdown:

- Formation of avalanche creates space charge (collection of charge or cloud of charge).
- Space charge leads additional electric field.
- The electric field enhance the growth of new avalanche.
- Ionized region grows quickly & expand.
- When the energy gained by the electrons greater than lattice ionization potential formation of avalanche takes palace. (Condition for avalanche breakdown)
- Breakdown occur when avalanche exceeds critical size & leading to formation of many avalanche

Types of breakdown mechanism in Solid Dielectrics

2. Electromechanical breakdown :

(i) solid dielectrics are subjected to high electric fields

(ii) electrostatic compressive forces which can exceed the mechanical compressive strength.

Consider a solid dielectric material

- The thickness of solid dielectric material=do
- Applied voltage = V
- Thickness after the applied voltage = d . (i.e material is compressed)

Types of breakdown mechanism in Solid Dielectrics

2. Electromechanical breakdown :

$$\varepsilon_0 \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \qquad (1)$$

- Equation (1) represents electrically developed compressive stress in equilibrium.

where Y is the Young's modulus.

From (1) find the voltage V^2

$$V^2 = d^2\left[\frac{2Y}{\varepsilon_0 \varepsilon_r}\right] \ln\left[\frac{d_0}{d}\right] \qquad (2)$$

- Usually, mechanical instability occurs when

d/do = 0.6 or do/d= 1.67 **(3)**

- ***Substitute (3) in (2)***

Max Value of Electric field before breakdown is given by

$$E_{max} = \frac{V}{d_0}$$

$$E_{max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}}$$

Types of breakdown mechanism in Solid Dielectrics

3. Thermal breakdown :

- Most of the insulation failures in high voltage power apparatus occur due to thermal breakdown.
- When an electric field is applied to a dielectric, conducts current, however small it may be, flows through the material.
- The current heats up the specimen and the temperature rises.
- The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces.

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3. Thermal breakdown :

Mathematical Expression:

The heat generated under d.c. stress E is given as

$$W_{d.c.} = E^2\sigma \quad \text{W/cm}^3 \qquad (1)$$

Where 'σ' is the D.C. conductivity of the specimen.

Under A.C. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \quad \text{W/cm}^3 \qquad (2)$$

$f =$ frequency in Hz,

$\delta =$ loss angle of the dielectric material, and

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3. Thermal breakdown :

Mathematical Expression:

The heat dissipated (WT) is given by

$$W_T = C_V \frac{dT}{dt} + \text{div}\,(K \text{ grad } T) \quad (3)$$

where, $C_V =$ specific heat of the specimen,

$T =$ temperature of the specimen,

$K =$ thermal conductivity of the specimen, and

$t =$ time over which the heat is dissipated.

- Normally Wac or Wdc equals to WT
- Breakdown occur when Wac or Wdc >WT

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3. Thermal breakdown :

Thermal Breakdown Stresses in Dielectrics

Material	Maximum thermal breakdown stress in MV/cm	
	d.c.	a.c.
Muscovite mica	24	7.18
Rock salt	38	1.4
High grade porcelain	—	2.8
H.V. Steatite	—	9.8
Quartz—perpendicular to axis	1200	—
parallel to axis	66	—
Capacitor paper	—	3.4–4.4
Polythene	—	3.5
Polystryene	—	5.0

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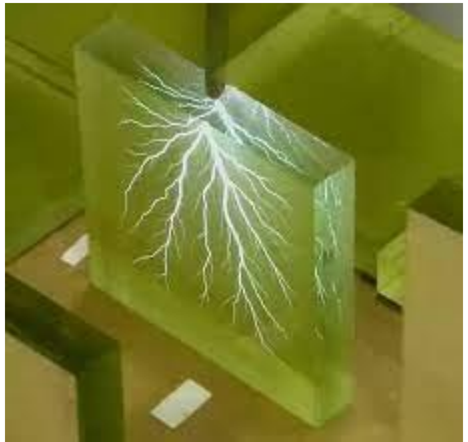
Breakdown due to treeing & tracking

