Lec 1 Tutorial Questions

1) Compare the pros and cons of overhead lines, gas insulated lines and underground cables.

Advantage of overhead lines:

- Insulating Material: Air
- High voltages are easy to handle with sufficient distances/clearances and lengths
- Permitted phase wire temperature of phase wires is high
- Overhead lines are defined by their natural power rating P_{Nat}
- Thermal Power limit is a multiple of P_{Nat}
- Simple and straightforward layout, (Relatively) easy and fast to erect and to repair
- Large load capacity and overload capability
- Lowest (capacitive) reactive power of all systems
- Long physical life, Lowest investment costs, Lowest unavailability

Disadvantages of overhead lines:

- High failure rate (most failure are arc failures without consequences)
- Impairment of landscape (visibility)
- Low electromagnetic fields can be achieved through distances and arrangements
- Highest losses
- Highest operational costs because of current-dependent losses

Advantages of GIL:

- High transmission capacity
- large overload capability
- Minimal dielectric losses
- Low mutual capacitance ⇨ low charging current / power
- Good heat dissipation to the environment
- Large transmission capacity
- High load capacity
- High overload capability
- Lower impedance per unit length than overhead lines
- Low failure rates
- High lifespan expected (Experience with GIS)
- No ageing
- Lowest electro-magnetically fields
- Lower losses than cables
- Lower operational costs (including losses) than cable lines

Disadvantages of GIL:

- High Requirements to purity and gas-tightness
- Higher reactive power than overhead lines
- Gas monitoring, failure location, PD-monitoring
- Higher unavailability than cables because of long period of repair
- Short operational experience, only short distances in operation
- Large sections necessary, only limited usage of soil possible, issues with SF_6
- Investment costs 7-12 times higher when compared to overhead lines

Advantages of cables:

- Large load capacity possible with thermal foundation and cross-bonding
- Lower impedances per unit length when compared to overhead lines
- Lower failure rate than overhead lines
- No electrical field on the outside
- Losses are only 50% of an overhead line
- Operational costs (including losses) are about half of the costs of an overhead line

Disadvantages of cables:

- High requirements to purity of synthetic insulation and water- tightness
- Overload only temporary possible, otherwise influences lifespan of insulation
- High reactive power, compensation necessary
- Unavailability is notable higher when compared to overhead lines (high repairing efforts)
- Lifespan: 30 to 40 years (assumed)
- Extensive demand of space, drying out of soil, only very limited usage of line route possible
- 3-6 times investment costs compared to overhead lines

2) What are the functionalities of a bushing?

It is sometimes required to take a high voltage conductor through a wall or the tank of a transformer. In such cases a bushing is required to support the high voltage conductor and to provide the necessary insulation in the axial and the radial directions. A porcelain or resin bushing is used for this purpose.

3) Which two purposes are served by the oil in a transformer?

The oil fills possible voids, while also serving as coolant that can circulate by natural convection or being pumped.

4) What are the pros and cons of AC and DC transmission?

HVAC systems enjoy the advantage of:

- easy transformation of energy between different voltage levels,
- mature technology

Disadvantages include

- transmission and compensation of reactive power,
- stability problems

In recent years, there has been increasing adoption of HVDC (direct current) due to the advantages such as:

- No (capacitive) charging currents
- No stability problems (frequency)
- Higher power transfer
- No inductive voltage drop
- No Skin-Effect
- High flexibility and controllability

5) Define electric field and discuss its significance in HV system design.

A field can be described as a spatial distribution of a quantity, which may or may not be a function of time. Electric fields are caused by the voltage difference between electrodes. It is also the distribution of the ***Electric stress*** which is the force, E, on a unit of charge placed in insulant. Charged particles acquire kinetic energy under action of this force.

Electric fields are important in high voltage engineering due to the following effects:

- The most important concepts in HV is strength and stress, the latter is closely related to electric field. The stress of electric insulating materials is adversely affected by excessive electric field magnitudes.
- The presence of electric fields causes induced voltages on non-earthed objects. Similarly, the charge at the base of a thundercloud causes an electric field near the earth surface that may induce charge on objects such as transmission lines. Under dynamic conditions, when the charges vary with time, currents flow in conducting objects.

6) Using the electric field theory as underpinning, explain why an air filled void in a solid insulation may experience partial discharge.

Imagine a boundary between a solid insulator like polyethylene (ε_r=2.2 (ε_2)) and a gas such as air (ε_r=1 (ε_1)) . Then:

- $D = \varepsilon_o \varepsilon_1 E_1 = \varepsilon_o \varepsilon_2 E_2,$
- $E_1 = \varepsilon_2 E_2 / \varepsilon_1$

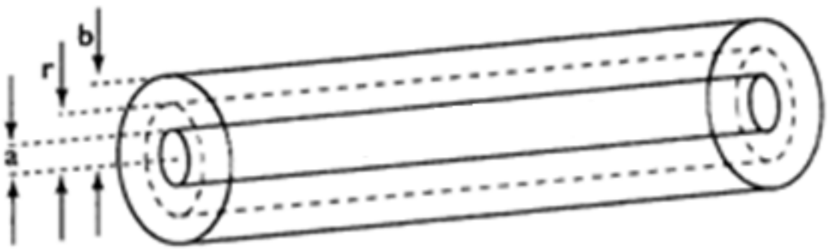
  Stress in air E_1 = 2.2x stress in solids

  Significance: weaker insulating material has higher stress

7) A simple coaxial cable is made out of a central cylindrical conductor of 5mm diameter, with an outer conducting sheath, also cylindrical, coaxial with the central conductor. The internal diameter of the outer sheath is 20mm. The space between the two cylinders is empty. Determine the electric strength at the surface of the inner conductor when the potential difference between the conductors is 500V.

$V=q/2\pi\varepsilon \ln(20/5)$ $\therefore q = V \cdot 2\pi\varepsilon/\ln 4$
$E=q/(2\pi\varepsilon \times 2.5mm)=500/\ln 4/2.5mm=144.27kV/m$

8) The inner conductor of a concentric cable has a diameter of 3cm, the diameter over the insulator being 8.5cm. The cable is insulated with two materials having permittivity of 5 and 3 respectively, with corresponding safe working stresses of 38kV/cm and 26kV/cm. Calculate the radial thickness of each insulating layer and the design voltage of the cable.



A=1.5cm, b=4.25cm
$E_1=q/(2\pi\,\varepsilon_0\varepsilon_1 \times 1.5cm) \rightarrow q= E_1(2\pi\,\varepsilon_0\varepsilon_1 \times 1.5cm)$
$E_2=q/(2\pi\,\varepsilon_0\varepsilon_2 \times r) \rightarrow q= E_2(2\pi\,\varepsilon_0\varepsilon_2 \times r)$
$r= 38/26\times5\times1.5/3=3.65cm$
Thus the radial thickness of dielectrics are: *(3.65-1.5)=2.15cm, (4.25-3.65)=0.6cm*
$V_1= q/2\pi\,\varepsilon_0\varepsilon_1 \times\ln(3.65/1.5)=38\times1.5\times\ln(3.65/1.5)=50.7kV$
$V_2= q/2\pi\,\varepsilon_0\varepsilon_2 \times\ln(4.25/3.65)=26\times4.25\times \ln(4.25/3.65)=14.45kV$
$V= V_1+ V_2=50.7+14.45=65.15kV$

8. A capacitor bushing with three layers of conductors is designed for the power transformer as data tabulated below.

Internal diameter of the conductor: 20mm
Internal diameter of the earthed flange: 80mm
Internal diameter of the other two layers of copper foils are: 40mm and 60mm respectively.
Length of earthed flange: 100cm
Relative permittivity of the mica insulator: 3.5

(i) calculate the axial length of the conducting foils to withstand maximum stress in the insulator layer.
(ii) Develop the 66kV capacitor bushing with labelling of relevant dimensions and showing the place of conductive foils used.

