High Voltage Engineering

- Wk1 - Introduction, Electric Field
- Wk2 - Insulation materials and breakdown mechanisms
- Wk3 - Insulation in HV Plant Items
- Wk4 - HV Insulation Coordination
- Wk5 - HV generation, measurement, and testing
- Wk6 - Seminar and revision

Prof. Chengke Zhou
Email: c.zhou@gcal.ac.uk

Wk 1 - Introduction

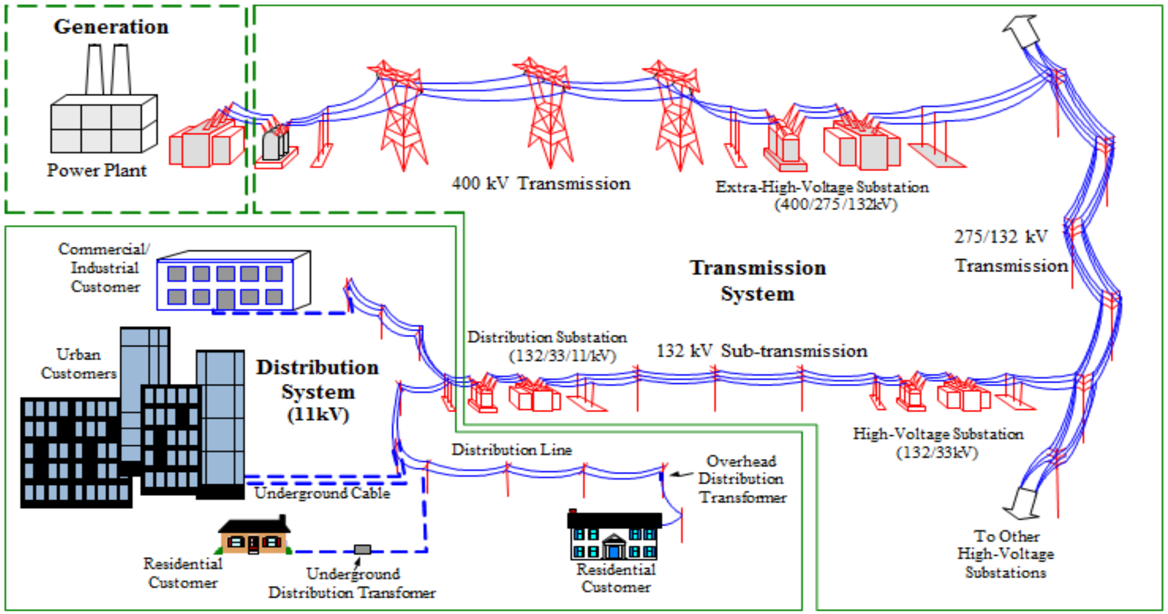


Fig. 1 In power system in the UK, power is usually generated at a level of 11kV at large power stations. Power generated is then transmitted to load centre at voltage levels of 400/275/132kV. Power distribution voltage levels include mainly 33kV and 11kV. The distribution transformers reduce the voltage to 400V/230V, which supplies the houses, shopping centres, etc.

Voltage Classification

- Two factors considered in classifying a voltage as "high voltage" are the possibility of
  - causing a spark in air,
  - and the danger of electric shock by contact or proximity.
  - The definitions may refer to the voltage between two conductors of a system, or between any conductor and ground.
- In electric power transmission engineering, high voltage is usually considered any voltage over approximately 35,000 volts. This is a classification based on the design of apparatus and insulation.
- The International Electrotechnical Commission and its national counterparts (IET, IEEE, etc.) define *high voltage* as above 1000 V for alternating current, and at least 1500 V for direct current—and distinguish it from low voltage (50 to 1000 VAC or 120–1500 VDC) and extralow voltage (<50 VAC or <120 VDC) circuits. This is in the context of building wiring and the safety of electrical apparatus.

HVAC systems

Pros:

- Easy transformation of energy between the different voltage levels,
- convenient and safe handling (application),

Cons:

- transmission/ compensation of reactive power,
- stability problems,
- voltage differences and load angle issues at long lines.

