HV plant and Insulation Systems

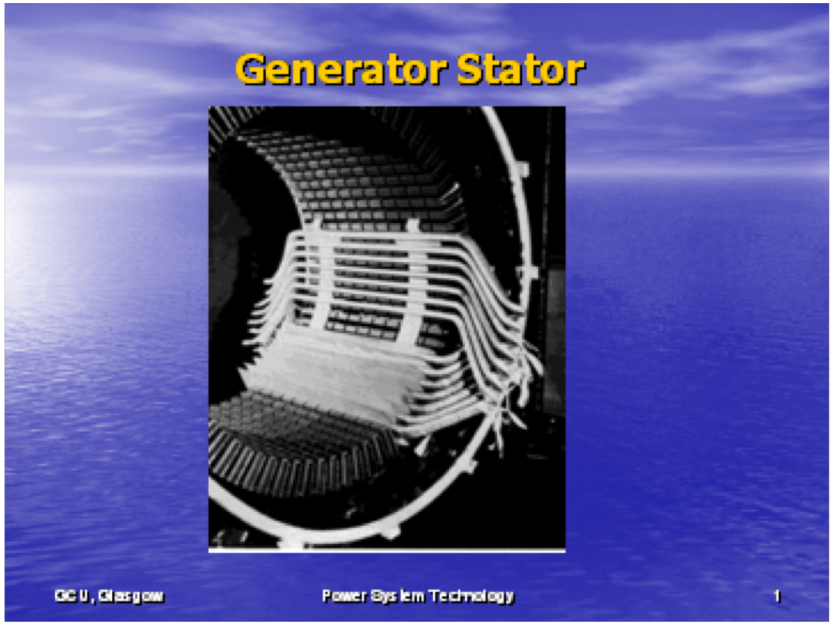
- Rotating machinery
- Transformers
- Switchgear
- Cable
- Overhead line/Insulator

Prof. Chengke Zhou
c.zhou@gcu.ac.uk

Learning Objectives

- To appreciate the insulation systems as applied to various power plant items
- To appreciate the stresses, and aging factors of insulation and their design requirements
- To appreciate the mechanisms of degradation of various insulation systems
- To understand the importance of reducing losses in insulation systems
- To demonstrate the nonlinear voltage distribution in insulation systems
- To understand the design and categorisation switchgears and their advantages and disadvantage
- To carry out simplified engineering calculations on insulator design

Rotating Machines

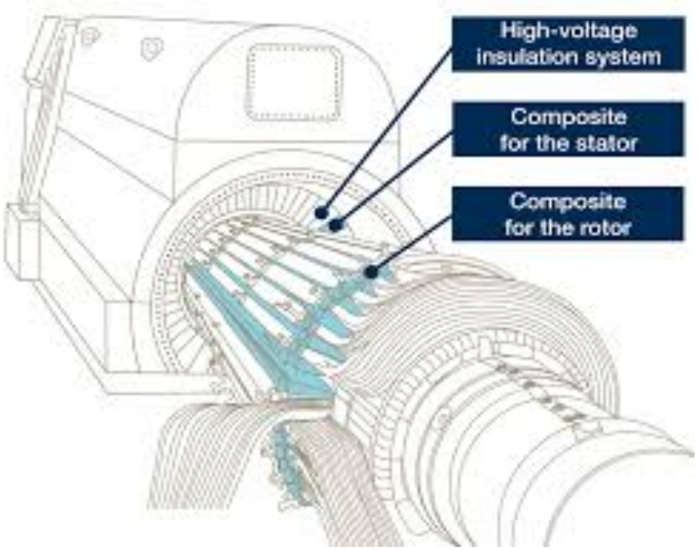


For stator windings, each conductor is made of small conductors insulated with glass braid and resin.

The main insulation is mica flakes bonded with epoxy resin. It is usually heat and pressure formed and should be void free.

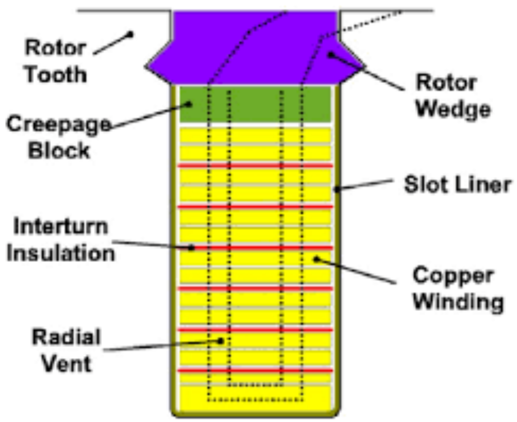
An important feature of the stator bar is the corona protection tape which is wound on the outside of the bar for the complete length.

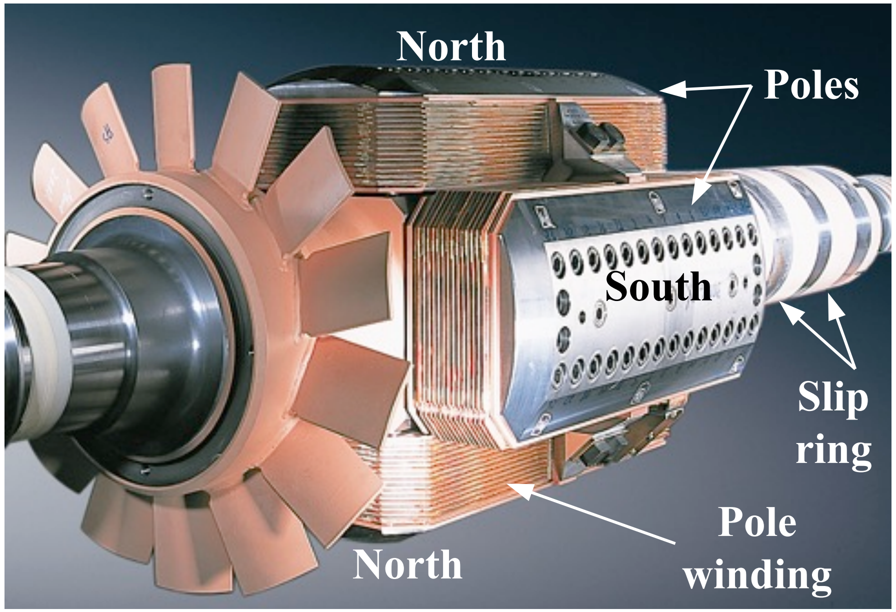
Rotating Machines



Insulation between coils and rotor body is resin-bonded glass-fibre.

Coils are often pre-fabricated and heat consolidated.





Insulating materials

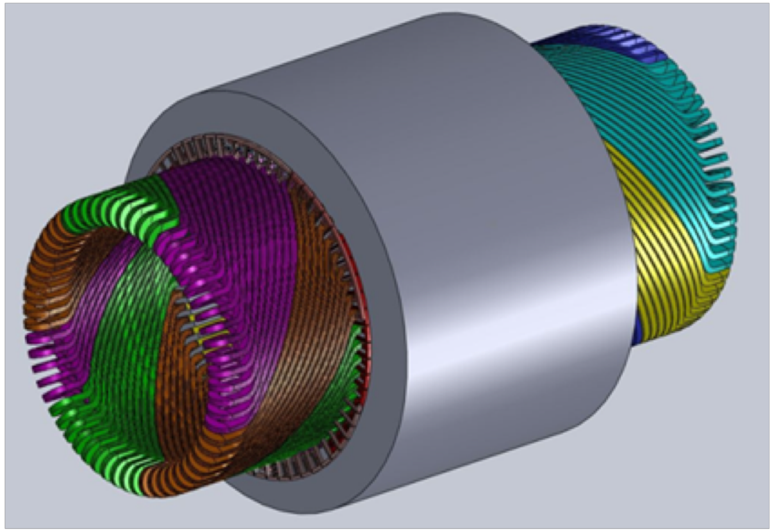
- 7 classes---Y, A, E, B, F, H and C
- Class Y – up to 90˚, unimpregnated paper, cotton, silk, natural rubber etc.
- Class A – up to 105˚, paper, cotton, silk impregnated with oil or varnish.
- Class E – up to 120˚, phenol formaldehyde laminats with cellulosic materials, epoxy resin
- Class B – up to 130˚, inorganic fibrous and flexible materials such as mica, glasses, fibres bonded and impregnated with organic resin.
- Class F – up to 155˚, as class B with approved resins.
- Class H – up to 180˚, as class B, with silicone resin, silicone rubber
- Class C – above 180˚, mica, asbestos, ceramics, glass ect.