(iii) determine the voltage V1, V2 and V3 across each layer.

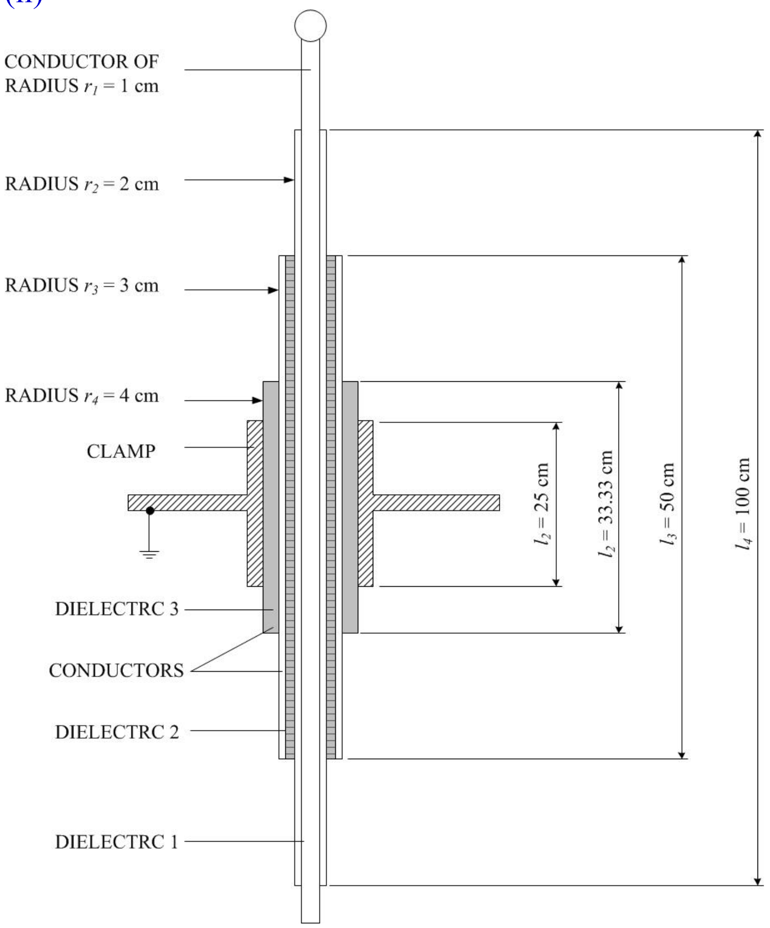
(Note: Capacitance between concentric cylinders C= [εr x L]/[18 ln (R/r)] nF)

8. *Solutions*

(i) L1*r1=L2*r2=L3*r3=L4*r4 = 100*1

Therefore, L1 =100/2=50cm, L2 =100/3 = 33.3cm, L3 =100/4=25cm.

(ii)



(iii) Capacitance between concentric cylinders C= [εr x L]/[18 ln (R/r)] nF

C1 = [3.5x0.5]/18 x ln(2/1)] = 140.25 nF

C2 = [3.5x0.33]/[18 x ln(3/2)] = 158.18 nF

C3 = [3.5x0.250/[18 x ln(4/3)] = 169.12 nF

Because: C1V1 = C2V2 = C3V3

V2 = V1 (C1/C2) = V1 (168.3/143.8) =0.88V1

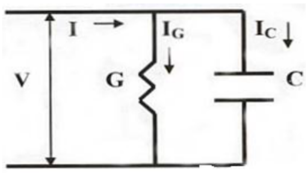
V3 = V1 (C1/C3) = V1 (168.3/135.3) = 0.82V1

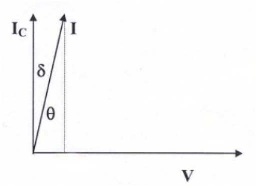
Total voltage V1 +V2 +V3 = 66kV/sqrt(3) = 38.1 kV

(V1+0.88V1+0.82V1) = 38.2, V1 = 14.11kV, V2 = 12.41kV, V3 = 11.57kV

Lec 2 Tutorial Questions

1. Provide definition of dielectric loss angle tanδ and relative permittivity in HV systems and explain their significance in HV plant design and condition monitoring.





(i)

- In insulations, Charging current I = VωC
  Power loss P = VIcosΘ =ωC V2tanδ, where tanδ is dielectric loss coefficient or loss tangent
- 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.

(ii)

- 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

2. List the advantages and disadvantages of gaseous insulation, solid insulation, and liquid insulation respectively, and provide two breakdown mechanisms with brief explanations for each of them.

A comparison of the various types of insulating materials

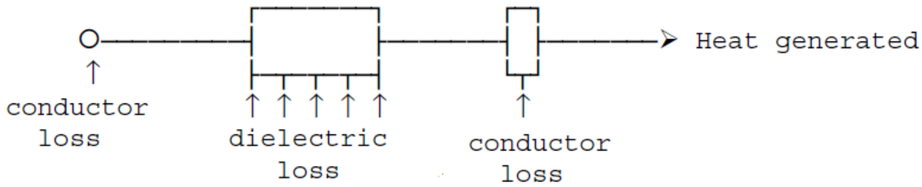
	Air	SF_6	Solids	Liquids
Dielectric constant	1	1	3-6	2 - 4
Dielectic strength (kV/cm)	30 (at 1 bar)	120 (at 4 bar)	200 - 400	240
Advantages	- Can flow - Self-restoring - Abundant	- Can flow - Self-restoring - High dielectric strength - Good arc quencher in circuit breakers	- Can support conductors - High 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

Electrical breakdown occurs within a gas when the dielectric strength of the gas is exceeded. Regions of intense voltage gradients can cause nearby gas to partially ionize and begin conducting. The voltage that leads to electrical breakdown of a gas is approximated by Paschen's Law.

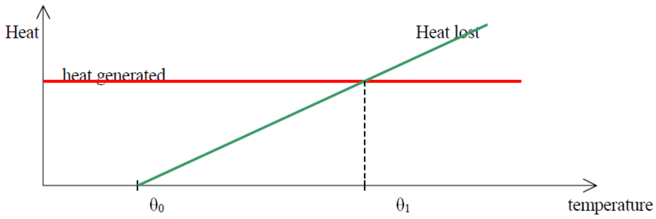
1) Townsend discharge
   Townsend discharge is a gas ionisation process where free electrons are accelerated by an electric field, collide with gas molecules, and consequently free additional electrons. Those electrons are in turn accelerated and free additional electrons. The result is an avalanche multiplication that permits electrical conduction through the gas. The discharge requires a source of free electrons and a significant electric field
2) Streamer discharge
   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.
3) 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.

Solid insulation: better insulating materials than liquids and gases. Unlike gases and liquid, solid insulating materials are generally not self-restoring.

1) thermal breakdown
   During normal operating condition, plant insulation receives heat from adjacent conductor loss (I2R) and dielectric loss (ωC V2tanδ). 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.



