Lec 2 Insulation Materials, Properties and Breakdown Theory

Prof Chengke Zhou

c.zhou@gcu.ac.uk

Learning objectives:

- Introduce the concept of insulation materials, the forms of breakdowns
- Introduce the concepts of insulation properties and provides the properties of selected insulation materials
- Assess the breakdown mechanisms of solids insulation materials
- Demonstrate the concept of partial discharge (PD) and how to numerically analyse the PD activities
- Assess the breakdown mechanism of gases insulation materials
- Appreciate Paschen's Law and its engineering significance

Insulation materials

- Electrical Insulation --- insulating material used in bulk to wrap electrical cables or other equipment. It is to support and separate electrical conductors without allowing current through themselves.

- The term insulator is used more specifically to refer to insulating supports used to attach electric power distribution or transmission lines to utility poles and transmission towers.

- Dielectric (or dielectric material) is electrical insulation that can be polarized by an applied electric field.

- A perfect insulator does not exist, because even insulators which contain small numbers of mobile charges (charge carriers) can carry current.

Insulation materials

- Air ---
  - able to restore its insulating properties after disconnection of the voltage.
- Gases – SF_6
  - electronegative and arc-extinguishing ability - discharges are suppressed by the de-ionizing action of the gases. It is used at a higher pressure in compact metal clad gas-insulated substations (GIS)
- Liquids (oil)
  - having better insulating properties than gases.
- Solid
  - better insulating materials than liquids and gases. Unlike gases and liquid, solid materials are generally not self-restoring.

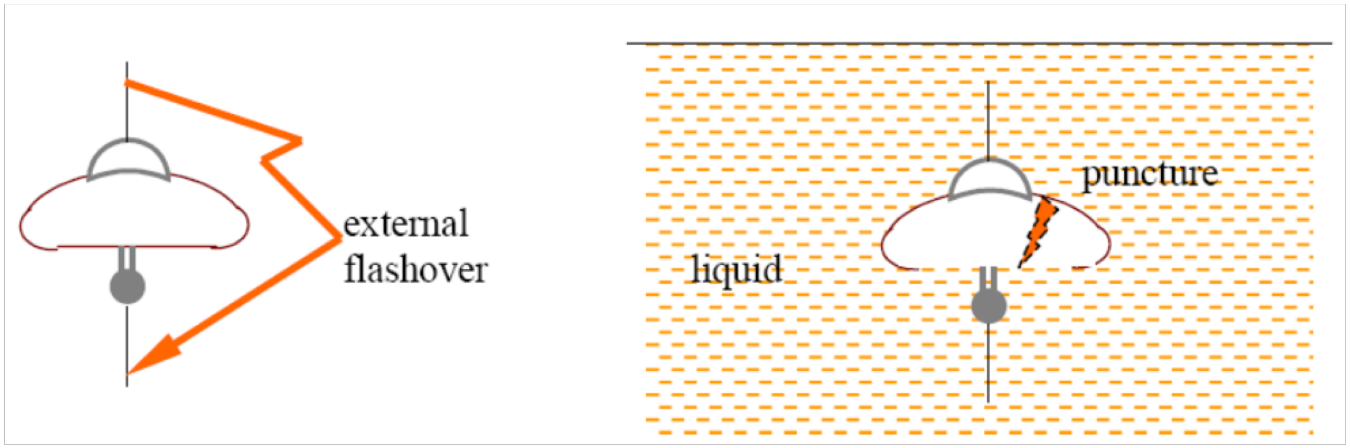
- Insulation Breakdown --- All insulators become electrically conductive when the voltage applied is so high that the electric field tears electrons away from the atoms.

Forms of insulation breakdown

- Flashover –overvoltage or the increased electric field strength causing the air in the gap (often associated with insulator) to break down (flashes over) - vs.- puncture in solid insulation

- Once the gap has flashed over an arc is formed (provided that the impedance Z is not too high)

- If the impedance is high, it may not be possible for a stable arc to form; in such cases intermittent or repetitive sparking may occur.

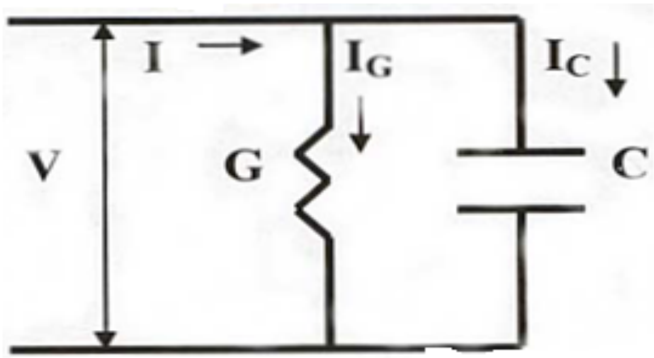


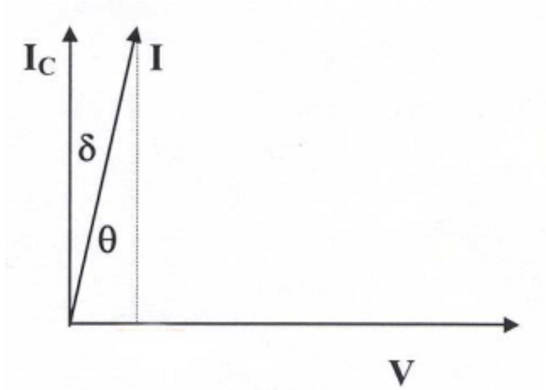
Total Failures due to Insulation Breakdown