HVDC (direct current)

- No (capacitive) charging currents
- Grid coupling (without rise of short-circuit current)
- No stability problems (frequency)
- Higher power transfer
- No inductive voltage drop
- No Skin-Effect
- High flexibility and controllability

Material properties in HV systems

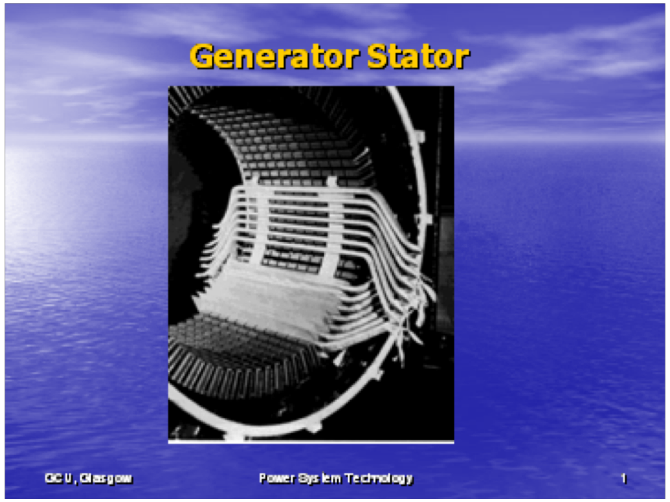
The use of higher voltages introduces a number of new aspects that have to be taken into account in order to prevent current leakage or flashover.

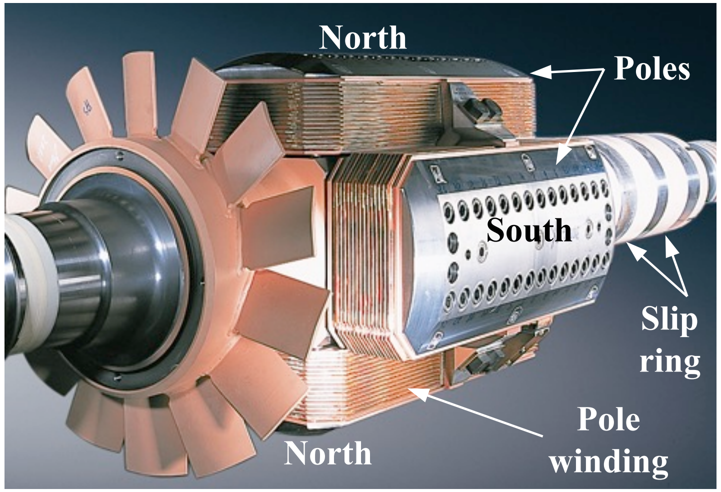
	Material	Conductivity (σ), S/m	Permittivity (ε_r)
Conductors	Silver	$6.17 \cdot 10^7$	-
	Copper	$5.8 \cdot 10^7$	-
	Aluminium	$3.82 \cdot 10^7$	-
	Iron	$1.03 \cdot 10^7$	-
	Carbon (graphite)	$1.0 \cdot 10^5$	-
	Water (sea)	4	-
	Water (fresh)	10^{-3}	-
Insulators	Water(distilled)	$2 \cdot 10^{-4}$	80
	Porcelain	10^{-10}	6
	Glass	10^{-10}	5
	Air	-	1.0006
	SF_6	-	1