Insulation Stress

- Thermal:
  - Cumulative thermal degradation resulting in delamination, cracking, embrittlement or depolymerisation
- Electrical:
  - Internal discharges causing erosion, transient pulsing from switching surges, tripping on overload
- Mechanical:
  - Differential expansion and contraction. Bar vibration
- Environmental:
  - Contamination from water, oil, dust, carbon, salt, rust, sand. Radiation degradation.

Insulation Design

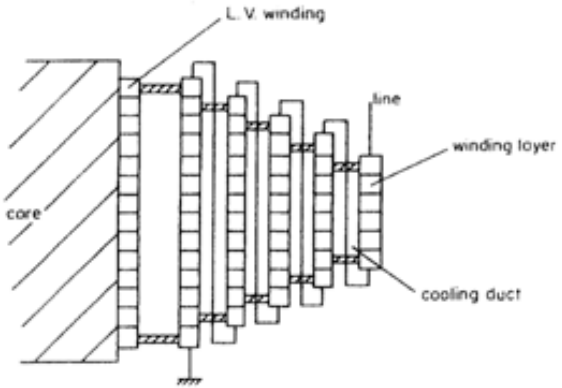
- Factors:
  - Properties of materials
  - Operating conditions particularly temperature and vibration
  - Cost of materials



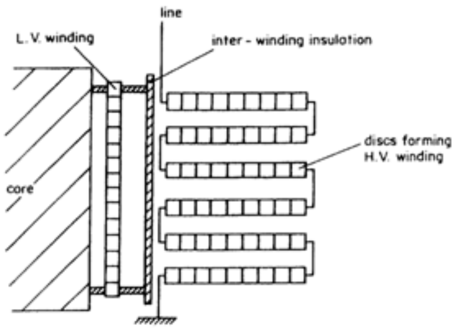
- Main areas of concern:
  - Main wall insulation thickness
  - Stresses at coil corners
  - Discharges where coil leaves slot
  - Temperature cycling
  - Mechanical integrity
- Insulation testing
  - Insulation resistance, high voltage, surge overvoltage, high DC voltage, 50Hz tanδ, discharge and dielectric loss.

Insulation in transformers

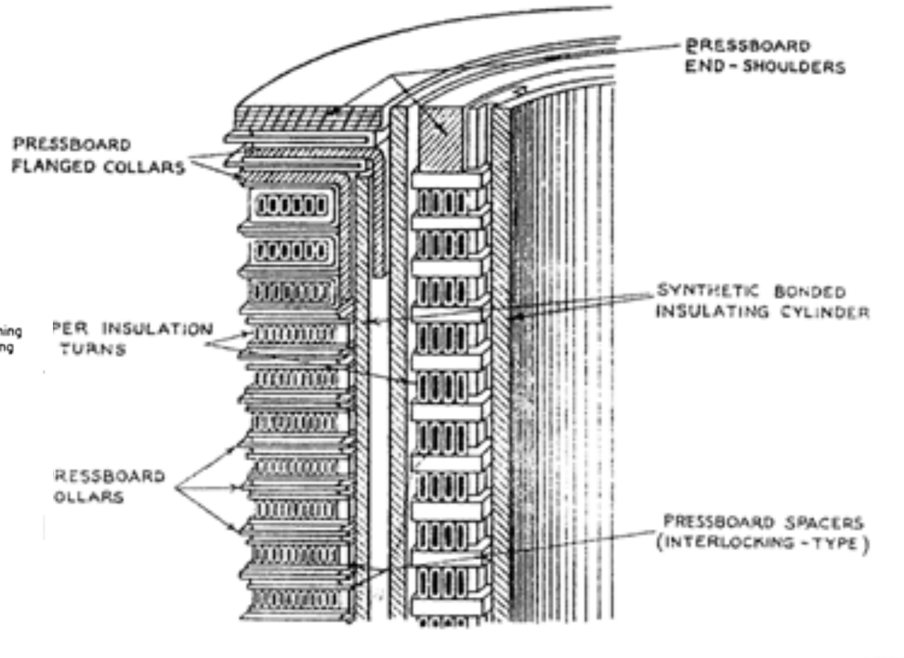
- Core type--exclusively used in UK.
- Materials: Oil and paper/pressboard
- Windings: layer or disc type.



A multi-layer winding



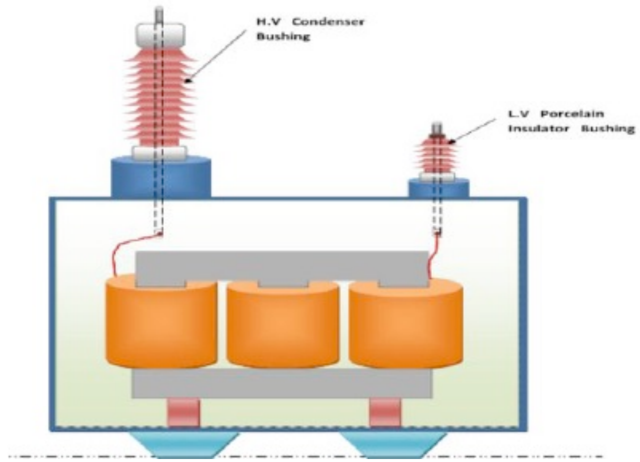
Disc-type HV winding



Disc Winding

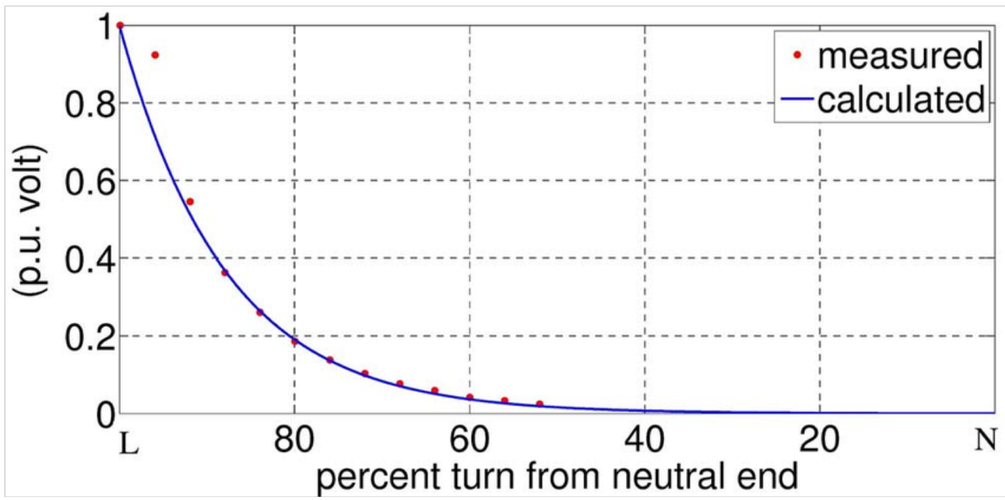
Transformer insulation

- Transformer insulation has to play a number of roles apart from insulation
  - Oil cools transformer as well as providing insulation
  - Pressboard and plywood have to provide mechanical strength and forming cooling ducts for oil circulation
  - Paper provides conductor insulation
  - Assembly is complex and design stresses are low in many non-uniform field locations.
  - A particular problem is the non-uniform distribution of surge voltage.
  - Without careful control of capacitance to earth, much of the surge voltage would appear in the first few turns of windings, severely stressing the winding insulation.