Component	**Percentage of insulation failure**
Transformers	84%
Circuit Breakers	21%
Disconnect Switches	15%
Insulated Switchgear Bus	95%
Bus duct	90%
Cable	89%
Cable Joints (splices)	91%
Cable Terminations	87%

Based on IEEE Gold Book Table 36

Insulation Properties - Loss Tangent tanδ

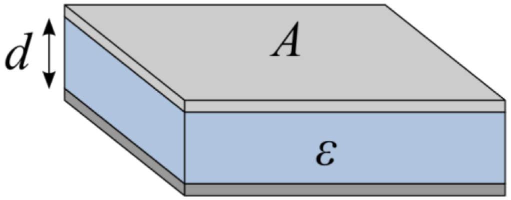




- Charging current $I = V\omega C$
- Power loss $P = VI\cos\Theta = \omega C\, V^2 \tan\delta$

- The loss tangent tanδ is usually small, but it increase when there is moisture ingress and with aging, so it has been a good indicator of insulation condition.

Permittivity, Relative permittivity or dielectric constant



$$C = (\varepsilon_r \varepsilon_o A)/d$$

- Permittivity describes the amount of charge needed to generate one unit of electric flux in a particular medium.
  - A charge will yield more electric flux in a medium with low permittivity than in a medium with high permittivity.

- Relative permittivity(εr) is the factor by which the electric field between the charges is decreased relative to vacuum (ε0).

- Insulation materials always have high value of relative dielectric constant, high value of ε_r leads to low electric stress

- $\varepsilon_o = 8.85\text{x}10^{-12}$ F/m

Dielectric loss Tangent

- All dielectrics have two types of losses
  - Conduction loss due to flow of charge through dielectrics
  - Dielectric loss due to movement or rotation of atoms or molecules in an alternating field.

- When considering dielectric loss, permittivity is often considered as a complex number
  - $\varepsilon = \varepsilon' + j\varepsilon''$ or $C = C' + jC''$
  - $\tan \delta = \varepsilon''/\varepsilon'$

Material	Dielectric constant (typical)	tan δ (typical)	Typical Electric strength (kV/mm)	Properties	Applications
Mica	5.5 - 7	$30.\ 10^{-4}$	-	Stable at high temperatures	Insulation of rotating machine windings (up to 20 kV) together with epoxies.
Paper	-	$20 – 50.\ 10^{-4}$	-	-	Oil-impregnated in HV transformer winding insulation.
Glass	4.5 - 7	$10 - 100.\ 10^{-4}$	10 -50	Brittle	Glass cap and pin insulators. Glass fibres together with epoxy resin
Porcelain	6	$3 – 30.\ 10^{-4}$	20 - 40	-	Insulators, bushings
Polythene	2.3	$1 - 10.\ 10^{-4}$	30 - 40	-	Cross-linked (XLPE) polythene used in hv cables up to 110 kV
PVC	5.5	$>100.\ 10^{-4}$	11 - 30	-	LV cables
PTFE	2	$2.\ 10^{-4}$	19	-	High temperature applications.
Epoxy resin, with silica filler	4	-	18	-	Encapsulation of MV Ct's and VT's Transformer bushings and insulators: cycloaliphatic resin
EPDM rubber	2 - 3	-	-	-	Insulators, using a fibreglass core
Silicone rubber	3 - 6	-	-	Hydrophobic surface properties	Insulators, using a fibreglass core

A comparison of the various types of insulating materials

	Air	SF_6	Solids	Liquids
Dielectric constant	1	1	3-6	2 - 4
Dielectic strength (kV/cm)	30 (at 1 bar)	120 (at 4 bar)	200 - 400	240
Advantages	- Can flow - Self-restoring - Abundant	- Can flow - Self-restoring - High dielectric strength - Good arc quencher in circuit breakers	- Can support conductors - High dielectric strength - Some types can be moulded (epoxies)	- Can flow - Can be cleaned/ recirculated and be replaced - Can be used as coolant - circulated
Disadvantages	- Low dielectric strength - Low dielectric constant a problem when used in series with solid or liquid insulating materials	- Hot house gas - Breakdown products toxic	- Not self-restoring - Can not fill small spaces	- Absorbs moisture - Affected by impurities