Main Power Plant Items

- Generator
- substation
- Transformer
- Switchgear
- Cables/overhead lines

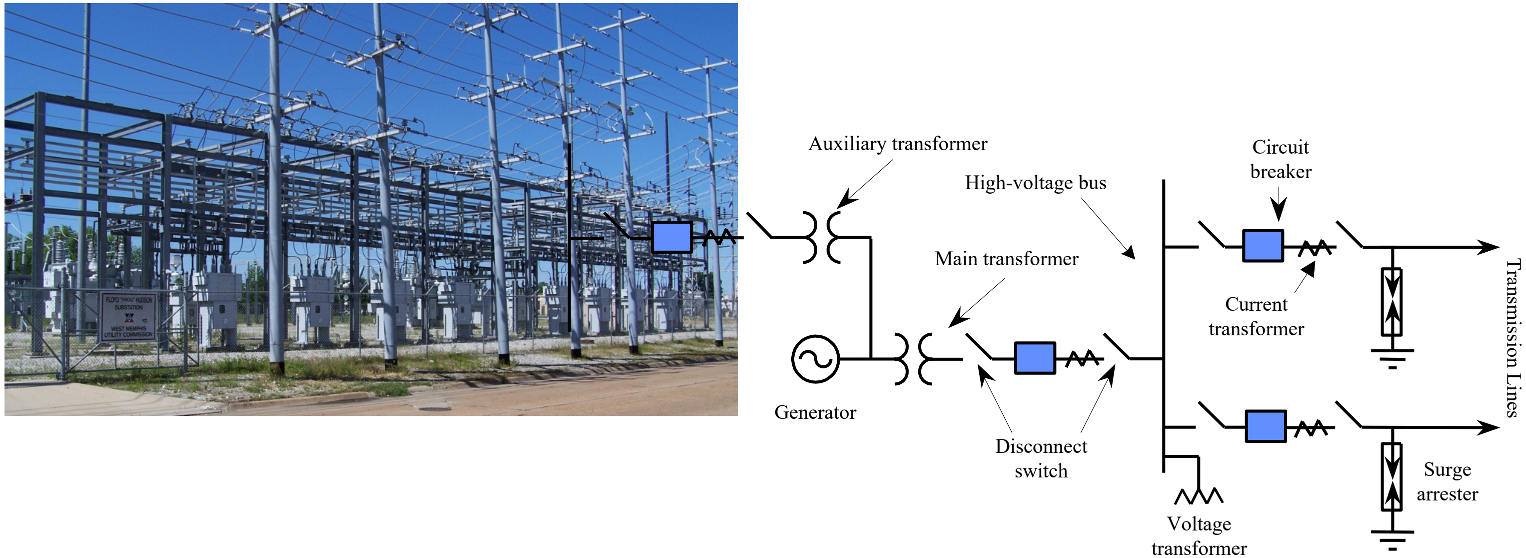
Rotating Machines





Large generator voltage is typically between 10 and 25 kV. The insulation of the stator bars relative to the stator slots poses a particularly difficult insulation problem in the light of the limited space, high voltage and temperature. Mica, bonded with epoxy resin is usually applied as insulation material.

Substation

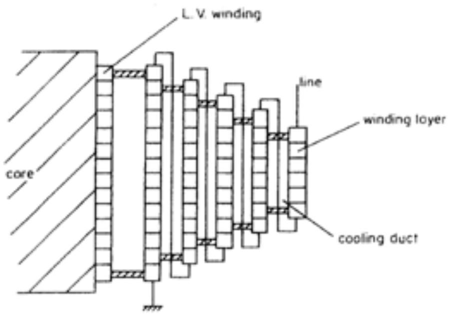


The substations are the nodes in the power system where several lines and transformers are connected together. It hosts transformers, instrument transformers, switchgears, lines, cables, protection equipment, ancillary devices etc. Insulation coordination is important.