Insulation Electrical Design

- Steady state field
  - Between H.V. and L.V. windings
  - Fields within H.V. windings – layer stress is important
  - Field from H.V. windings to core, bushing and tank
- Impulse stress
  - Voltage distribution



Failure mechanism - PD

- Due to temporary over-voltage, weakness in the insulation introduced during manufacturing, or as a result of degradation over the transformer lifetime.

- Due to different classes of defects: bad contacts, floating components, suspended particles, protrusions, rolling particles, and surface discharges.

PD is undesirable because of the possible deterioration of insulation with the formation of ionized gas due to this breakdown that may accumulate at or in a critical stress region. This generally involves non-self-restoring insulation that may be subject to permanent damage.

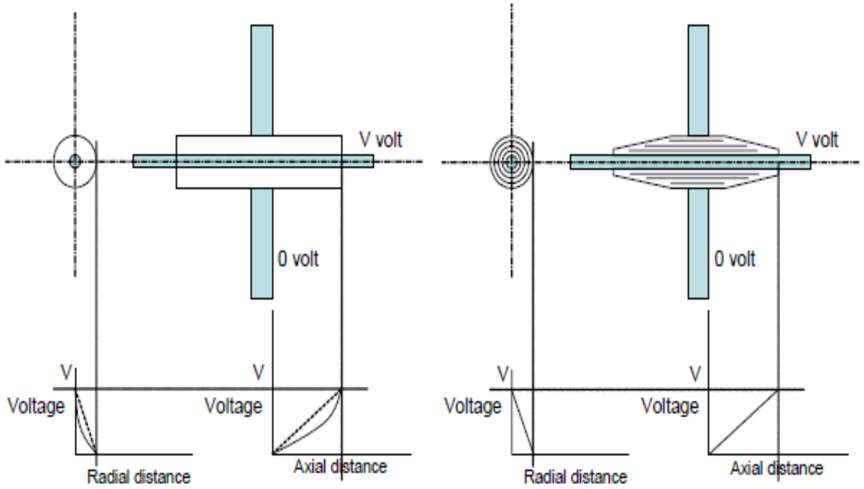
Failure mechanism

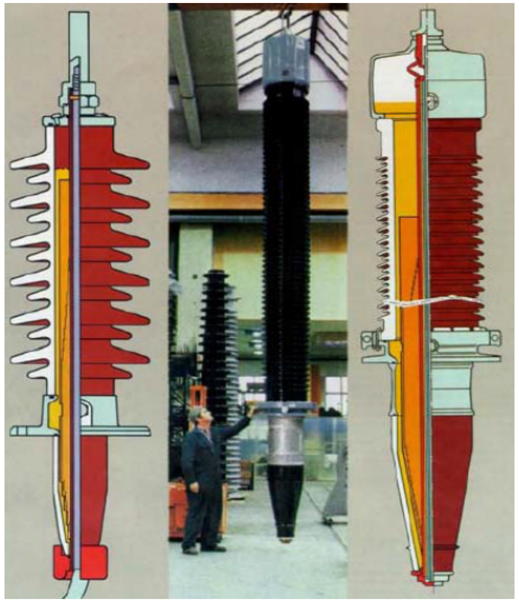
- Insulation degradation
  - Insulation material, mainly – cellulose and mineral oil,
  - Both deteriorate or decompose under thermal and electrical stress
- Winding failure – operational issues
  - Winding failure ----lightning, overload, or short-circuits. Overload and short-circuits cause extra heat, may cause damage to the winding.
  - Lightning or external short-circuits ----result in mechanical stress on the transformer winding, leading to deformation

Failure mechanism --- LTC

- Tap changers usually have a higher failure rate than transformers, although smaller consequences.
- Improper tap position can cause excessive core loss and consequently excessive heating.
- Contact coking is a major problem.
  - Initial deposition of carbon on LTC contacts leads to increased contact resistance, which in turn leads to increased heating and the buildup of carbon.
- Like transformers, LTCs also experience arcing and overheating problems.
- Concentration of fault gases in ‘problem’ LTCs are significantly higher than the levels in a trouble-free unit.

Failures - Bushing

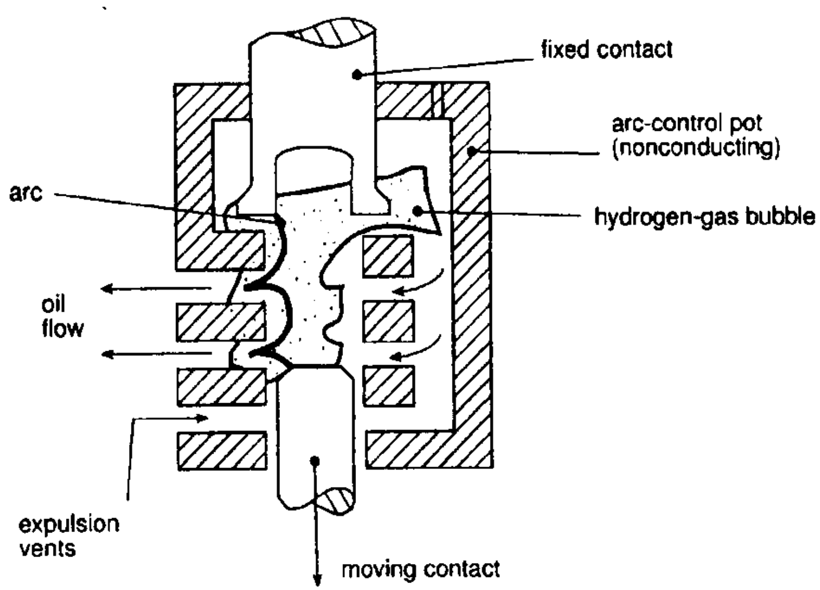




- Bushings - insulated path for energized conductors to enter grounded plant.
- Not only exposed to high electrical stress but also may be subjected to high mechanical stress, affiliated with connectors and bus support.
- Its deterioration can have severe consequences. The deterioration mechanisms include a combination of cracking, corrosion, wear and contamination.
- Failure of a bushing can cause flashover, short circuit. Accounted for large proportion of outage of the transformer.