Breakdown in solid insulation

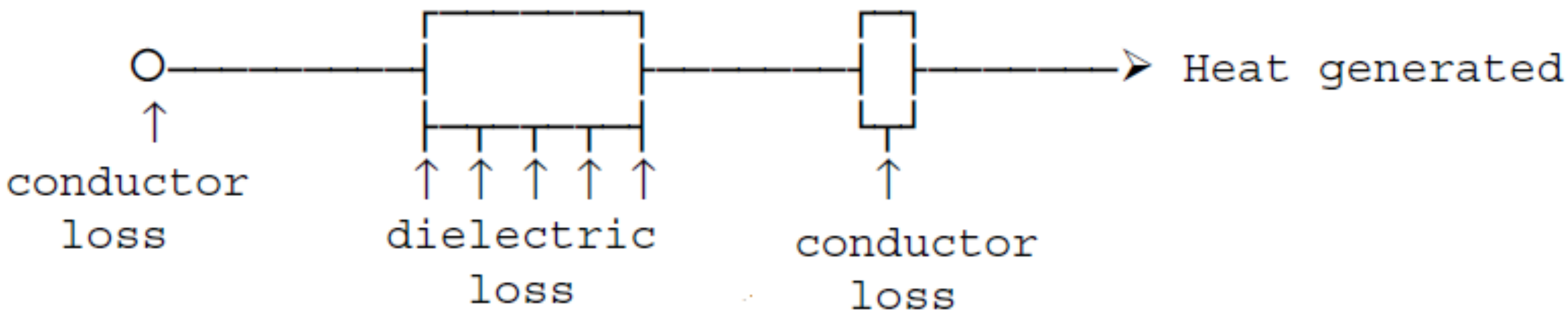
Forms of breakdown

- Thermal breakdown
- Treeing/Tracking
- Chemical and electrochemical breakdown
- Breakdown by internal partial discharge

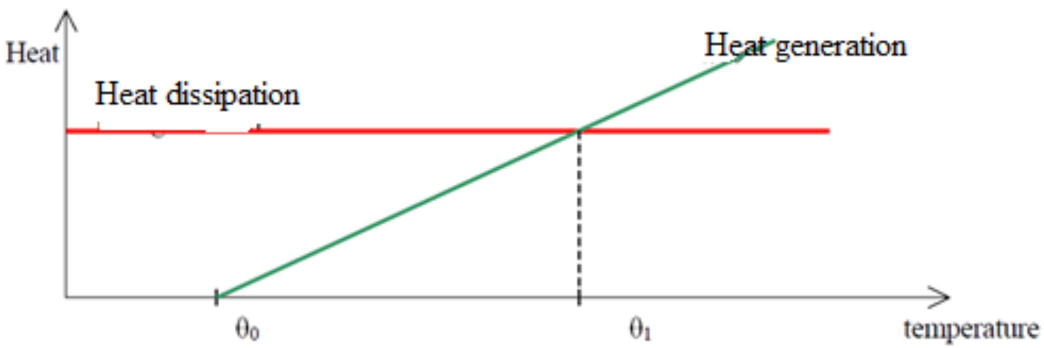
Solid insulation – thermal breakdown

- During normal operating condition, plant insulation receives heat from adjacent conductor loss (I^2R) and dielectric loss ($\omega C V^2 \tan\delta$).
- The heat raises the temperature of insulation. Thermal runaway happens when the process becomes cumulative.
- Thermal conductivity and cooling is an important in HV design.

Thermal breakdown



- In HV design, it is important that dielectric loss is considered.



Thermal breakdown

Treeing/tracking

- Tracking/ treeing is an electrical pre-breakdown phenomenon in solid insulation. It is a damaging process due to partial discharges.
- It first occurs and propagates when a dry dielectric material is subjected to high and divergent electrical field stress over a long period of time.
- Originate at points where impurities, gas voids, mechanical defects, or conducting projections cause excessive electrical field stress within small regions of the dielectric.

Partial Discharge (PD)

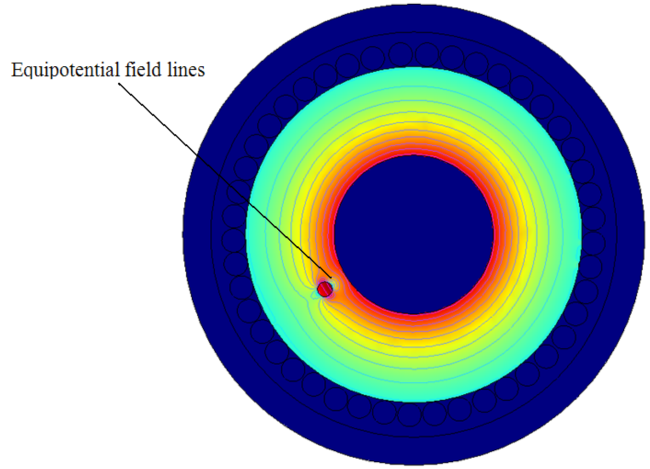
- A localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress, which does not bridge the space between two conductors.

- Symptom and mechanism of insulation degradation – means of condition monitoring

- Electrical discharges occurring inside medium and high voltage insulation (flaws, cracks, voids, irregularities). These imperfections create voltage stresses and cause eventual failure of the insulation.

- Protracted partial discharge can erode solid insulation and eventually lead to breakdown of insulation.

- A corona discharge is usually revealed by a relatively steady glow or brush discharge in air, partial discharges within solid insulation system are not visible.