- breakdown occurs when a solid dielectric material subjected to electric stress for a long time.
- Presence of conducting path inside solid dielectric material due to moisture.
- leakage current passes through the conducting path finally leading to the formation of a spark.
- Insulation deterioration occurs as a result of these sparks, sparks erodes the surface, generates heat & surface becomes dry.
- The spreading of spark channels said to be **tracking**, in the form of the branches of a tree is called **treeing**

Breakdown due to treeing & tracking

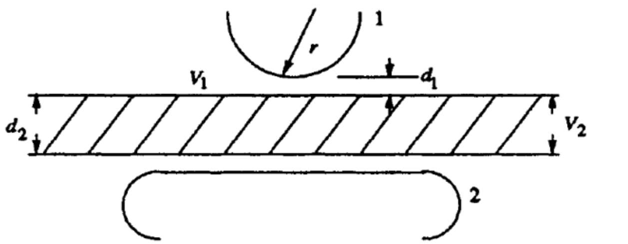
- As time passes, breakdown channels spread through the insulation in an irregular "tree" like fashion leading to the formation of conducting channels. This kind of channeling is called treeing.
- Usually, tracking occurs even at very low voltages of the order of about 100V, whereas treeing requires high voltage.
- It is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes.
- This phenomena happening the layers of Bakelite, paper, cables and similar dielectrics built of laminates.



Breakdown due to treeing & tracking

1. When a dielectric material lies between two electrodes as shown in Fig. There is a possibility for two different dielectric media, the air and the dielectric, to come in series.

Breakdown due to treeing & tracking



Arrangement for study of treeing phenomena. 1 and 2 are electrodes

2. The voltages across the two media are as shown (V_1 across the air gap, and V_2 across the dielectric). The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2}$$

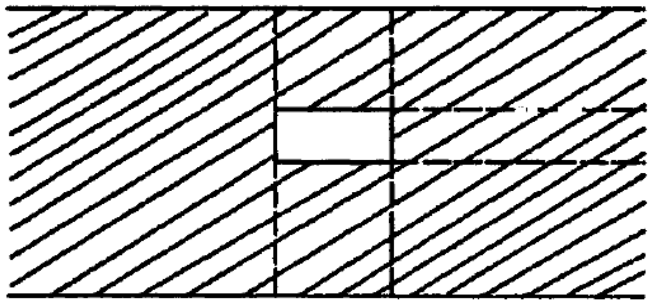
Prevention of treeing & tracking??

1. Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment.
2. The materials chosen should be resistant to tracking.
3. Usage of moisture repellant greases. But this needs frequent cleaning and regressing.
4. Increasing creepage distances should prevent tracking, but in practice the presence of moisture films defeat the purpose.
5. Usually, treeing phenomena is observed in capacitors and cables, and extensive work is being done to investigate the real nature and causes of this phenomenon.

Breakdown due to Internal Discharge

1. Due to voids or cavities present inside the insulating materials.
2. These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation.
3. The electric field strength in the voids is higher than that across the dielectric.
4. Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur.

Breakdown due to internal discharge



Liquid Dielectrics

Properties of **good liquid dielectric material**

1. High density
2. High dielectric strength
3. Should free from moisture
4. Should free from oxidation
5. High resistivity
6. High heat transfer characteristics
7. Chemically stable
8. Applications- Transformer oil, Silicon oil, Synthetic hydro carbon(power cable) & chlorinated hydro carbon

Breakdown in liquid dielectrics

- Impurities like gas bubbles, suspended particles may lead to dielectric breakdown.
- Breakdown mechanism depends upon nature of electrodes, physical properties of the liquid dielectrics, presence of impurities & gas present in the liquid

Theories supported for dielectric breakdown in **Liquid dielectric material**

1. Suspended particle theory
2. Cavitation & bubble mechanism
3. Electro convection breakdown
4. Electronic breakdown

Suspended particle theory

- Commercial liquids will always contain solid impurities like fibers or dispersed solid particles & gaseous bubbles.
- Consider the permittivity of liquid dielectrics Ɛ1 & permittivity of solid impurities being Ɛ2.
- Consider the impurities (solid or gas) to be spherical particles of radius ‘r’, and if the applied field is ‘E’ then the particles experience a force ‘F’

$$F = \frac{1}{2r^3} \frac{(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2} \operatorname{grad} E^2$$