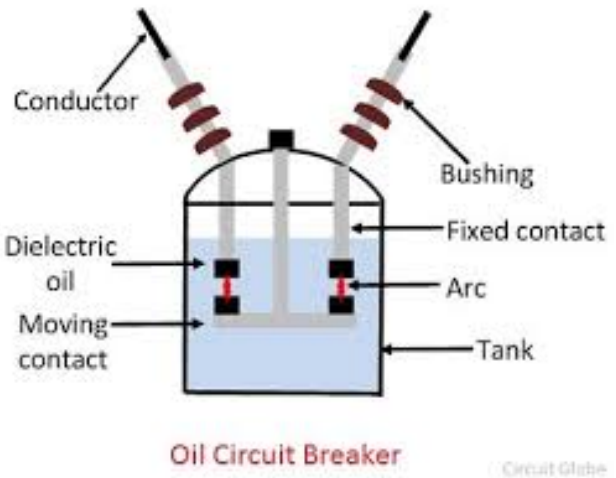
Insulation in circuit breakers

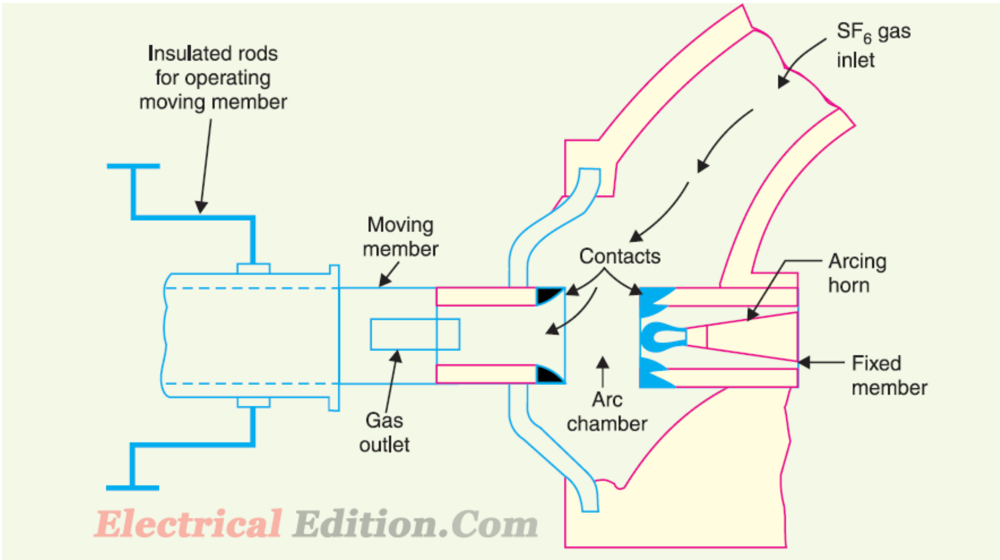
- CBs are filled with insulating fluids
  - Air at atmospheric pressure
  - Compressed air
  - Oil(produces hydrogen for arc extinction)
  - Sulphur hexafluoride
  - Ultra high vacuum

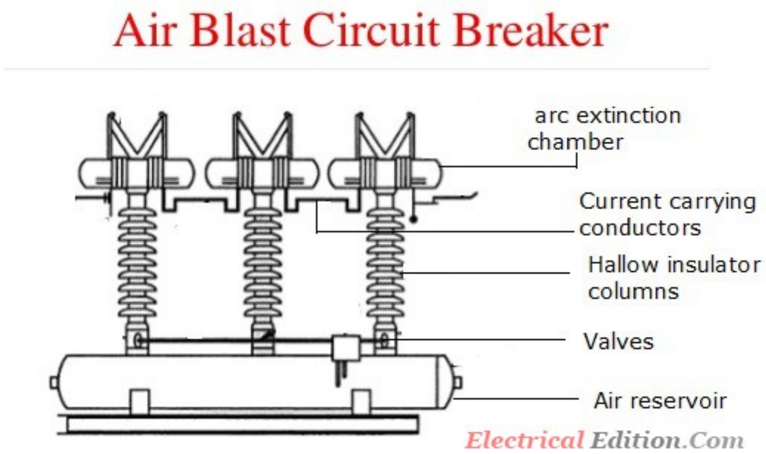


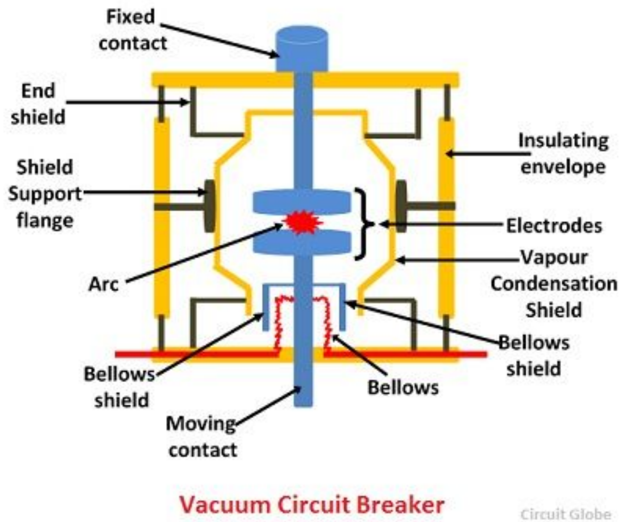
- Insulating fluid filling breakers has 2 functions
  - Extinguishes arc between contacts
  - Provides insulation between contacts and earth

Circuit Breakers



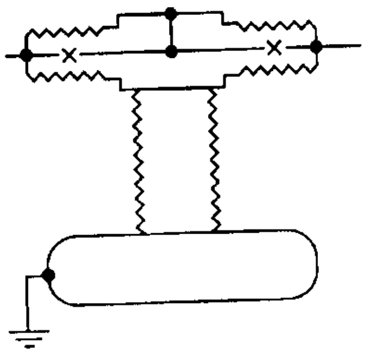


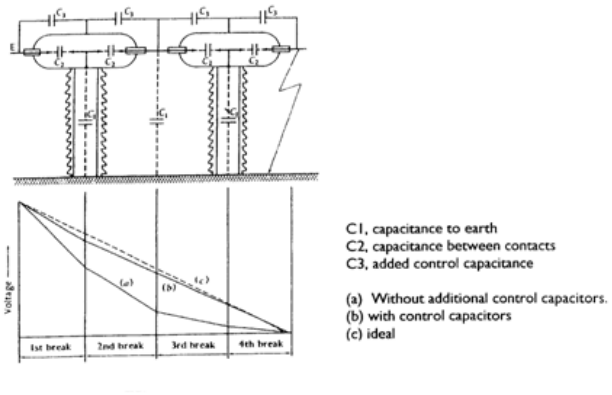




CB tanks

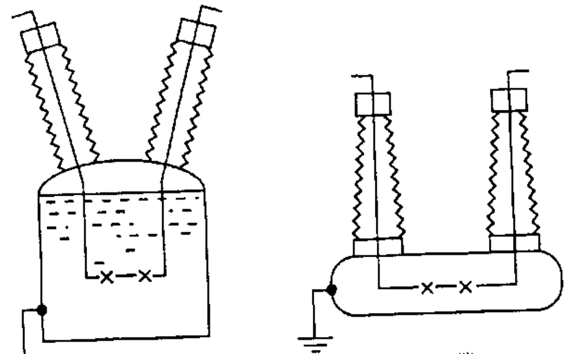
- Live tank: metal tank insulated from ground typically by porcelain insulator





Voltage distribution for circuit breakers

- Dead tank: metal tank at ground potential



(i) (ii)

Oil Circuit Breakers (OAB)

Mature technology, reliable, suitable to work at HV
Environmental concerns

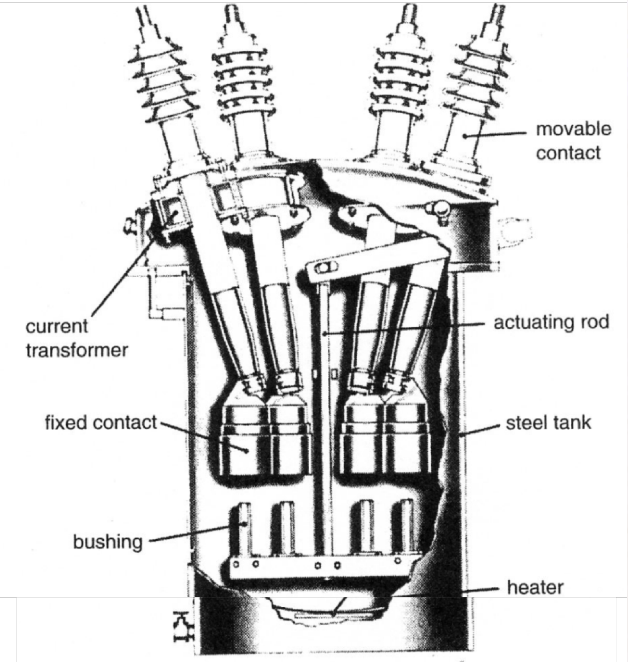


Figure 26.2
Cross-section of an oil circuit breaker. The diagram shows four of the six bushings; the heater keeps the oil at a satisfactory temperature during cold weather. *(Courtesy of Canadian General Electric)*