Partial discharge measurement

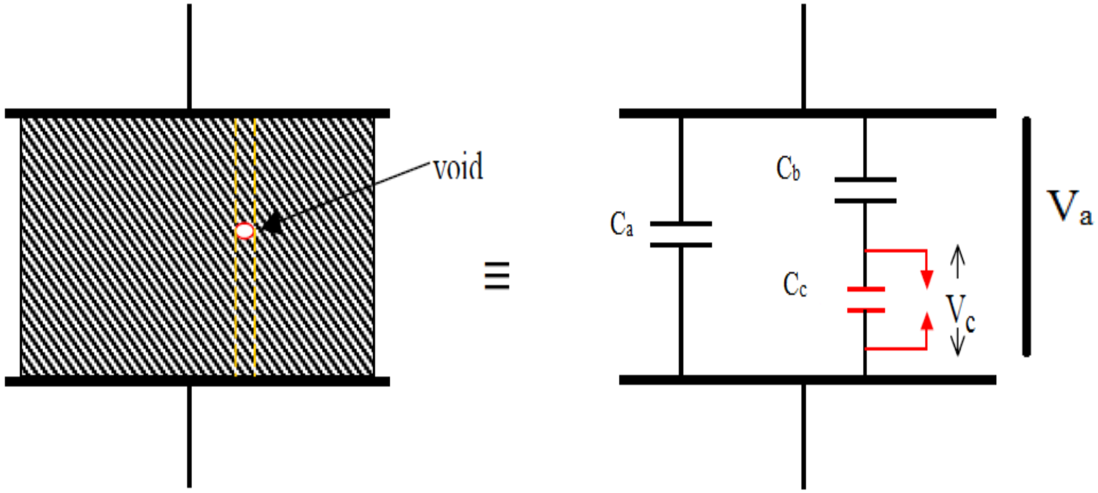
- There exist numerous discharge detection schemes
- Partial discharge currents tend to be of short duration and have rise times in the nanosecond realm.
- Partial discharges appear as evenly spaced burst events that occur at segments in the supply voltage sinewave. Random events are arcing or sparking.
- The usual way of quantifying partial discharge magnitude is in picocoulombs (pC, integration of current pulse over time).
- The intensity of partial discharge is displayed versus time.
- A phase-related depiction of the partial discharges provides additional information, useful for the evaluation of the device under test.

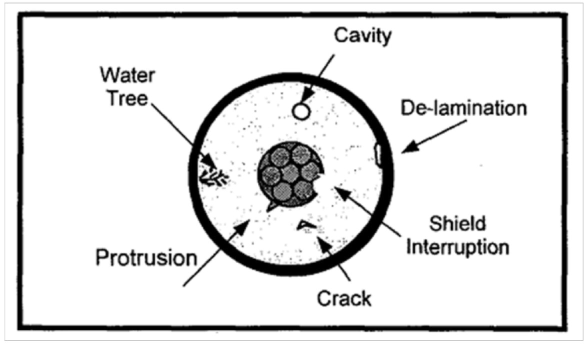
PD inception voltage and apparent discharge

- When the applied voltage Va is increased to a certain value known as the discharge inception voltage, so that the peak electric stress in the cavity is equal to the electric strength of the gas in it, an electric discharge occurs in the gas.

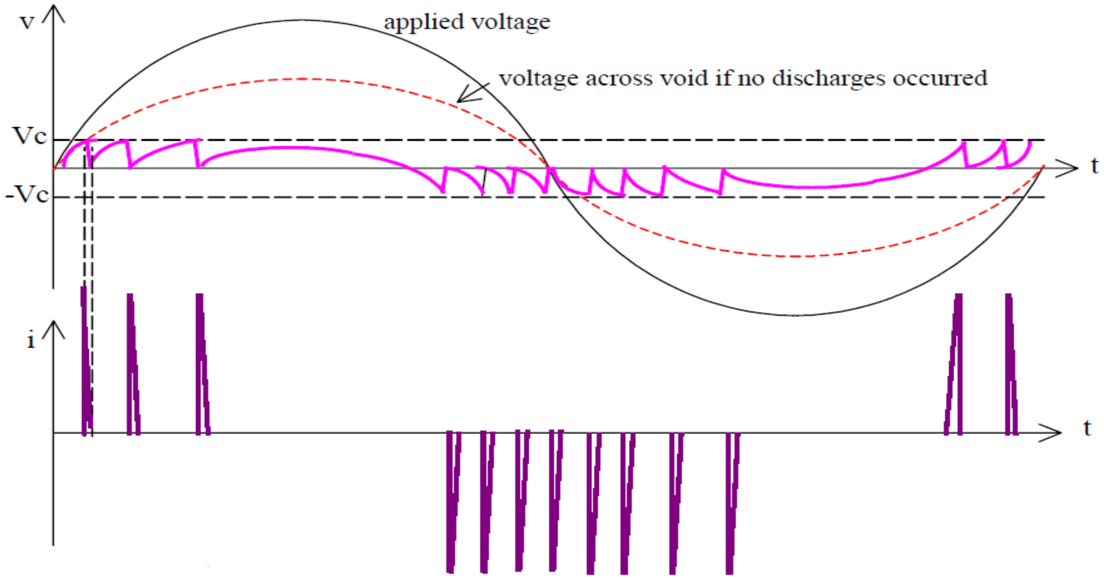
- The actual charge change that occurs due to a PD event is not directly measurable, apparent charge is used instead. Apparent charge' is usually expressed in picocoulombs.