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



Thermal breakdown

2) 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.
3) Partial Discharge (PD)
A localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress, does not bridge the space between two conductors. 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. Electrical discharges occur 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

Liquids (oil) insulation: can be used as insulating materials, having better insulating properties than gases
1) Electronic breakdown
Production of free electronics in the gap by electron emission from the cathode
Acceleration of electrons by field and loss of energy through collision with liquid or impurity molecules
Ionisation leading to instability
2) Cavitation mechanism – formation of bubbles, the breakdown occurs when local stress exceeds oil insulation strength, due to
Gas pockets in electrode surface
Electrostatic repulsion between space charge
Gaseous products of ionisation molecules
Vaporisation of liquid by discharges from irregularity on electrode surface

3. Define and contrast Townsend discharge, Streamer discharge and Corona discharge.

1) Townsend discharge
Townsend discharge is a gas ionisation process where free electrons 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
2) Streamer discharge
•A type of transient electrical discharge.

•Needs a large potential difference. 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.

•(Townsend discharges) create ionized, electrically conductive regions in the air. The space charge created by the electron avalanches 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.

3) 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.

4. Explain the concept of PD inception voltage and apparent discharge.

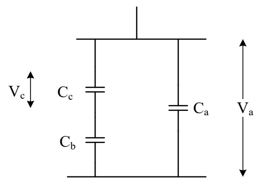
When the applied voltage V_a is increased to a certain value known as the discharge inception voltage, so that the peak electric stress in the cavity is equal to the electric strength of the gas in it, an electric discharge occurs in the gas.

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 Pico coulombs.

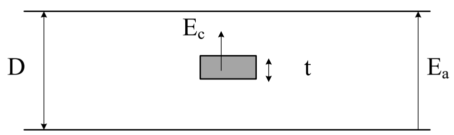
5. Show that for a solid insulating material of relative permittivity ε_r containing a cylindrical air-filled void of depth *t* which is small in relation to the thickness *D* of the dielectric, that

$$E_c = E_a\left[\frac{\epsilon_r}{1+\frac{t}{D}(\epsilon_r-1)}\right]$$

Where E_c is the stress of the void and E_a the stress in the solid dielectric.



Equivalent Circuit



$$C_a = \frac{\varepsilon_0\varepsilon_r A}{D} \qquad C_b = \frac{\varepsilon_0\varepsilon_r A}{D-t} \qquad C_c = \frac{\varepsilon_0 A}{t}$$

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

$$\therefore V_c = \frac{\varepsilon_r}{\varepsilon_r+(\frac{D}{t}-1)}V_a \qquad E_c\cdot t = \frac{\varepsilon_r}{\varepsilon_r+(\frac{D}{t}-1)}E_a\cdot D$$

$$\therefore E_c = \frac{\varepsilon_r}{1+\frac{t}{D}(\varepsilon_r-1)}E_a$$

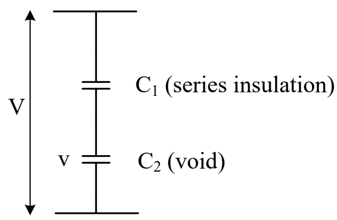
6. A solid insulating material of relative permittivity 2.2 is used in a capacitor between two metal electrodes. The thickness of the insulating sheet is 0.22 cm. Voids are known to occur in the sheet and their sizes are small relative to the insulation. The depth of each void lies in between 0.02 cm and 0.05 cm. The breakdown characteristics of the gas in void (equivalent to Parchen's curve) is as follows.

Gap length (cm)	0.02	0.03	0.04	0.05	0.06
Electric field at breakdown (kV_{pk}/cm)	125	110	105	100	95

Estimates the 50Hz root mean square inception voltage.

The thickest void will discharge first. For the void of 0.05cm, the breakdown voltage will be

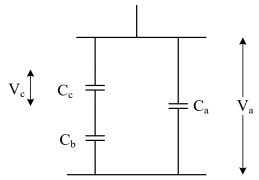
v = 100×0.05 *kV*=5*kV peak*



$$V = v\left[\frac{(C_1+C_2)}{C_1}\right] = v\left[\frac{(\frac{\varepsilon_0\varepsilon_r A}{D-t}+\frac{\varepsilon_0 A}{t})}{\frac{\varepsilon_0\varepsilon_r A}{D-t}}\right] = v\left[\frac{(\frac{\varepsilon r}{D-t}+\frac{1}{t})}{\frac{\varepsilon r}{D-t}}\right] = v\left[\frac{(\frac{2.2}{0.22-0.05}+\frac{1}{0.05})}{\frac{2.2}{0.22-0.05}}\right]$$

$$\therefore V(r.m.s) = 5\times\left[\frac{32.94}{12.94}\right]\times\frac{1}{\sqrt{2}} = 9kV$$

7. 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

$$V_c = \frac{C_b}{C_c+C_b}V_a \therefore V_a = \frac{0.011}{0.01}\times\frac{950}{\sqrt{2}} = 7.4kV\ (10.46kV\ pk-pk)$$

(ii) the apparent discharge magnitude, and

$$q_a = \frac{C_b^2}{C_c}V_a = \frac{0.001^2}{0.01}\times 10460 = 1.045pC$$

(iii) the energy dissipated by a single discharge

(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 =

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

8. Explain, with the aid of an electrical equivalent circuit, the mechanisms of PD occurring in a solid insulation containing a air voids. Using sketches to illustrate the voltage waveform across the void, the applied voltage and the PD current waveforms during an ac cycle.

Solution:

For a solid insulating material, shown in Figure below, of relative permittivity ε_r containing a cylindrical air-filled void which is small in relation to the thickness of the dielectric,

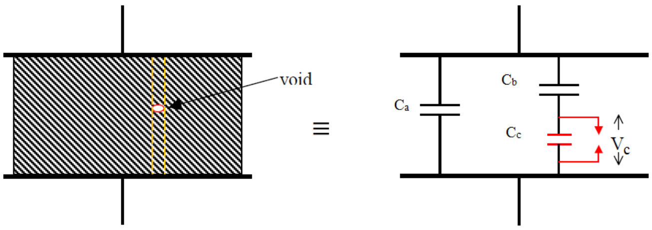


Figure Solid insulation with a void and its equivalent circuit, where C_c represents the capacitance of the void, C_b the capacitance of the sum of insulation material in parallel with the void and C_a the capacitance of all other parts of the insulation.

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. Once a PD is initiated in the void, the voltage collapses in it. The voltage will rise again with the applied voltage until it reaches the PD inception voltage again. This repeats in both the positive half and negative half voltage cycles.

When partial discharge occurs, it may appear many times each cycle of power supply, as shown in the pattern.

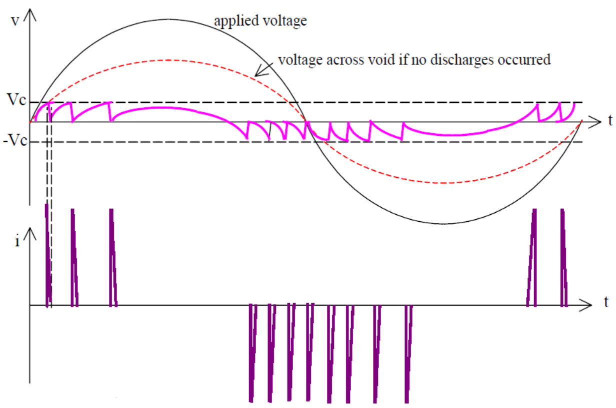


Figure Internal PD pattern over a cycle of power supply, voltage waveforms applied and in a void during PD process (top), and the discharge current pulses (bottom).