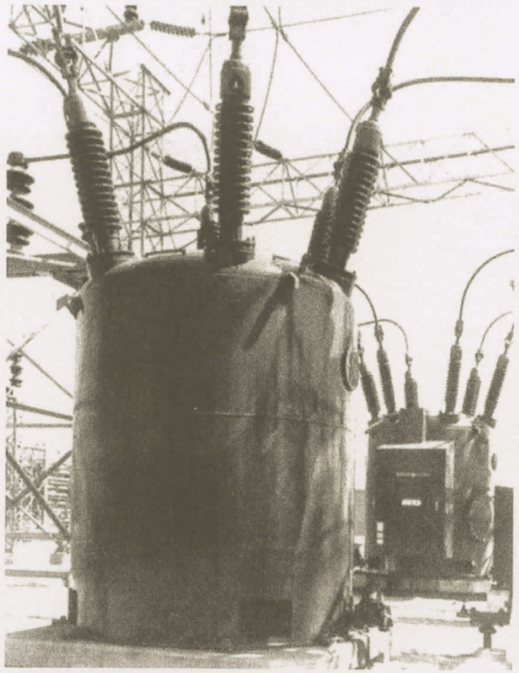


Figure 26.3
Three-phase oil circuit breaker rated 1200 A and 115 kV. It can interrupt a current of 50 kA in 3 cycles on a 60 Hz system. Other characteristics: height: 3660 mm; diameter: 3050 mm; mass: 21 t; BIL: 550 kV. (*Courtesy of General Electric*)

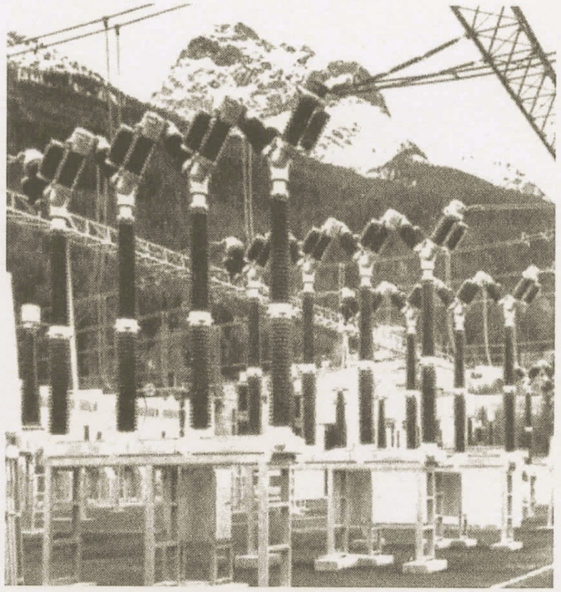


Figure 26.4
Minimum oil circuit breaker installed in a 420 kV, 50 Hz substation. Rated current: 2000 A; rupturing capacity: 25 kA; height (less support): 5400 mm; length: 6200 mm; 4 circuit-breaking modules in series per circuit breaker. (*Courtesy of ABB*)

Air Blast Circuit Breakers (ABCB)

- 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
is discharged to the open atmosphere
- Current chopping
- Restriking voltage

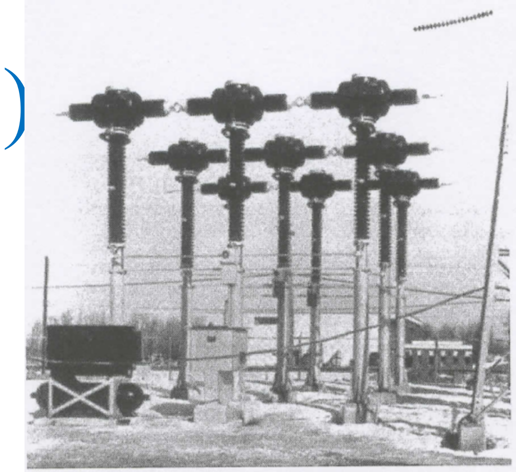


Figure 26.5
Air blast circuit breaker rated 2000 A at 362 kV. It can interrupt a current of 40 kA in 3 cycles on a 60 Hz system. It consists of 3 identical modules connected in series, each rated for a nominal voltage of 121 kV. The compressed-air reservoir can be seen at the left. Other characteristics: height: 5640 mm; overall length: 9150 mm; BIL 1300 kV.
(*Courtesy of General Electric*)

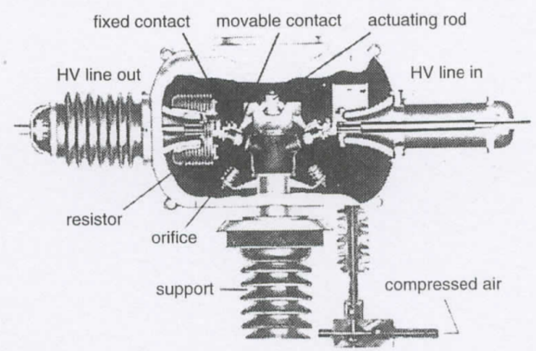


Figure 26.6
Cross-section of one module of an air-blast circuit breaker. When the circuit breaker trips, the rod is driven upward, separating the fixed and movable contacts. The intense arc is immediately blown out by a jet of compressed air coming from the orifice. The resistor dampens the overvoltages that occur when the breaker opens.
(*Courtesy of General Electric*)

SF6 Circuit Breakers (SF6 CB)

- Reliable current interruption, no restriking voltage
- Quiet operation
- The closed gas circuit keeps interior dry, so that there is no moisture problems
- 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.

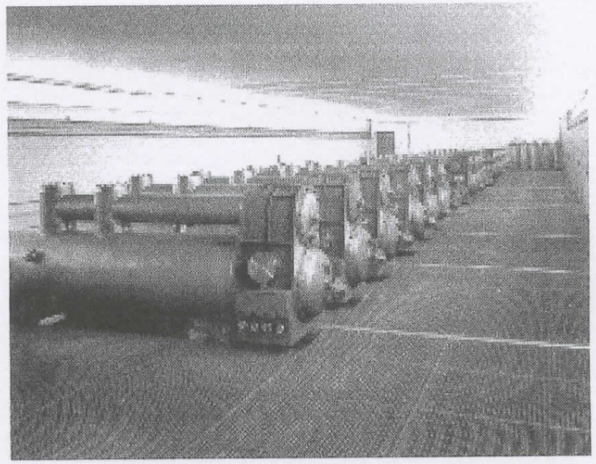


Figure 26.7
Group of 15 totally enclosed SF_6 circuit breakers installed in an underground substation of a large city. Rated current: 1600 A; rupturing current: 34 kA; normal operating pressure: 265 kPa (38 psi); pressure during arc extinction: 1250 kPa (180 psi). These SF_6 circuit breakers take up only 1/16 of the volume of conventional circuit breakers having the same interrupting capacity.
(*Courtesy of ABB*)

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

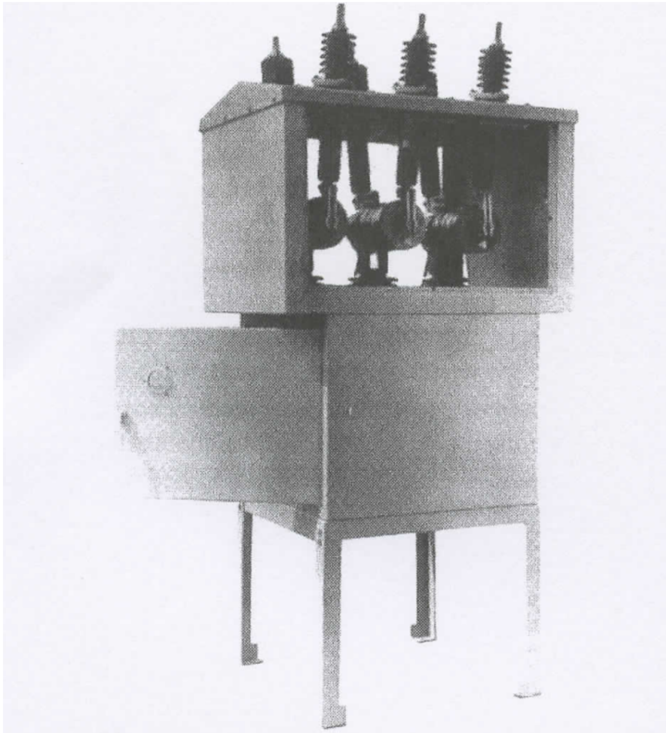


Figure 26.8
Three-phase vacuum circuit breaker having a rating of 1200 A at 25.8 kV. It can interrupt a current of 25 kA in 3 cycles on a 60 Hz system. Other characteristics: height: 2515 mm; mass: 645 kg; BIL: 125 kV. (*Courtesy of General Electric*)