PD Model





$$V_c = \frac{V_a \times C_b}{C_c + C_b}$$



$$Apparent\ discharge \quad q_a = \frac{C_b^2}{C_c} V_a$$

Calibration in PD measurement

- The apparent charge (q) of a PD event is the charge that, if injected between the terminals of the device under test, would change the voltage across the terminals by an amount equivalent to the PD event.

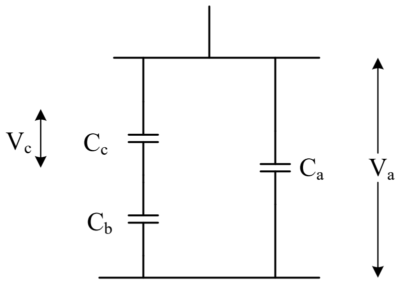
- Apparent charge is not equal to the actual amount of changing charge at the PD site, but can be directly measured and calibrated.

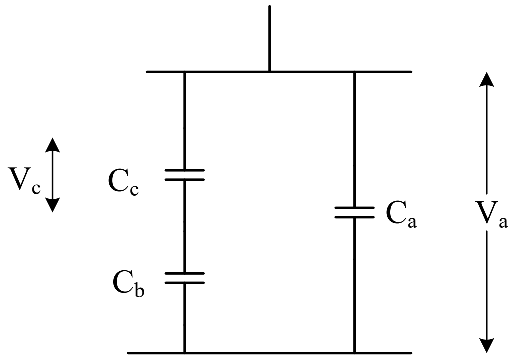
- This is measured by calibrating the voltage of the spikes against the voltages obtained from a calibration unit discharged into the measuring instrument.

- The calibration unit is quite simple in operation and merely comprises a square wave generator in series with a capacitor connected across the sample.

Example

A dielectric containing a single discharge cavity can be represented by the equivalent circuit below.





Where C_c represents the cavity. If C_a=0.1µF, C_b=0.001pF and C_c=0.01pF. The voltage across the cavity at the instant of breakdown is 950V, calculate

(i) the rms discharge inception voltage, assuming a sinusoidal waveform

(ii) the apparent discharge magnitude, and

(iii) the energy dissipated by a single discharge

Solutions

(i) $V_c = V_a \frac{C_b}{C_c+C_b}$, so the RMS inception voltage =$V_c \frac{C_c+C_b}{C_b} = \frac{950}{\sqrt{2}} \times \frac{0.011}{0.001}$=7.4kV (10.46kV pk-pk)

(ii) Apparent discharge =

$q_a = \frac{C_b^2}{C_c} V_a = 10.46 \times 1000 \times \frac{0.001^2}{0.01}$=1.045pC

(iii) Energy dissipated in the discharge =

$$\frac{1}{2}\frac{C_b^2}{C_c}V_a^2 = \frac{1}{2} \times \frac{0.001^2}{0.01} \times 10460^2 = 5470\, pico\ Joules = 5.47 \times 10^{-9} J$$

Relevant standards in relation to PD measurement

- IEC 60060-2 : 1989 High-voltage test techniques — Part 2: Measuring systems
- IEC 60270:2000/BS EN 60270:2001 "High-Voltage Test Techniques – Partial Discharge Measurements"
- IEC 61934:2006 "Electrical insulating materials and systems - Electrical measurement of PD under short rise time and repetitive voltage impulses"
- IEC 60664-4:2007 "Insulation coordination for equipment within low-voltage systems – Part 4: Consideration of high-frequency voltage stress"
- IEC 60034-27:2007 "Rotating electrical machines – Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines"
- IEEE Std 436™-1991 (R2007) "IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers"
- IEEE 1434–2000 "IEEE Trial-Use Guide to the Measurement of Partial Discharges in Rotating Machinery"
- IEEE 400-2001 "IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems"

Breakdown in Liquids

Their breakdown mechanisms include:

- Electronic breakdown
  - o Production of free electronics in the gap by electron emission from the cathode
  - o Acceleration of electrons by field and loss of energy through collision with liquid or impurity molecules
  - o Ionisation leading to instability

- Cavitation mechanism – formation of bubbles, the breakdown occurs when local stress exceeds oil insulation strength