Lec 3: HV Plant Insulation

1. Briefly describe the four types of stresses high voltage power plant insulation systems are subjected in operation.

- Thermal stress: normal running temperature, overloads, stopping and starting
- Electrical stress: normal operation condition, impulse overvoltages from faults/switching/lightning
- Mechanical stress: thermal expansions of copper, steel and insulation, short-circuit, faults starting.
- Environmental stress: ambient temperature/moisture etc.

2. Discuss the electrical and mechanical stresses which may appear in a rotating machine, include the likely locations and causes.

Electrical Aging to Insulation is caused by:

- Core insulation
  - Overheating of ends of core due to under exciting
  - Overheating of back of core due to overexciting
- Stator winding insulation
  - Electrical discharges
- Partial discharge
- Discharges at conductor surface
- Internal groundwall discharge
- Discharges at the outer surface (slot discharges, end winding discharges)
- Surface tracking and moisture absorption
- System surge voltage
- Unbalanced supply voltage

Mechanical aging factors include:

- Core insulation
  - Core fretting, relaxation and failure
- Inadequate core building procedures
- High vibration in service
  - Back of core overheating and burning
- Stator winding insulation
  - 100Hz bar bounding forces
  - Electromagnetic forces in endwindings
  - Transient forces
  - Abrasive materials
  - Centrifugal forces

3. Describe the mechanisms and symptoms of thermal aging to core insulation and winding insulations in a rotating machine respectively.

Thermal aging to insulation includes:

- Core insulation
  - Burnout at high temperature
- Stator and rotor winding insulation
  - Thermal cycling
- Tape separation and girth cracking
  - Loosening of endwinding bracing and packing
  - Loosening of slot wedges
  - Abrasion

- Degradation at continuous high temperatures
  - Degradation of conductor stack bond
  - Degradation of groundwall bond
  - Degradation of slot packing, wedging and endwinding bracing
  - Differential expansion between coils and bracing materials

4. Contrast the advantages and disadvantages of Oil insulated CB, ABCB, SF6 and Vacuum CB in HV applications.

Oil insulated CB

Live tank:

- Construction: up to 12 breaks per phase, 400kV. Three support insulators
- Pollution: sufficient creep age, typically 2.5 to 3.5cms per kV rms.
- Voltage distribution: depends on value of capacitances between contacts and capacitance to earth.

Dead Tank:

Construction: single metal tank at earth potential: use of closed circuit gas system, suitable for expensive SF6, which has the following advantages:

- Blast noise minimal
- No exhaust to atmosphere
- Pollution: free from hazards of pollution.

Air-blast CB (ABCB) advantages:

- Cheapness and availability of interrupting medium and chemical stability.
- High speed operation
- Elimination of fire hazards
- Short and consistent arcing time and therefore, less burning of contacts
- Less maintenance
- Suitable for frequent operation
- Facility for high speed reclosure

The disadvantages are:

- An air compressor plant has to be installed and maintained
- Upon arc interruption, the air blast circuit breaker produces a high level of noise when air is discharged to the open atmosphere
- Current chopping
- Restriking voltage

SF6 CB

- Reliable current interruption, no restriking voltage
- Quiet operation
- The closed gas circuit keeps interior dry, so that there is no moisture problem
- Little erosion because of short arc time
- No carbon deposit
- As the circuit breaker is totally enclosed and sealed from atmosphere, it is particularly suitable for use in coal mines or in any industry where explosion hazard exists.

Vacuum Circuit Breakers (VAB)

- Long life with minimum maintenance
- Completely enclosed and seal construction for indoor and outdoor use
- Extremely short and consistent arcing and total break times
- Suitability for very fast automatic reclosure
- No fire risk
- No noise and no emission of gas or air during operation

5. State the considerations which must be made when designing overhead line insulators.

Insulators must support the conductors and withstand both the normal operating voltage and surges due to switching and lightning. Insulators are broadly classified as either pin-type, which support the conductor above the structure, or suspension type, where the conductor hangs below the structure. The invention of the strain insulator was a critical factor in allowing higher voltages to be used.

Insulators for very high voltages, exceeding 200 kV, may have grading rings installed at their terminals. This improves the electric field distribution around the insulator and makes it more resistant to flash-over during voltage surges.

6. Explain the process of insulator flashover and provide three methods which can help alleviate the problem.

The process of the flashover is:

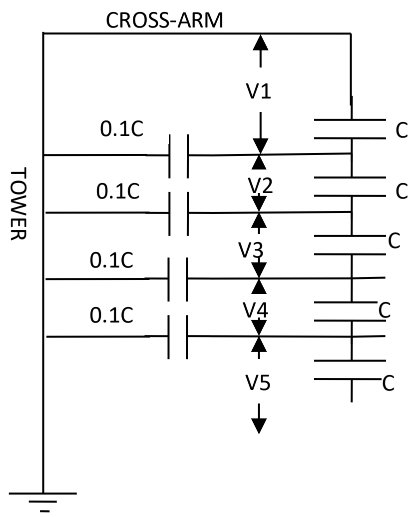
- arrival of nearly pure water at an insulator which carries a burden of pollution comprising soluble ionic;
- deposition of droplets from industrial fogs;
- build-up of frost, freezing fog or ice on the fouled surface of the insulator, the ionic components of the fouling then proceeding to depress the freezing point of the water and allow solution at the interface;
- switching in of a circuit containing wet, polluted insulators;
- Arrival of a lighting surge.

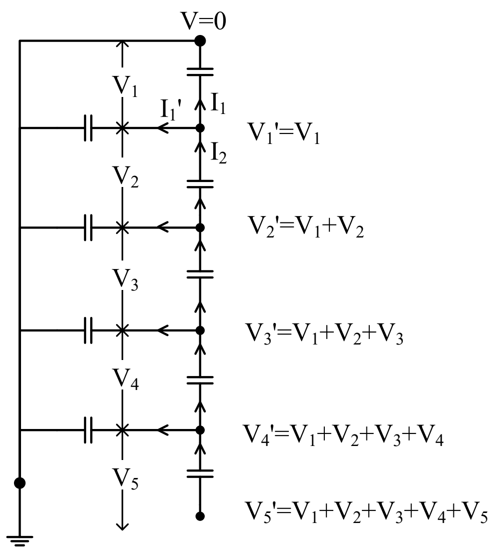
Means of remedy for Flashover include:

- Optimised insulator shapes and creepage
- Increase creepage path length without spoiling surface aerodynamics of insulator, inclination from the vertical, insulator profile to maintain air speed.
- Insulator washing (online and offline) (jets or spray) reduce the surface resident layer, Jet washing effective at moving solid pollution, costly high maintenance burden, could cause heavy wetting flashover on some types of insulator, high faults rate on washing equipment.
- Booster shed is a discharge resistant polymer fitted around existing insulator, increase surface creepage length, increases in tolerable pre-wetting is usually four fold, reduces water shedding
- Surface treatment

7. (i) A 33kV overhead line string insulator can be described electrically as shown in Figure below. A string of 5 insulator units each possessing a capacitance C is used to suspend a transmission line. The air capacitance between each of the unit cap/pin junctions to the earthed tower is 0.1C. Given that the wet surge flashover voltage is 70kV (peak) for each unit, determine whether any individual unit would flash over when the whole unit is subjected to a surge of 250kV (peak) on a rainy day.