- If the field exceeds the breakdown strength of the liquids, liquid dielectric breakdown will occur.
- If the number of impurities present are large, they becomes aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

Cavitation's (Bubble's Theory) Theory

- Theory states that dielectric strength of liquid dielectric material depends up on hydrostatic pressure (pressure exerted by a fluid at rest due to the force of gravity).
- Hydrostatic pressure proportional to higher electric field strength
- A small vapor bubble formed inside the liquid dielectrics may lead to dielectric breakdown.
- Reasons responsible for the bubble's formation in liquid dielectric material

- Gas pockets in the electrode surface
- Irregular surface of electrodes
- Change in temperature & pressure
- Dissociation of product by electron collision

Cavitation's (Bubble's Theory) Theory

- Value of breakdown field is given by

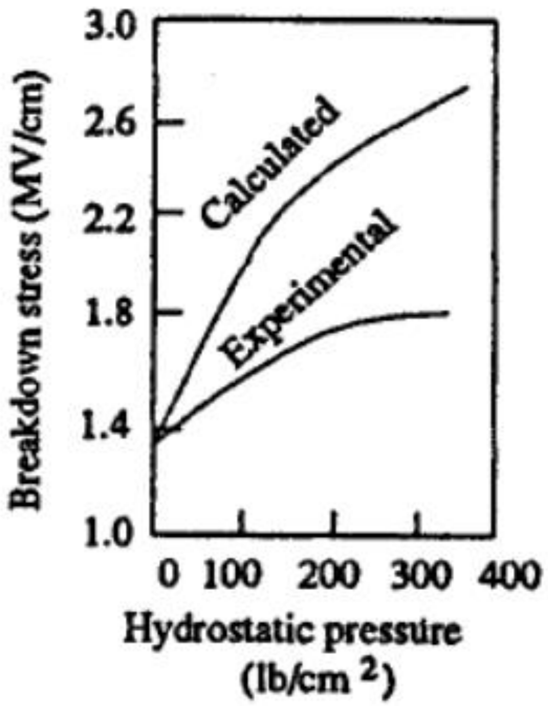
$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r}\left\{\frac{\pi}{4}\sqrt{\left(\frac{V_b}{2rE_0}\right)} - 1\right\}\right]^{\frac{1}{2}}$$

Where σ = surface tension of the liquid, Ɛ1=permittivity of liquid, Ɛ2= permittivity of gaseous bubble, r = initial radius of gas bubble Vb= Voltage drop in the bubble

- Breakdown strength depends upon <u>initial size of bubbles</u>, which influence by hydrostatic pressure & temperature.

Limitations Cavitation's (Bubble’s Theory) Theory

- This theory doesn’t mention about the formation of initial bubbles.
- Theoretical & experimental calculation of breakdown strength are different



Electronic breakdown

- When the voltage is applied in between two electrodes >> electrons are injected to the liquid
- Electron gains energy from the electric field >> Starts the collision process in between other electrons
- Electrons are accelerated under electric field & would gain a sufficient energy to knock out an electron & begin the process of avalanche.
- Condition of breakdown is referred as “Threshold condition”
- Threshold condition achieved when the energy gained by the electron equals to energy lost during ionisation

Electro-convection breakdown

- Breakdown in pure insulating fluid under high voltage
- Charge carrier injected to liquid surface
- Resulting the formation of space charge region
- Increase the columbic force
- Lead to hydrodynamic instability
- Formation of convection current
- The interaction between the space charge & the electric field give rise to eddy motion of liquid leads to breakdown

Conclusion

1. It is clear that no single theory can explain all the experimental observation satisfactorily.
2. All the above theories do not consider dependence of breakdown strength on the gap length.
3. Experimental evidence showed that the breakdown strength of liquids depends on the gap length

Power law

The below equation is termed as 'power law' equation.

The breakdown voltage depends on nature of voltage, mode in which the voltage is applied, Gap distance between electrodes & time of application.

$$V_b = Ad^n$$

d = gap length,

A = constant, and

n = constant, always less than 1.

THANK YOU