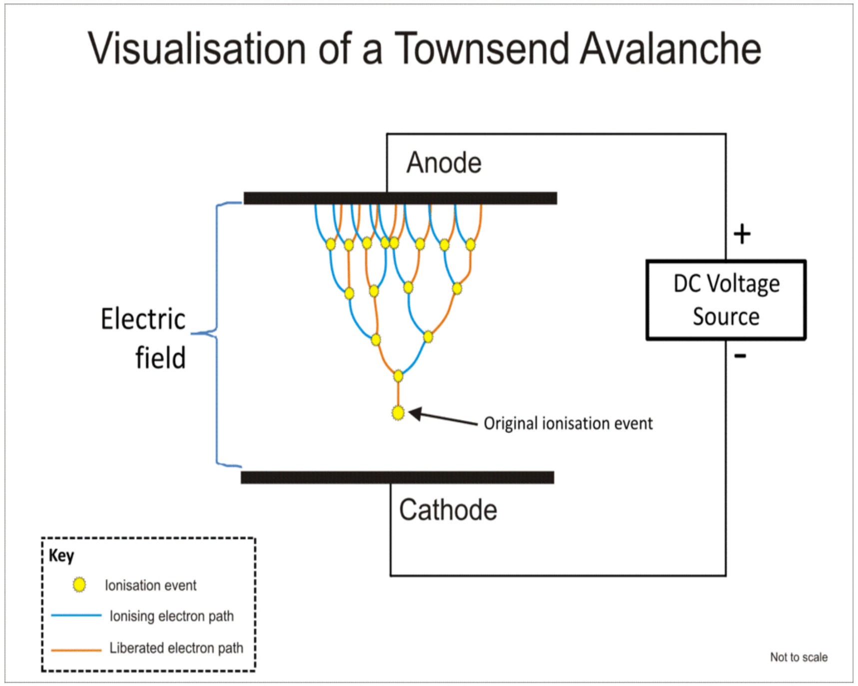
Breakdown in insulating gases

- Insulating gases include air, compressed air or SF6
  - Normally, the gas atoms have zero charge as the positive and negative charges cancel out.
  - However, under a high electric field, the gases can become ionized as electrons are freed and cause the flow of electrical current, leading to - electrical discharges (sparks, arcs).

Townsend discharge

- Or Townsend avalanche is a gas ionisation process where free electrons (say, due to radiation) are accelerated by an electric field, collide with gas molecules, and consequently free additional electrons.

- Those electrons are in turn accelerated and free additional electrons. The result is an avalanche multiplication that permits electrical conduction through the gas. The discharge requires a source of free electrons and a significant electric field

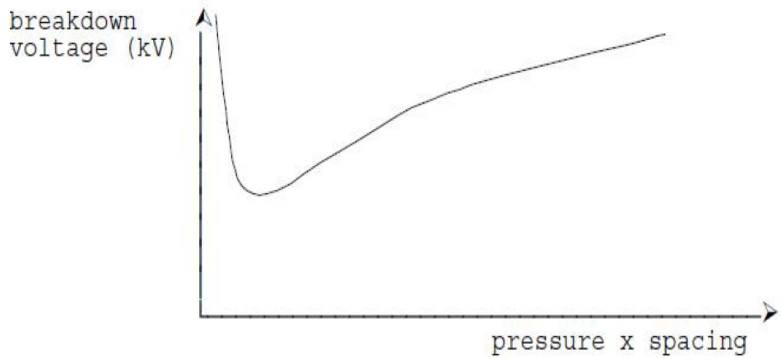


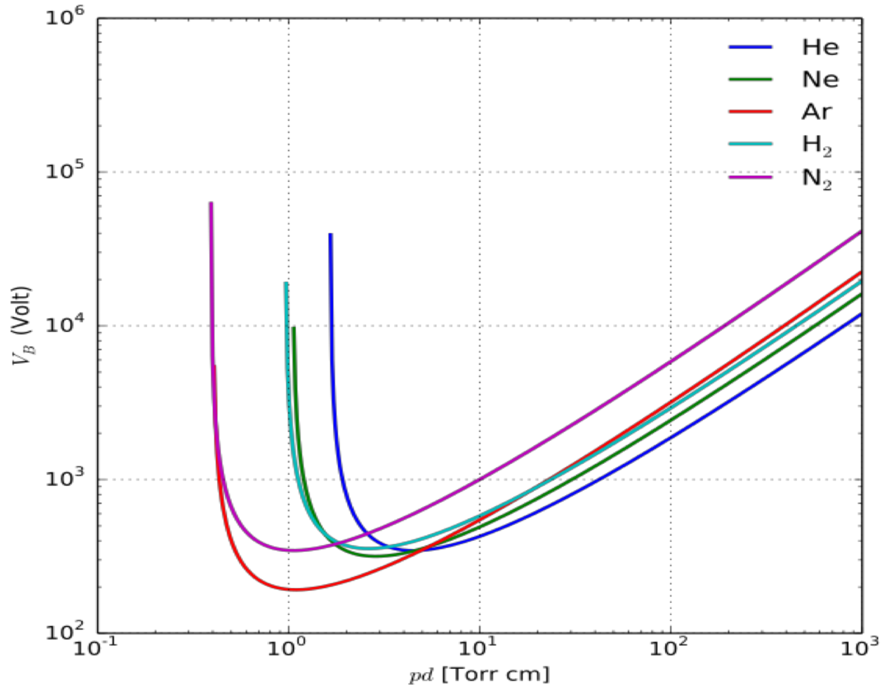
Streamer discharge

- A type of transient electrical discharge.
- Needs a large potential difference (> strength). When the electric field created by the applied voltage is sufficiently large, accelerated electrons strike air molecules with enough energy to knock other electrons off them, ionizing them, and the freed electrons go on to strike more molecules in a chain reaction.
- These electron avalanches create ionized, electrically conductive regions in the air near the electrode creating the electric field, gives rise to an additional electric field. This field can enhance the growth of new avalanches in a particular direction. Then the ionized region grows quickly in that direction, forming a finger-like discharge called a streamer.