(ii) With the design shown, the string efficiency is low due to non-uniform distribution of voltage. Provide one measure, with the aid of a sketch, that can help improve the string efficiency and explain how the improvement is achieved.





(i) From Kirchhoff's Law:

$I_2=I_1+I_1'$, therefore,

$2\pi fCV2=2\pi f0.1CV1+2\pi fCV1$; $V2=1.1V1$

Similarly:

$V3=V2+0.1\ (V1+V2)=1.1V2+0.1V1$

Substituting V2 for V1

$V3=1.31V1$

Similarly:

$V4=V3+0.1\ (V1+V2+V3) = 1.651V1$

And $V5 =V4+0.1\ (V1+V2+V3+V4) = 2.1571V1$

$V1+V2+V3+V4+V5 =V1+ (1.1V1) + (1.31V1) + (1.651V1) + (2.1571V1) = 250kV$.

Therefore, V1 = 33.64 kV

V2 = 38.10 kV, V3 = 45.37kV, V4 = 57.18kV, V5 = 74.71kV

Therefore, the unit at the bottom will flashover.

(ii) At a working voltage of 33kV,

$V1 + V2 + V3 + V4 + V5 = 33kV/1.732 = 19.050kV$.

V1=2.64kV, V2=2.90kV, V3=3.46kV, V4=4.36kV, V5=5.69kV

String efficiency =Vtotal/(5xV5) = 19050/(5x5690) = 0.670

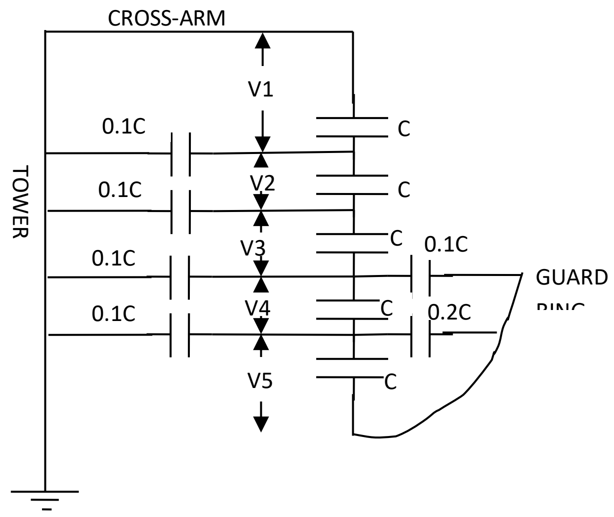
Significance: -- low string efficiency means that the withstand voltage of the insulator string is low with the same number of units, and the ones close to high voltage end can be more easily broken down.
The reason for the low efficiency is the non-linearity in voltage distribution among insulator units, resulted from the capacitance between the units and line towers. This can be seen from the solution procedures above. With the stray capacitances, the efficiency would be unity.

One solution using a Guard-ring is as shown below.
V4+0.1(V4+V5)=V3+0.1(V1+V2+V3)
and
V5+0.2V5=V4+0.1(V1+V2+V3+V4);
Therefore, V5=1.532V1, V4=1.364V1
V1 + V2 + V3 + V4 + V5 = 33kV/1.732 = 19.050kV, V5=4.63kV
String efficiency =Vtotal/(5xV5) = 19050/(5x4630) = 0.823

8. **(i)**A 33kV overhead line string insulator is made of 5 insulator units each possessing a capacitance C is used to suspend a transmission line. The air capacitance between each of the unit cap/pin junctions to the earthed tower is 0.1C. Given that the wet surge flashover voltage is 65kV (peak) for each unit, determine whether any individual unit would flash over when the whole unit is subjected to a surge of 250kV (peak) on a rainy day.

(ii) Determine the string efficiency in Q.1(a)(i). Explain what has been the cause of the non-linear voltage distribution across the insulators and what role the ring guard has played in voltage distribution.

(a) (i)



From Kirchhoff's Law

2πfCV2=2πf0.1CV1+2πfCV1; V2=1.1V1
Similarly:
V3=V2+0.1(V1+V2)=1.1V2+0.1V1
Substituting V2 for V1
V3=1.31V1

Similarly:
$V4+0.1(V4+V5)=V3+0.1(V1+V2+V3)$
Substituting V2 and V3 for V1
$1.1V4+0.1V5=1.651V1$ (equation 1)
Similarly:
$V5+0.2V5=V4+0.1(V1+V2+V3+V4)$; (equation 2)
Resolving equation 1 with 2
$V4=1.361V1$; $V5=1.532$
$VT=V1+V2+V3+V4+V5=250kV$
Then: V1=39.66kV, V2=43.63kV, V3=51.96kV, V4=53.98kV, V5=60.76kV
Given the wet surge flashover voltage is 65kV, the figure above indicates the bottom unit would not flashover.

(ii)

String eff. = $V_{totoal}/5V_5$ = 250/5x60.76=0.823
Clearly the stray capacitance to the power caused the non-linear voltage distribution, without which every unit of the insulator string would have exactly the same voltage. The cause for the imperfect efficiency is caused by the stray capacitance.

The ring guard helped to improve the string efficiency by directly more currents to the units on the top, reducing stray effects. This can be understood from the mathematical formulae in calculations in part (a)(i).

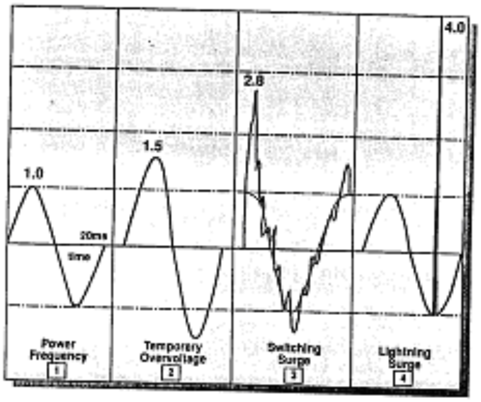
Lec 4: Insulation Coordination

1. Give the three types of overvoltages which need to be considered in insulation design and coordination for HV power plant. Explain their source and their manifestation

- *Temporary overvoltage, switching surge, lightning impulse*
- *Source*

  Temporary overvoltage --- Earth fault, Load sheding, Live energisation, resonance
  Switching surge – switching activities in power systems
  Lightning --- weather related
- *Manifestation*

  Transient overvoltage --- less than 50% higher
  Switching surge -- Upto 2.5 times of rated voltage , According to IEC71, switching surge can be simulated by a periodical waveform with front duration of hundreds of μs and a tail duration of thousands of μs.
  Lightning impulse – up to 4 times rated voltage. According to IEC71, lightning surge can be simulated by a aperiodical waveform with a front duration of the order of one of μs and a tail duration of tens of μs.