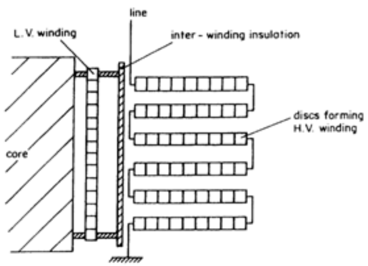
Transformers

- Materials: Oil and paper/pressboard

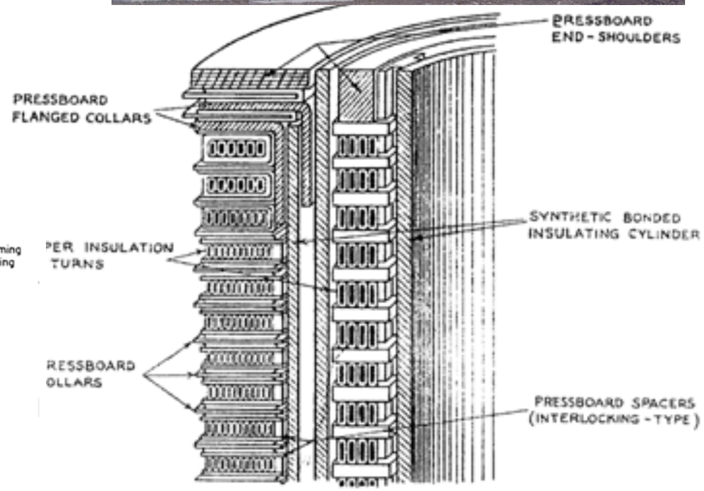
- Windings: layer or disc type.



A multi-layer winding



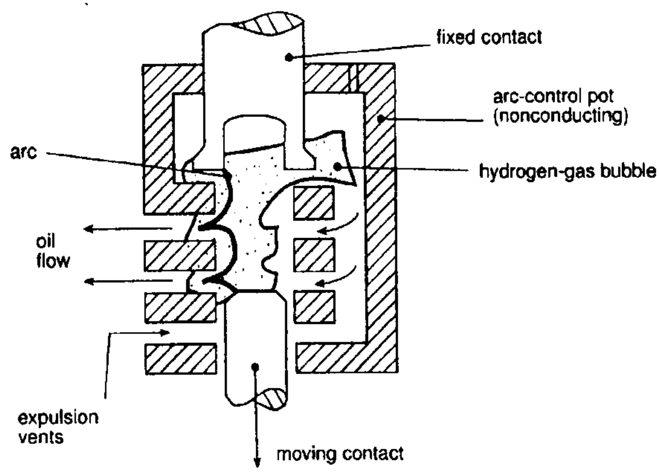
Disc-type HV winding



Disc Winding

Circuit breakers

- CBs are filled with insulating fluids
  - Air at atmospheric pressure
  - Compressed air
  - Oil(produces hydrogen for arc extinction)
  - Sulphur hexafluoride
  - Ultra high vacuum



- Insulating fluid filling breakers has 2 functions
  - Extinguishes arc between contacts
  - Provides insulation between contacts and earth

Cable/Overhead line/GIL

They differ in insulation systems, each having own advantages and disadvantages

Overhead lines -- properties and advantages:

- 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 PNat
- Thermal Power limit is a multiple of PNat
- 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

Power cables properties

- Insulating Materials: Plastics/Synthetics (PE, XLPE), Oil – Paper
  - Polypropylene Laminated Paper (PPLP): reduced power loss and higher electrical strength than oil-paper cables
- high capacitance, large capacitive currents, limits maximum cable length
- Transferable power is limited by:
  - permitted temperature of the dielectric
  - high thermal resistances of accessories & auxiliary equipment
  - soil condition
- Thermal Power S_{therm} is essential for continuous rating/operation
- High voltage cables have a much higher P_{nat} than S_{therm} (of about 2...6)

Advantages/Disadvantages

Advantage

- 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

Disadvantage

- 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

GIL properties

- Insulating Material: SF_6 and N_2*:* Currently 80% N_2 and 20 % SF_6*; pressure: 3 to 6 bar*
- Currently no buried lines; laying only in tunnels or openly

Advantages:

- High transmission capacity/High load capacity/High overload capability
- Minimal dielectric losses
- Low mutual capacitance ⇨ low charging current / power
- Good heat dissipation to the environment
- Large transmission capacity
- 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

Electric Field Theory

- Terms:
  - ***Electric field*** --- the space surrounding an electric charge or in the presence of a time-varying magnetic field has a property called an **electric field**. This electric field exerts a force on other electrically charged objects
  - ***Electric stress-***--force, E, on a unit of charge placed in insulant. Charged particles acquire kinetic energy under action of this force.
  - ***Voltage*** --- between two points equals the work done in moving unit charge between them.

$$V = -\int E dx \qquad and \quad D = -\frac{dV}{dx}$$

    - Electric stress numerically equals the voltage gradient and can be calculated by E = V/d
    - Where V is applied voltage and d is the thickness of insulation.