Paschen's Law

- It is an equation that gives the breakdown voltage, that is, the voltage necessary to start a discharge or electric arc, between two electrodes in a gas as a function of pressure and gap length.
- The torr is a unit of pressure, now defined as exactly 1/760 of a standard atmosphere (101325 Pa). Thus one torr is exactly (≈ 133.32 Pa).





Torr – Unit of pressure

- The torr (symbol: Torr) is a unit of pressure based on an absolute scale, now defined as exactly 1/760 of a standard atmosphere (101325 Pa). Thus one torr is exactly (≈ 133.32 Pa).

Corona discharge

- A corona discharge is an electrical discharge due to the ionization of a fluid such as air surrounding a conductor that is electrically charged.
- A corona will occur when the strength of the electric field (potential gradient) around a conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects.

Comments on Corona:

- Corona causes power loss, however, this is not usually considered in design calculations

- It causes electromagnetic interferences due to the high frequency emissions during the process of discharge

- Average corona loss is 1-20kW/km in lines 300-750kV in fair weather. It may reach 300kW/km or 10% of power on foul weather.

Vacuum Breakdown

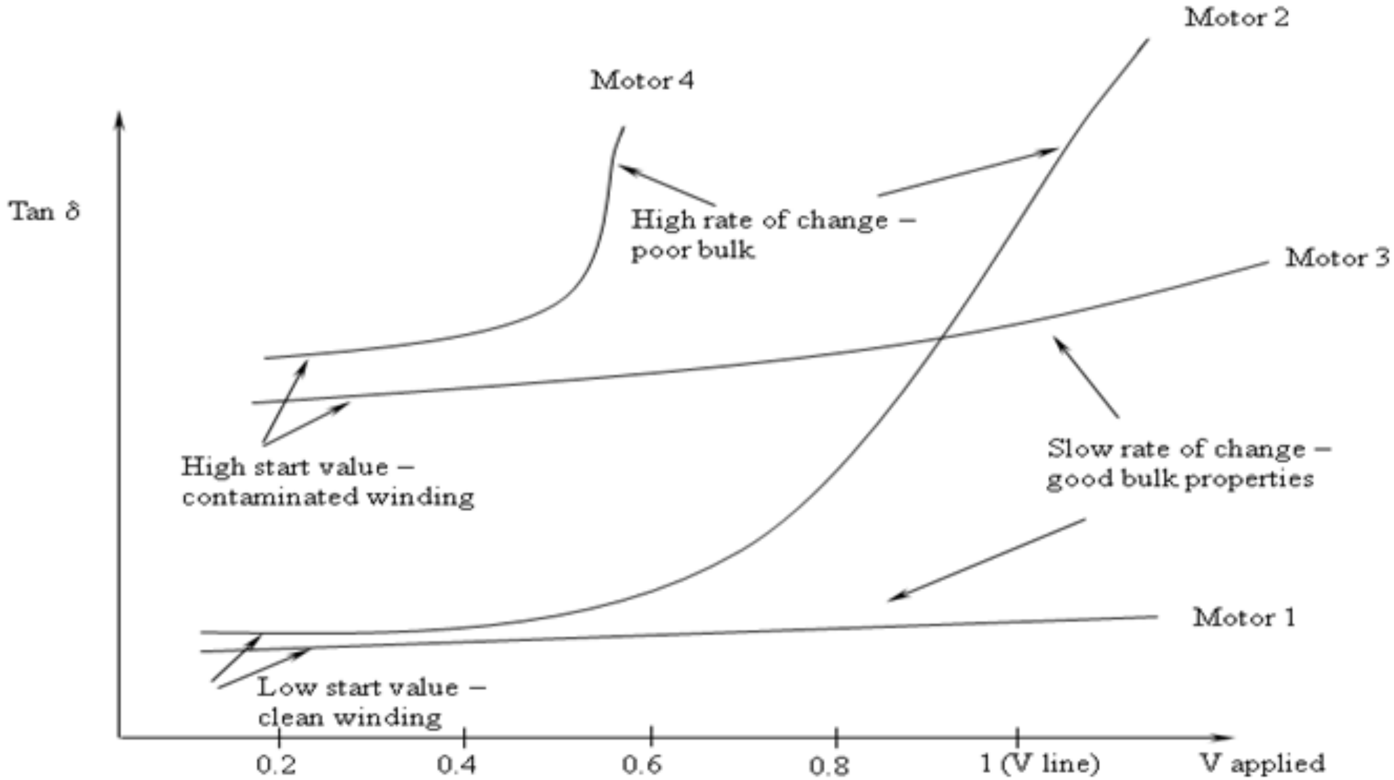
At gas pressure of about 10^{-4} torr, in gaps of a few centimetres, electrons will cross the gap without making collisions with gas molecules.