Application of circuit beakers

Type of CB	**Ark quenching medium**	**Volt.&capacity**
Miniture	Air at atmospheric pressure	400V-600V; <5MVA
Air-break	Air at atmospheric pressure	0.4kV-11kV; 5-750MVA
Bulk oil	Transformer oil	0.4kV-33kV; up to 300MVA
Minimum oil	Transformer oil	3.3-220KVA;150-25000MVA
Vacuum	Vacuum	3.3-33kV;250-2000MVA
SF6	SF6 at 5kg/cm2	3.3-765kV;1000-50000MVA
Air blast	Compressed air at 20-30kg/cm2	132-1100KV;2500-60000MVA

Cables

- Conduct heavy current up to rated value
- Maintain continuous working voltage and sustain HV lightning and switching surges

- Required dielectric properties:

  – High ac and impulse electric strength
  – Low permittivity and power factor---low dielectric loss
  – Physical and chemical stability
  – Good thermal conductivity
  – Flexibility for bending
  – Inexpensive and readily available

- Insulation --- Oil Impregnated Paper (OIP) or Polythelene

Cable Insulation --- paper

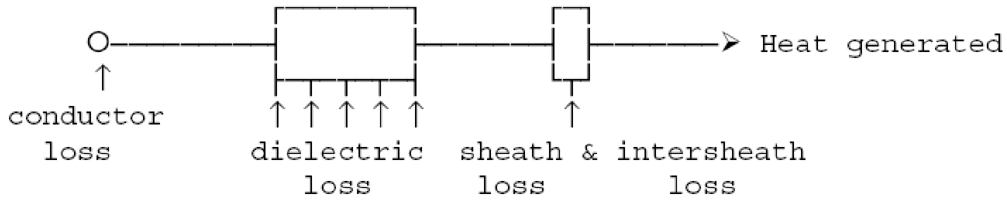
- The paper used for cable making is a felted mat consisting of long cellulose fibres
- the papers are normally 2-ply but 3-ply is occasionally used at higher voltages.
- The thickness of a single paper is normally between 65 and 190µm but the material density is actually relatively low. That of the fibres is around 1500kgm-3 while that of the finished paper is only around 650 to 1000kgm-3.
- This implies that there is a lot of ‘empty’ space within the fibres and this is generally filled with impregnating compound.

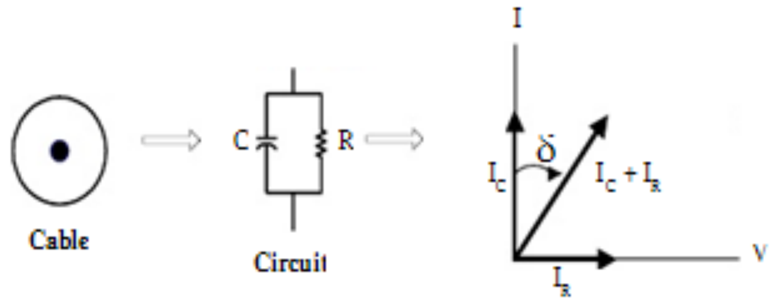
Impregnated oils and OIP

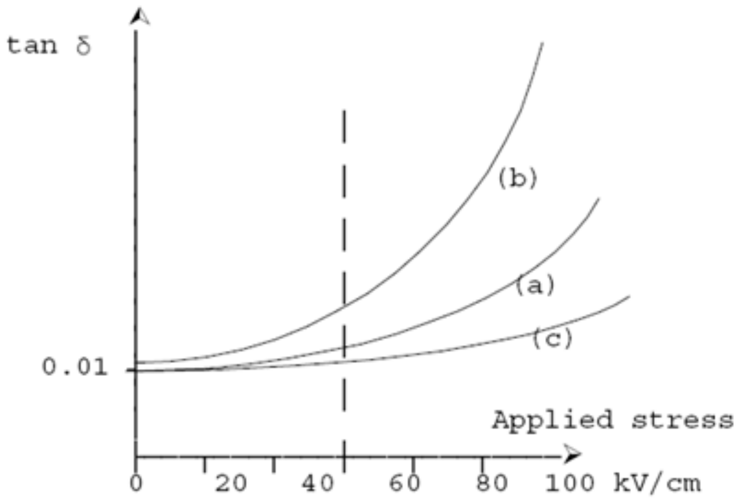
- Impregnated oil
  - Impart electric strength to the dielectric by excluding air and moisture
  - Act as a lubricant to facilitate movement of tapes when cable is bent
  - Increase thermal conductivity of dielectric
- OIP
  - Relative permittivity
    - Cellulose fibre: 5.5, OIP: 3.7, Oil: 2.3
    - Electric strength of OIP is 50kV/mm to standard short time 50Hz tests and about 200kV/mm when measured with 1/50μs impulse.
    - Deign stress varies from 3kV/mm at 11kV to 15kV/mm at 400kV.
- OIP is very gyroscopic, requiring metal sheath and terminations. Former reduces flexibility, both add cost.

Dielectric loss ---OIP

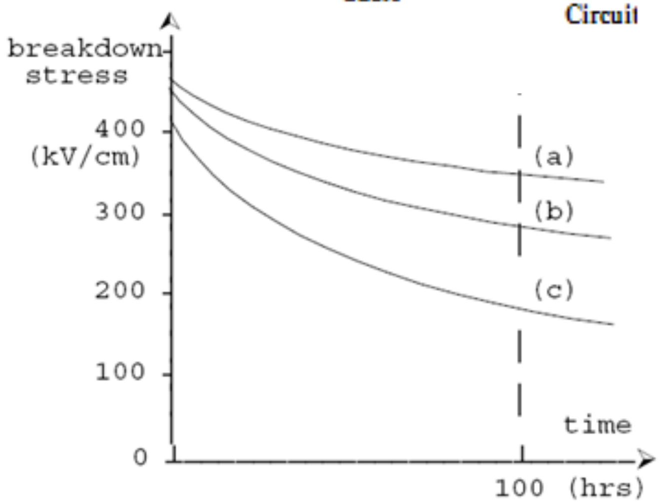
- Losses are $\omega C V^2 \tan\delta$
- *Synthetic material offers lower dielectric losses*







(a) impregnated (1 atmos)
(b) badly impregnated (1 atmos)
(c) badly impregnated (15 atmos)