Electric strength

- ***Electric strength*** --- strength of insulant or maximum stress insulant can withstand.

- Insulant can be gases, liquids and solids.

- Influencing factors include:
  - Pressure
  - Temperature
  - Voltage waveform
  - Electrode material
  - Presence of impurities
  - Field configuration

Field Theory

- ***Coulombs Law***: force between charge r apart

$$F = \frac{q_1 q_2}{4\pi\varepsilon r^2} \qquad \varepsilon = \varepsilon_o \varepsilon_r$$

  - Where ε_o: permittivity of free space 8.85×10^{-12} F/m

- ***Electric field strength***: force at a distance r on unit charge:

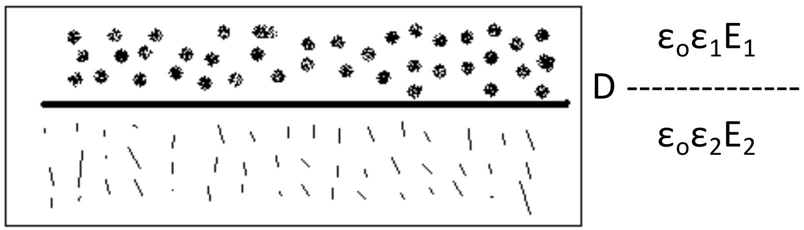
$$E = \frac{q}{4\pi\varepsilon r^2} \qquad volts / meter$$

  - This is the force on ions and electrons within insulating materials.
  - If the force is high enough, breakdown may occur.
  - Breakdown voltage of air is 30kV/cm.

Electric flux density

- Flux density: D = εE Coulombs/meter^2
- Consider the boundary between two insulating materials having ε_1 and ε_2
    - D is continuous at the boundary so
    - $D = \varepsilon_o \varepsilon_1 E_1 = \varepsilon_o \varepsilon_2 E_2$, thus: $$E_1 = \frac{\varepsilon_2}{\varepsilon_1} \cdot E_2$$

Material 1



Material 2

Example

- 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:

  – *Stress in air E1 = 2.2x stress in solids*

  – *Significance: weaker insulating material has higher stress*

    - *Case of gas filled void in solid insulating.*

Gauss's Law

- For any closed surface containing a system of charge, the flux out of surface is equal to the charge enclosed:
  - dS ---element of surface area. ∑q—total charge

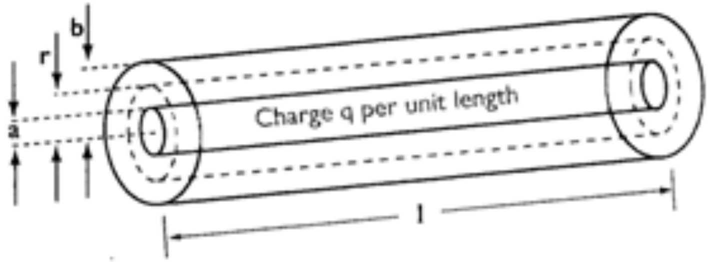
$$\oint_s D ds = \sum q$$

  - For a point charge q, surrounded by an arbitary closed surface S, flux density at any point r distance away is:

$$D = \frac{q}{4\pi r^2}$$

Application of Gauss's Law

- For a coaxial transmission line such as a cable



- Enclosed charge = ql
- Total flux across surface: $D2\pi rl = ql$
- *Since* $D = \varepsilon E$, *therefore:* $E = q/(2\pi\varepsilon r)$ *V/m.*
  - *This is field strength or stress in insulating material at radius r.*
  - *Voltage between conductor(r=a) and outer sheath(r=b) is:*