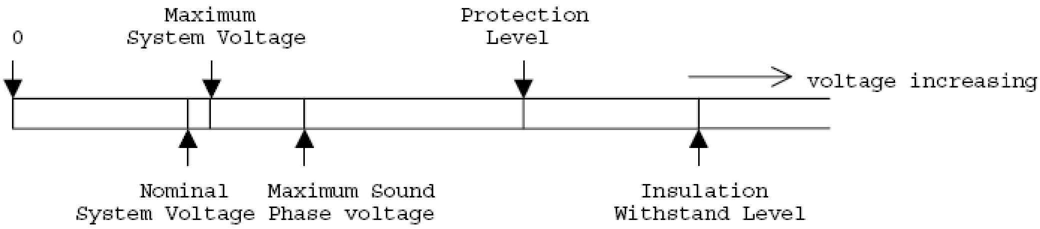


2. Provide the definition of the basic insulation level (BIL) of an insulation system, and explain its significance in HV system design

- When lightning impulse over voltage appears in the system, it is discharged through surge protecting devices before the equipment of the system gets damaged. Hence, the insulation of such equipment must be designed to withstand a certain minimum voltage before the lightning impulse over voltage gets discharged through surge protecting devices. Therefore, operating voltage level of surge protecting devices must be lower than the said minimum voltage withstanding level of the equipment. This minimum voltage rating is defined as BIL or basic insulation level of electrical equipment.
- Therefore, the voltage withstanding capacity of all equipments of an electrical substation or an electrical transmission system must be decided as per its operating system voltage. To ensure the stability of the system, during over voltage phenomenon, the breakdown or flash-over strength of all equipment connected to the system, should exceed a selected level.
- There are two basic classifications of insulation strength: basic insulation level (BIL) or lightning-impulse withstand voltage, and power-frequency withstand voltage (often called “hipot” voltage).

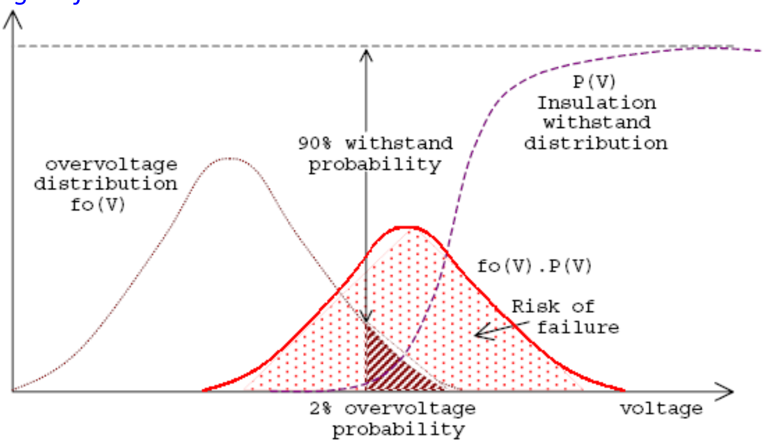
3. Describe and explain respectively how the conventional and statistical method of insulation coordination are applied in HV insulation system design.

The traditional insulation coordination is arranged as shown in the figure below.



By keeping an appropriate margin between each two of the adjacent stated voltages insulation is said to be coordinated.

The aim of statistical methods is to quantify the risk of failure of insulation through numerical analysis of the statistical nature of the overvoltage magnitudes and of electrical withstand strength of insulation.



In statistical method, the insulation is selected such that the 2% over voltage probability coincides with the 90% withstand probability as shown.

4. A transformer has an impulse insulation level of 1000kV and is to be operated with a margin of 15% under lightning impulse conditions. The transformer has a surge impedance of 1600Ω and is connected to a transmission line having a surge impedance of 360Ω. A short length of overhead earth wire is to be used for shielding the line near transformer from direct strikes. Beyond the shielded length, direct strokes on the phase conductor can give rise to voltage waves of the form $820e^{-0.05t}$ kV (where t is expressed in μs). if the corona distortion in the line is represented by the expression $\frac{\Delta t}{x} = \frac{1}{B}[1 - \frac{e_o}{e}]$ μs, where B=120m/μs and e_o=180kV, determine the minimum length of shielding wire necessary in order that the transformer insulation will not fail due to lightning surges.

The maximum permissible voltage is

1000kV x (100-15)%=1000 x 0.85 =850kV

The transmission coefficient is $\alpha = \frac{2 \times 1600}{1600 + 360} = 1.63$

Thus the maximum surge voltage allowed is 850/1.63= 521.47kV.

This means that the distortion along the lines must reduce the voltage to 521.47kV.

Therefore, 820e-0.05t = 521.47 kV. This gives the delay time as t = 9.05 μs

Substituting into equation, we have, $\frac{9.05}{x} = \frac{1}{120}[1 - \frac{180}{521.47}]$

solving the equation gives x =1658.5m.

So the minimum length of shielding wire should be 1658.5m.

5. A 3-phase 132 kV line having BIL of 300 kV is supported on steel towers and protected by a circuit breaker. The earthing resistance at each tower is 20 Ω whereas the neutral of the lines is solidly grounded at the transformer just ahead of the circuit breaker. During an electric lightning, one of the towers is hit by lightning stroke of 20 kA.

(i) Calculate the voltage across each insulator string under normal conditions and during the process of lightning. Describe the sequence of events during and after the lightning stroke.

(ii) Determine the maximum earthing resistance with which the line will not be tripped under the same lightening condition.

(i) Under normal conditions, the line-neutral voltage is 132kV/sqrt(3) = 76.2kV. This is below the BIL level so there is no current flowing through the tower earthing resistance. The ground tower will have the same potential as ground.
During the lightning, 20kA current flowing through the grounding resistance, giving a voltage of 20kAx20Ω=400kV across the tower and ground. So the impulse exceeds the BIL value and a flashover immediately occurs on all three insulators short circuiting all three lines to the steel cross arms.
The resulting three phase short circuit will be sustained by the heavy short circuit current fed from the source of supply. The short circuit current will trip the CBs and cause line outage

(ii) If the earthing resistance can be reduced to under 300kV/20kA = 15Ω, The lines will remain in service even if the lightning of the same magnitude occurs, as the impulse resulted from the lightning will be below the BIL.

6. A lightning arrestor having a flashover voltage of 650 kV is located on a main 132-kV busbar providing protection to a 132/33kV transformer having a surge impedance of 1600Ω. The arrestor is subject to a surge of 500kV rising at 1000kV/µs originating on a 132-kV line, of surge impedance 400Ω, connected to the transformer via a busbar. The transformer is effectively earthed.

(i) Assuming the arrestor is 90 meters away from the transformer, determine the time required to travel between the two plant items, transmission and reflection coefficient for the lightning impulse.
(ii) Sketch the voltage waveform at the location of arrestor and the location of transformer.
(iii) The lightning impulse insulation level of the transformer on the 132kV side is 900kV. Determine, stating any assumptions made, the maximum possible voltage at the transformer terminal.
(iv) What would have been the maximum separation permissible between the transformer and the lightning arrestor, if the BIL of the transformer was 1000 kV and a protective margin of 15 % is required, for the above case?