Vacuum breakdown mechanisms include:

- Particles exchange : self sustaining interchange of elementary particles between electrodes resulting from secondary emission processes.
- Electron beam mechanisms: electrons emitted from micro-protrusions on cathode cause localised resistance heating on cathode and anode heating where the beam impinges. Vapour is released, gaseous ionisation and breakdown occur as a result.
- Clump mechanisms: small pieces of electrode contamination or electrode material may cross the gap in high fields causing local evaporation on electron impact.

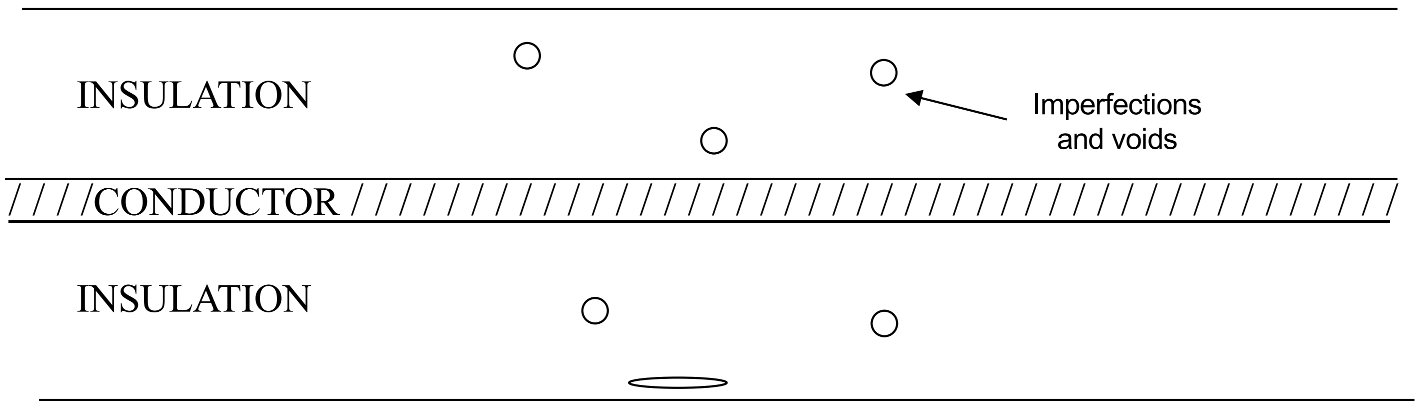
Tan δ/PD – used for motor winding condition assessment

Motor windings are often tested for its dielectric loss in relation to increasing voltages (in steps). The test results can be used to assess the insulation condition as shown in the example below.



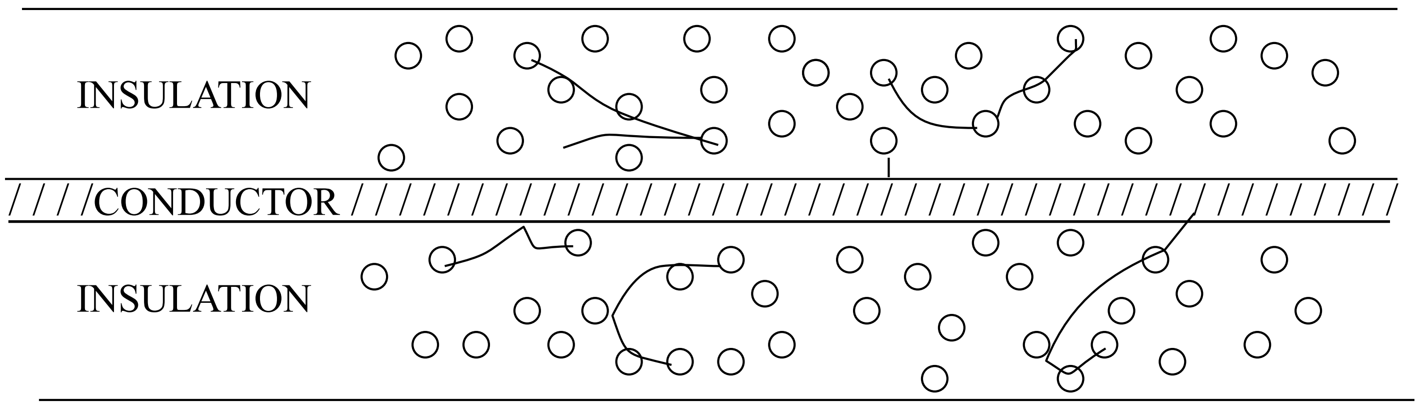
Cable insulation failure mechanism due to PD
STAGE 1 - imperfections

No problems, minor voids resulting in minor partial discharges or no PD at all



STAGE 2 - Tracking begins

Over time, deterioration happens and tracking develops



STAGE 3 – cable fails

Eventually breakdown (conduction between phase conductor and ground/earth) happens.