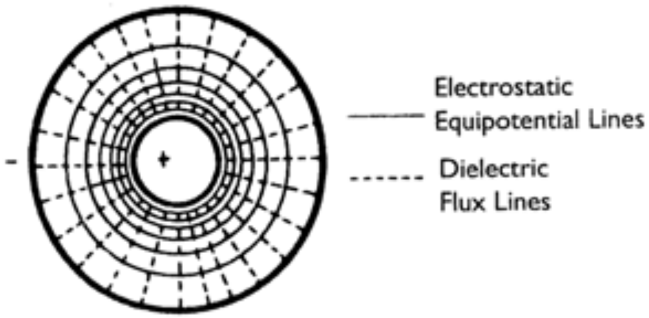
$$V = \int_a^b E_r dr = \int_a^b \frac{q}{2\pi\varepsilon} \frac{dr}{r} = \frac{q}{2\pi\varepsilon} \ln \frac{b}{a}$$

Electric stress and voltage in coaxial cable

- *Voltage between conductor(r=a) and outer sheath(r=b) is:*

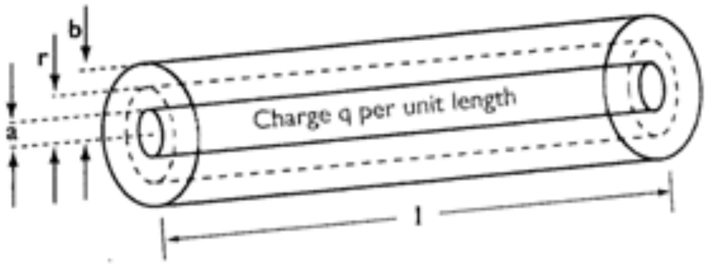
$$V = \int_a^b E_r dr = \int_a^b \frac{q}{2\pi\varepsilon}\frac{dr}{r} = \frac{q}{2\pi\varepsilon}\ln\frac{b}{a}$$

- *Electric stress:*



Example

- The inner conductor of a concentric cable has a diameter of 3cm, the outer diameter of the insulation is 8.5cm. The cable is insulated with two materials having a relative 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. (Note: the voltage applied to a concentric cable is given as: , where a and b are the inner and outer radius of the insulants respectively.)



Solutions:

Electrical stress at radius x of a concentric cable is given by:

$$E = \frac{q}{2\pi\varepsilon x}$$

Stress at surface of conductor and at interface of two insulants are therefore given as:

$$E_1 = \frac{q}{2\pi\varepsilon_o \times 5 \times 1.5}$$

$$E_2 = \frac{q}{2\pi\varepsilon_o 3 \times r}$$

Equating q gives: $r = \frac{E_1}{E_2} \times \frac{5 \times 1.5}{3} = \frac{38}{26} \times \frac{7.5}{3} = 3.65cm$

Thus the radial thickness of dielectrics are:

Inner: 2.15cm, outer: 0.6cm.

For inner insulants: E =38kV/cm, a = 1.5 and b = 3.65 therefore

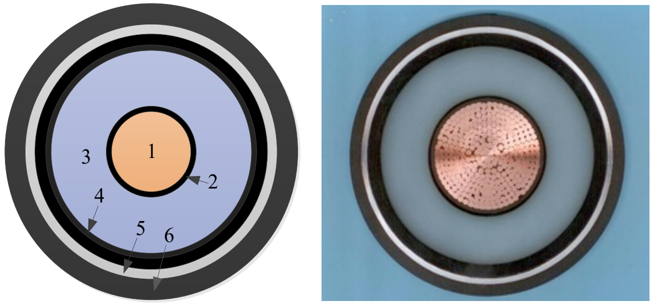
$$\text{V} = 38 \times 1.5 \times \ln\frac{3.65}{1.5} = 50.7kV$$