[Note: $E_t = E_a + \beta(de/dt)\times 2l/300$]

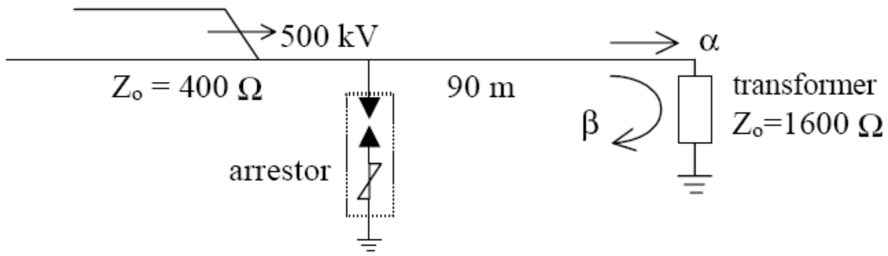
Solution:

(i) If the separation is 90 m, travel time of line J = 90/300 = 0.3 µs

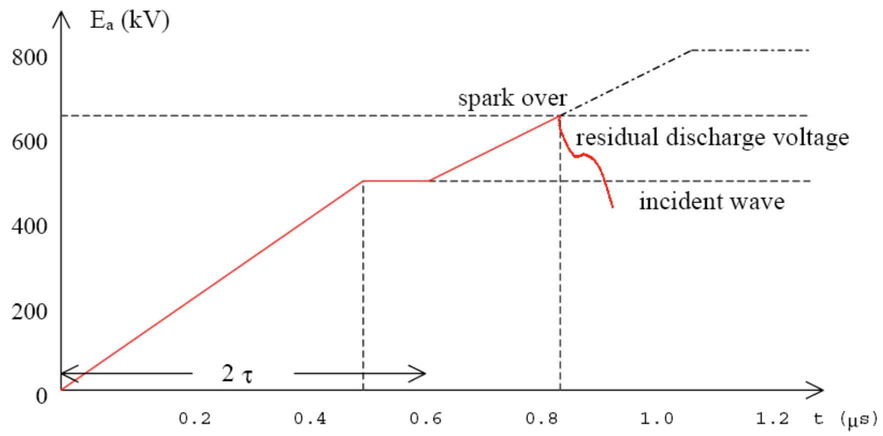
Transmission coefficient $\alpha = 2 \times \frac{1600}{1600+400} = 1.6$

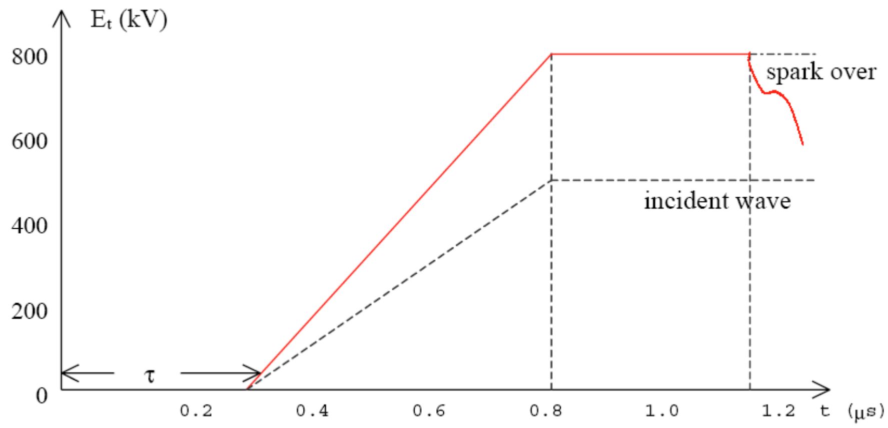
Reflection coefficient $\beta = 1.6 - 1 = 0.6$

(ii) The voltage waveforms at the arrestor location and at the transformer location can be sketched as follows.



The voltage waveforms at the arrestor location and at the transformer location can be sketched as follows.





(iii)

The maximum value of the voltage E_t at the terminal for each case can be determined from $E_t = E_a + 0.6\frac{de}{dt} \times \frac{2l}{300}$ up to a maximum of 0.6 E_a.

For 90 m, maximum E_t -> 650 + 0.6 x 1000 x 90 x 2 / 300 = 1010 kV (the peak impulse could be higher than 500kV, which can result in higher transformer terminal voltage)

Therefore maximum E_t = 800 kV (800kV obtained from the drawing)

(iv)

For a protective margin of 25 %, maximum permissible surge at transformer = 1000/1.15 = 869.56 kV

Therefore 869.56 = 650 + 0.6 x 1000 x 2 L / 300

This gives the maximum permissible length L = 54.89 m.

Lec 5 – HV Generation and Testing

1. List three types of techniques which can be adopted for HV voltage measurement, contrast their principles of operation.

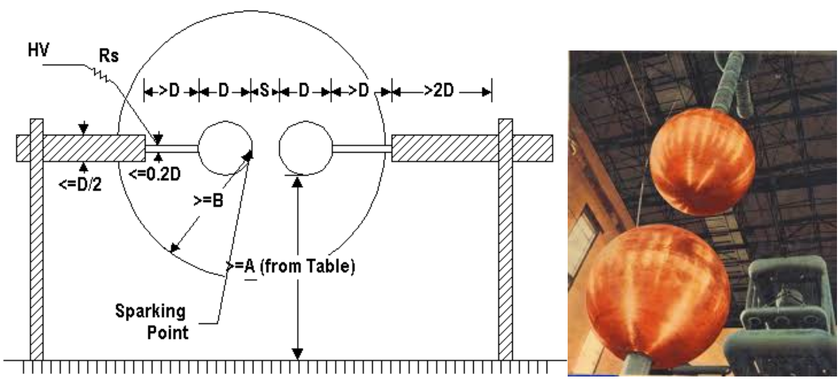
In high voltage, due to safety reasons, the meters cannot be connected directly to the high voltage conductors. It is therefore necessary to use equipment to scale down the voltage signal to a safe value that can be displayed on instruments. On the power system, voltage and capacitive voltage transformers are used, while other techniques are used in the laboratory. Obviously, accuracy of the whole system is of the utmost importance.

HV measurement techniques include:

- DC measurement: sphere gap, electrostatic voltmeter, series resistance micrometer and resistance divider
- AC measurement: sphere gap, electrostatic meter, series impedance ammeters, potential transformer and resistance or capacitance divider
- Impulse or high frequency measurement: sphere gap, peak meter and potential dividers with oscilloscope

- Sphere gap for voltage measurement

According to Paschen's Law, there exists a relationship between the flashover voltage, the gap length and the gas density. International standards have been drawn up to relate the gap length with flashover voltage. Provision has been made to correct for air pressure and temperature. Usually an accuracy of about 3 % can be obtained. Specifications such as IEC 52-1960 and BS358 contains tables for various sphere diameters and gap sizes.
Fig below shows a schematic and a picture of the real world sphere gap. The relationship of the voltage to be measured and the length of the gap can be found from BS 358.



Schematic diagram and picture of sphere gap for high voltage measurement.

- Voltage divider

Fig below shows the principle of a voltage divider, where the impedance values determine the proportion of the voltage V_2 over V_1. For DC measurement, the impedances take the form of resistors. Both resistors and capacitors can be used for AC and impulse measurement.

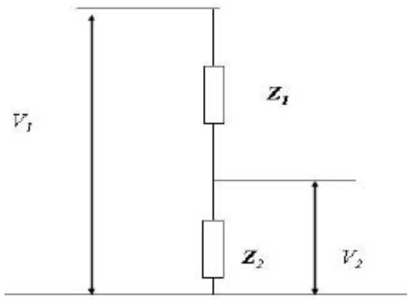


Fig. The principle of voltage divider for high voltage measurement.
Clearly,

$$V_2 = \frac{Z_2}{Z_1 + Z_2} V_1$$

For capacitive and resistive dividers.

$$V_2 = \frac{C_1}{C_1 + C_2} V_1 \qquad\qquad V_2 = \frac{R_2}{R_1 + R_2} V_1$$

Stray capacitance of resistors may affect accuracy in measurements.