(a) 15 atmospheres
(b) 8 atmospheres
(c) 1 atmosphere

Variations with pressure

3-phase screened and belted cables

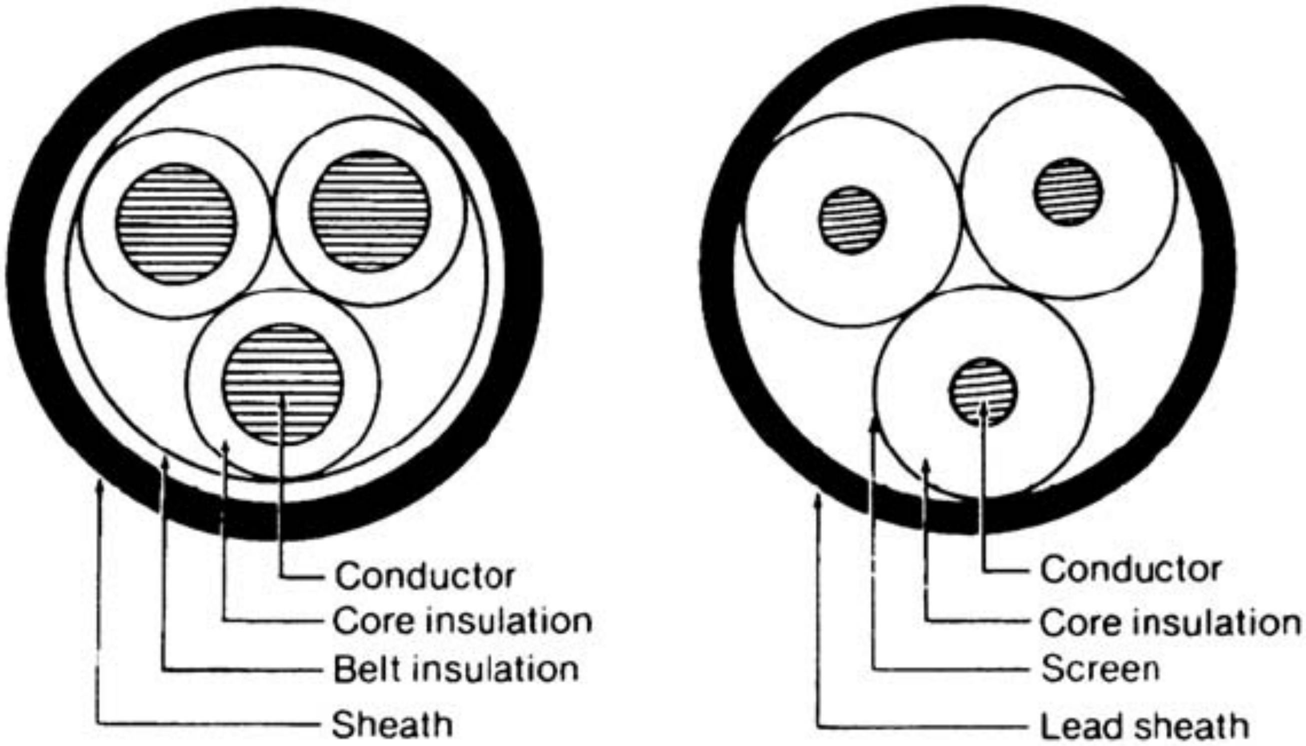


Figure 9 - Belted (left) and screened (right) paper cable

Alternatives to OIP

- Polyethylene (PE)
  - Excellent dielectric property, $\varepsilon_r = 2.3$, $\tan\delta = 0.0003$ at 20°C. Loss less than 10% of OIP.
  - Problem:
    - contracts on cooling, leading to void formation;
    - low melting temperature;
    - low discharge resistance
- Polypropylene/paper laminate
  - Important functions of paper in the laminates:
    - Maintenance of impregnation path;
    - mechanical reinforcement;
    - protection from discharge

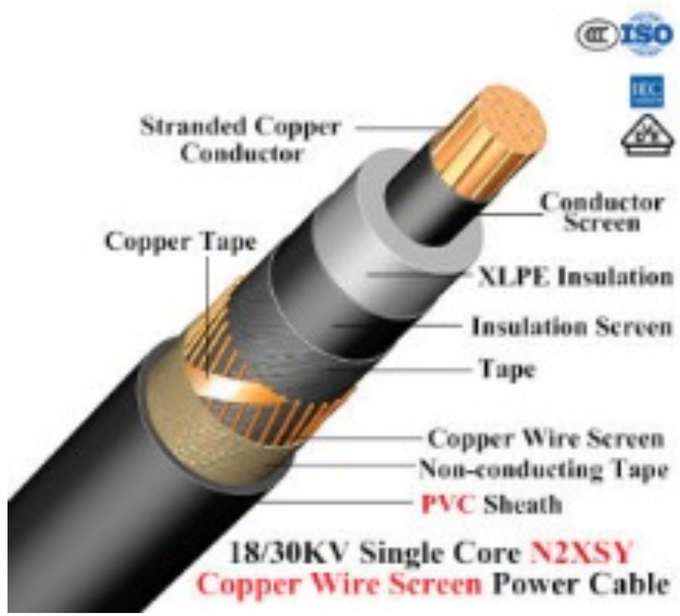
Alternatives to OIP

- Ethylene Propylene Rubber (EPR)
  - ε_r = 3.5, tanδ=0.004, dielectric property not good as PE
  - Superior thermal properties and good discharge resistance

- Compressed Gas-Insulated Designs
  - Applications are short, hundreds metres.
  - Usually associated with GIS switchgear and substations
  - Compressed GI cables has very low tangent and ε_r = 1.
  - Spacer flashover and particular contamination is the main problem.

XLPE cable

- It refers to: Cross-linking polyethylene
- It can withstand 90° temp, 15° higher than paper cables
- Moisture is dangerous so solid metallic sheath is commonly used as moisture barrier
- Usually thicker than paper insulation, more difficult to handle
- Showing less discharges, particularly with semi-conducting layers
- No need for reservoirs and alarms.
- Applied to most voltages.



	PVC	XLPE	PAPER
Relative permittivity (at 50Hz)	6 - 8	2.3	2.2 – 3.8
Tanδ	0.08	0.0003	0.001 – 0.004

Other components Conductor & Insulation Shields

- It is desirable to reduce the electric stress across the cable insulation to the minimum possible for the chosen cable design.

- Any protrusions or imperfections in the cable conductor will raise the electric field at the point.

- In polymeric cables an additional semi-conductive layer is manufactured between the conductor and the dielectric in polymeric cables.

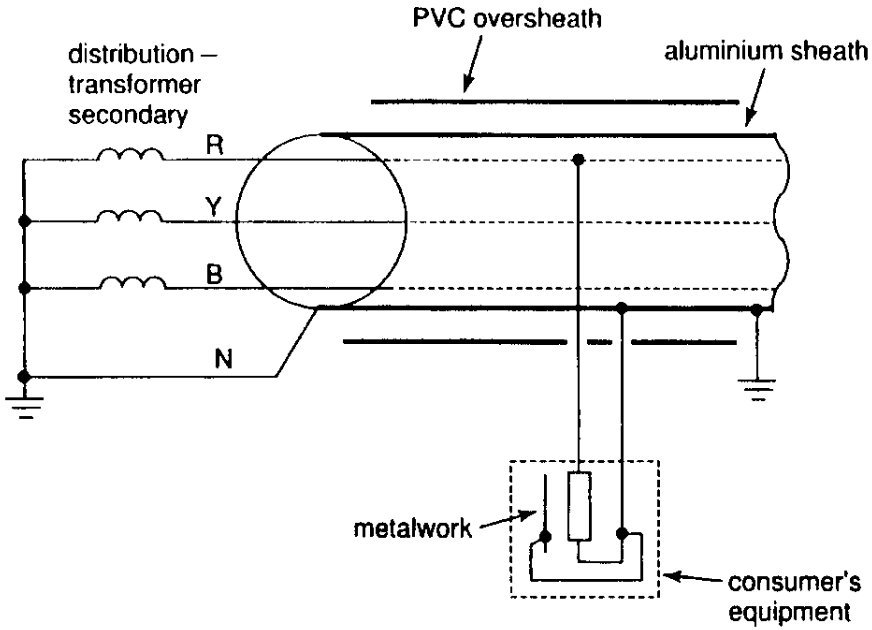
- The semi-conductive layer smoothes out any rough edges that the conductor material may have. This layer, known as the conductor shield, is also used to ensure there are no voids in the inner layer of the main dielectric, which might also cause partial discharges.