For outer insulants: E =26kV/cm, a = 3.65 and b = 4.25 therefore

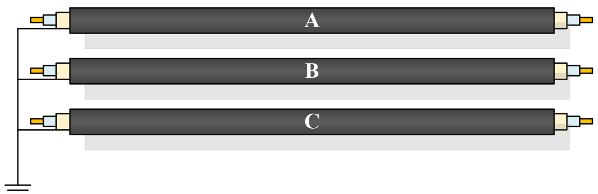
$$\text{V} = 26 \times 3.65 \times \ln\frac{4.25}{3.65} = 14.4kV$$

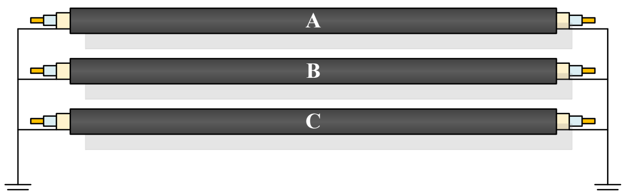
The total voltage = 50.7+14.4 = 65.1 kV

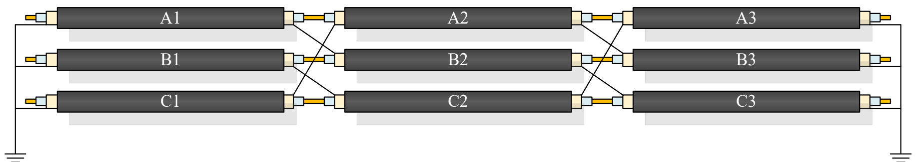
Practical cable design and earthing



1. Core conductor
2. Conductive screen
3. XLPE insulation
4. Insulation screen
5. Metallic sheath
6. Outer sheath

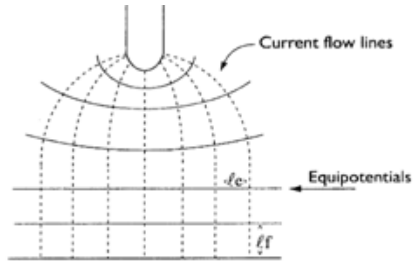






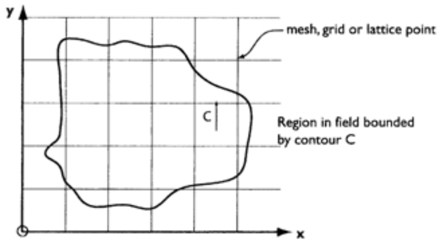
Electric Field Sketching

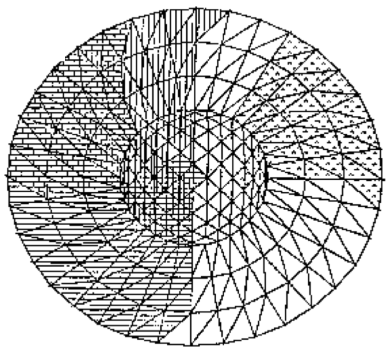
- Current flow lines
  - are 90° to the electrodes determined by the force on charged particles.
  - spread out on leaving electrodes to decrease current density and thus voltage gradient.
- Equipotentials
  - Perpendicular to current flow so that dV between equipotential lines are constant.

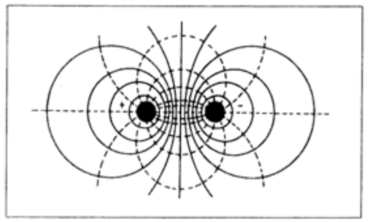


Computer Solutions

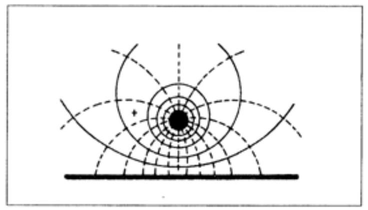
- Based on Finite Element or Finite Difference method (2-D, 3-D)
  - Procedure, differential equations, mesh, boundary conditions, FE method, solution
- Largely replaced experimental method for field estimation.