- **Electrostatic voltmeters**

Electrostatic voltmeters rely on the Coulomb force of attraction between two electrodes that have a potential difference between them. Such a measuring system has the advantage that the measurement relies on the laws of physics. In addition, the input impedance of the meter is capacitive. Especially in the case of DC, the meter therefore does not load the measured circuit.
Attractive force between electrodes of a parallel plate condenser is:

$$F = \frac{1}{2} \epsilon_o V^2 \frac{A}{s^2}$$

Where, A is the electrode area and s the separation between plates. When one of the electrodes is allowed to move, the force on it can be measured.

2. A resistor divider has a high voltage arm of 39.6MΩ and a low voltage arm of 0.4 MΩ. Determine the reading on an electrostatic voltmeter (measuring rms value) connected across the low voltage arm when the following voltages are applied.

(i) 40000+10000$sin100\pi t$,

(ii) 40000$sin100\pi t$+10000$sin(200\pi t)$

(i) Ratio of resistor divider: (0.4/(39.6+0.4))=0.01, therefore the voltage appearing across the low voltage arm becomes: 400+100sin100πt, reading of the meter is:

$$=\sqrt{400^2 + \frac{100^2}{2}} = 405V$$

(ii) Reading: $=\sqrt{\frac{400^2}{2} + \frac{100^2}{2}} = 292V$

3. For Q2, if capacitors of 4000pF and 196,000pF are connected in parallel with the resistors across the high voltage and low voltage arms respectively, determine the reading of the electrostatic voltmeter.

i)Ratio of capacitor divider: (4000/(4000+196000))=0.02, therefore the voltage appearing across the low voltage arm becomes(DC component unaffected, R>>Zc): 400+200sin100πt, reading of the meter is: $\sqrt{400^2+\frac{200^2}{2}}$*=424V*

(ii) voltage appearing across the low voltage arm becomes: 800+200sin100πt, reading of the meter is: $\sqrt{\frac{800^2}{2}+\frac{200^2}{2}}$*=583V*

4. It is important to determine the dielectric strength of solid insulants in HV design. Outline the procedures, with the aid of schematic diagrams, for carrying out such tests. Explain also how the maximum safe working voltage is determined from test results.

Solution:

- *Sometimes insulators after manufacture are found to contain flaws in the form of voids or air spots. These spots (due to non-homogeneity) have a lower breakdown strength than the material itself, and if present would gradually deteriorate and cause ultimate breakdown after a number of years.*
- *High degree ionisations caused in these spots would give rise to high energy electrons which would bombard the rest of the material, causing physical decomposition. In plastic type of materials, there might be carbonizations, polymerisations, chemical decomposition etc., which would gradually diffuse into the material the by-products, causing chemical destruction.*
- *The useful life of a component using such material will depend on the weak spots and the applied voltage. If the applied voltage is small, the life of the component is longer. From design considerations the voltage to be applied if a particular life span is required can be calculated.*
- *The loss factor of a material does not vary much for low voltages, but as the voltage is increased at a certain value it starts increasing at a faster rate. This is the long time safe working voltage, since beyond this, the specimen would keep on deteriorating.*
- *If the apparatus need be used only for a short period, the applied voltage can be higher than this safe value. In a long length of cable, the greater part of the cable would be in good conditions but with a few weak spots here and there.*

- *The method is to apply suitable high voltage to sample, and subject it to a number of duty cycles (heat cycles, make and break cycles). Discharges caused are made to give pulses to a high frequency amplifier. The discharges caused are observed before and after such duty cycles to see whether there is any appreciable increase in the pulse intensity after the cycle of operation.*

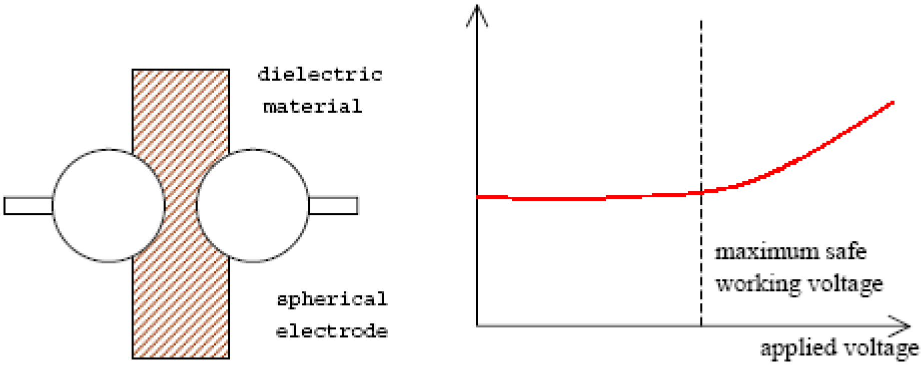


Figure (left): test regime, (right): Variation in losses. Dotted line indicates maximum safe working voltage.

5. Explain why HVDC are often applied to test AC cables. Discuss why DC test can result in failures when cables are reinstated for operation after test.

- High cable capacitance resulting in requirement of large capacity of testing equipment makes impossible to carry out AC test. With DC supply, there is no steady state capacitive current requirement.
- DC test can leave space charge, which can increase local electrical field or stress, leading to insulation breakdown.

6. Explain why HV tests need to be carried out on HV materials and equipment. Lists the various types of tests often carried out on (i) insulation materials, and (ii) completed equipment.

- To make sure electrical equipment and the associated insulation systems are capable of withstanding working voltage and overvoltages.
- testing of insulating materials (samples of dielectrics)
  - permittivity, dielectric loss per unit volume, and the dielectric strength of the material

tests on completed equipment.

  - capacitance, the power factor or the total dielectric loss, the ultimate breakdown voltage and the flash-over voltage.

7. Explain why switching and lightning impulse tests are often carried out on HV equipment and describe the test waveforms required for the tests.

- To investigate the influence of surges in transmission lines, breakdown of insulators and of the end turns of transformer connections to line.
- The IEC Standard impulse wave of 1.2/50μs wave is generally used.
- Overvoltages of much higher duration arise due to line faults, switching operations etc, for which impulse waves such as 100/5000 μs duration may be used.

8. Lists the factors that may affect the dielectric loss.

- thickness of the sample tested
- shape of the sample
- previous electrical and thermal treatment of the sample

- shape , size , material and arrangement of the electrodes
- nature of the contact which the electrodes make with the sample
- waveform and frequency of the applied voltage (if alternating)
- rate of application of the testing voltage and the time during which it is maintained at a constant value .
- temperature and humidity when the test is carried out
- moisture content of the sample.

9. Polarisation index (PI) is often applied to rotating machine insulation tests. Explain what is PI, and how it is applied to a winding insulation test.

- The index is calculated from measurements of the winding insulation resistance.
- Before measuring the insulation resistance, remove all external connections to the machine and completely discharge the windings to the grounded machine frame.
- Proceed by applying either 500 or 1000 volts dc between the winding and ground using a direct-indicating, power-driven megohmmeter.
- For machines rated 500 volts and over, the higher value is used. The voltage is applied for 10 minutes and kept constant for the duration of the test.
- The polarization index is calculated as the ratio of the 10-minute to the 1-minute value of the insulation resistance, measured consecutively.
- Polarization Index = $\frac{\text{Resistance after 10 minutes}}{\text{Resistance after 1 minute}}$
- The recommended minimum value of polarization index for ac and dc motors and generators is 2.0.
- Machines having windings with a lower index are less likely to be suited for operation.
- The polarization index is useful in evaluating windings for:
  - Buildup of dirt or moisture.
  - Gradual deterioration of the insulation (by comparing results of tests made earlier on the same machine).
  - Fitness for overpotential tests.
  - Suitability for operation.