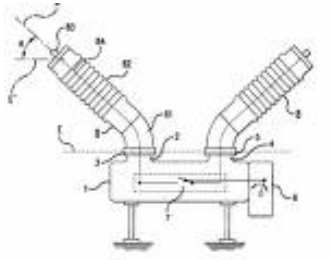
Electrostatic Field Pattern between Two Oppositely Charged Parallel Cylinders



Electrostatic Field Pattern between Oppositely Charged Plane and Cylinder (Note: Equal 1/2 of Plot shown in Figure 1.12(a))

Design of Bushings

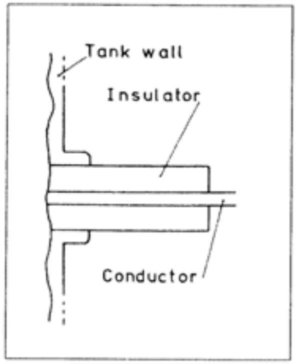
- Bushing --- insulate a HV conductor where it passes through an earthed wall.
- Simple insulation plate insufficient---flashover when dirty or wet.

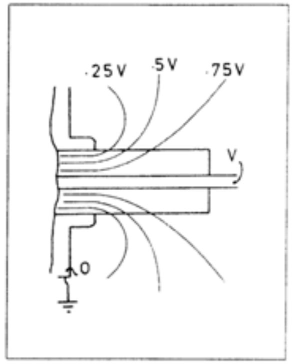


Examples

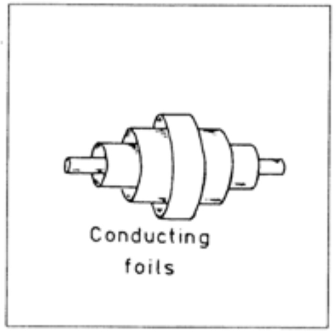
- A simple bushing

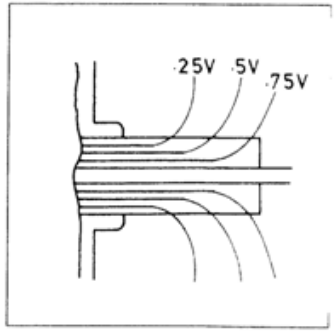
  and volt. distribution





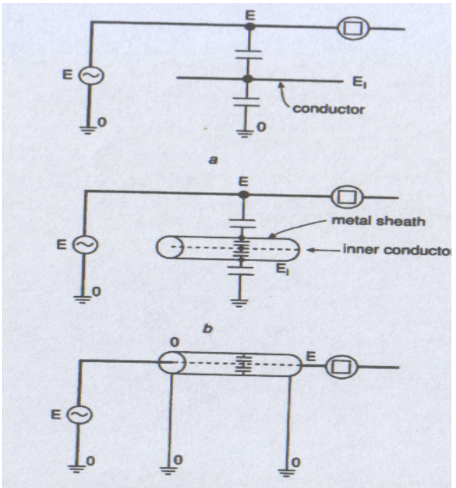
- Stress can be reduced by using concentric metal cylinders.





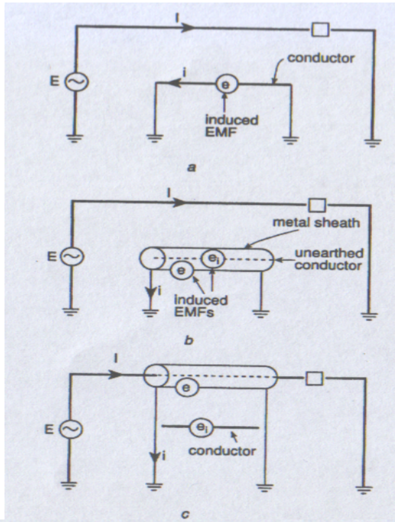
Electrical and Magnetic field

- Electrical and magnetic field arising from power system has health and safety implications



The electric field

a Conductor in electric field
b Screening effect of cable sheath from external electric field
c Screening effect of cable sheath from internal electric field



The magnetic field

a Conductor in magnetic field
b Partial screening effect of cable sheath from external source of magnetic field
c Partial screening effect of cable sheath from internal source of magnetic field