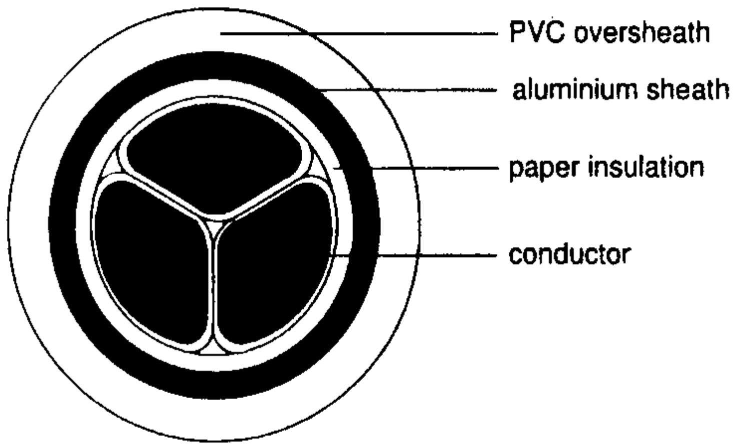
- In paper cables, it is common to find a thin foil layer or a carbon black paper layer placed around the conductor, for the same purpose.

Other Components -- Sheath/Armour/Oversheath

- Impregnated paper insulation and XLPE insulation are both vulnerable to moisture ingress, the latter extremely so.
- The cable sheath is used to prevent moisture penetrating into the insulation system.
- The cable sheath is also used as a fault current path in the event of a cable fault, to prevent the risk of electric shock and to collect capacitive current that flows from the conductor to the insulation shield.
- The cable oversheath is a layer that provides environmental protection for the cable. It is normally an extruded jacket made from a polymer such as PVC.
- Armouring is an additional metallic layer placed around the oversheath. This is designed to give extra mechanical protection.

Typical 415V mains cables (post-1968)

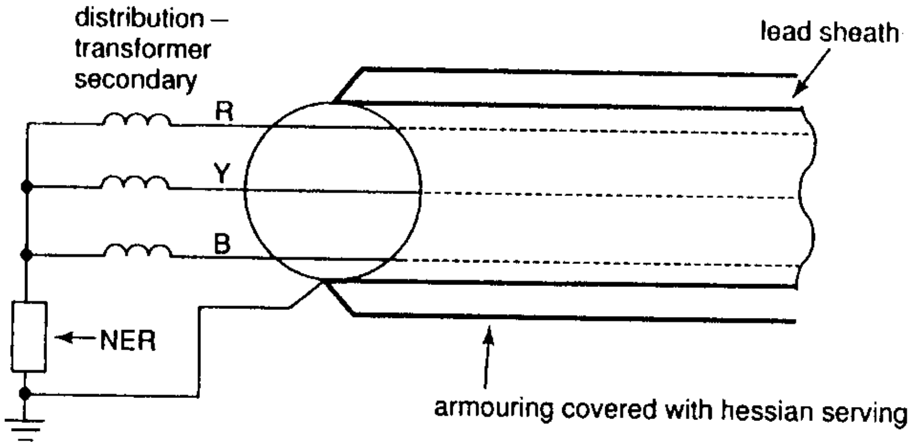




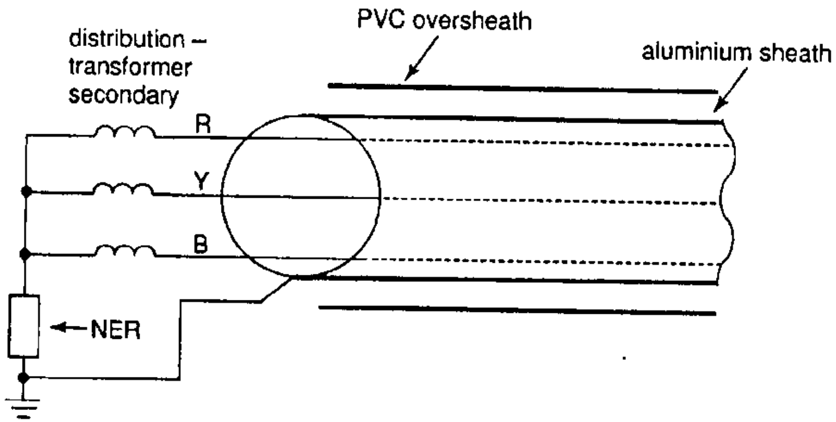
Schematic and cross-section of the cable

- 3 core solid alum conductor
- Alum neutral sheath
- Impregnated paper insulation
- PVC insulating oversheath

11kV distribution system cable



11 kV distribution-system cable with lead sheath



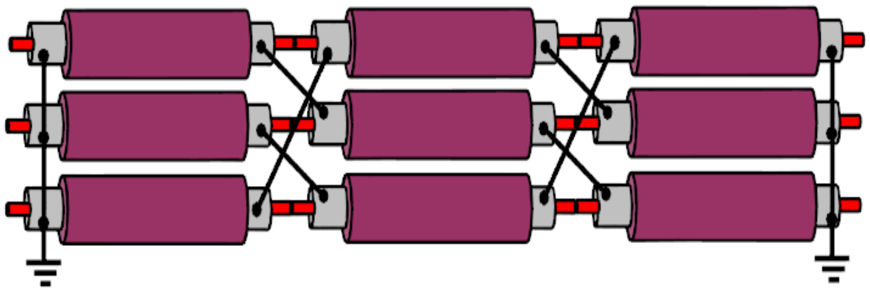
11 kV distribution-system cable with aluminium sheath

- 3-core stranded alum conductor
- Impregnated paper insulation-belted
- Lead sheath
- Wire armour
- Hessian tape with lime-wash finish

Earthing of HV Cables

Single-end bonding

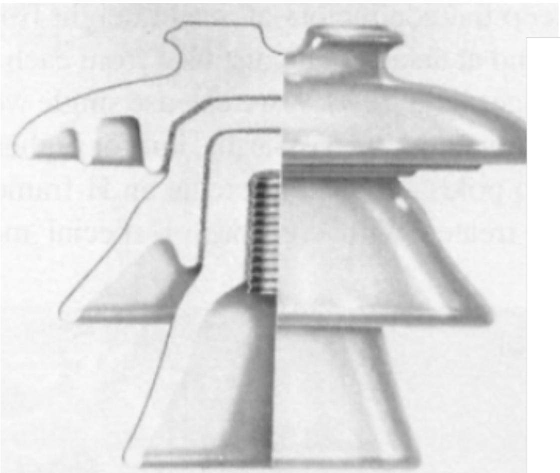
Both-end bonding

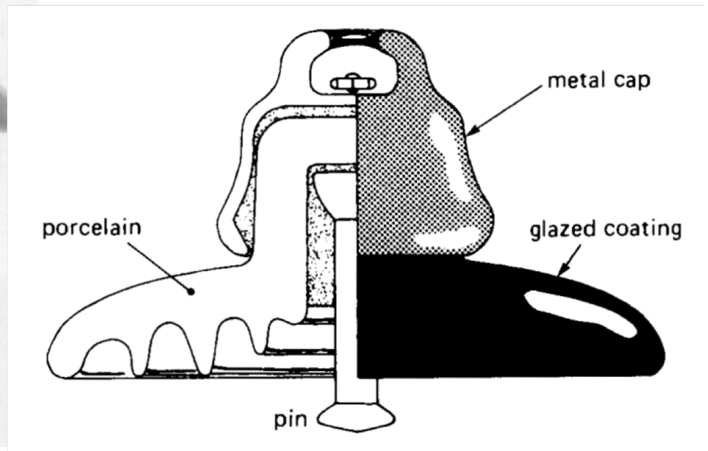


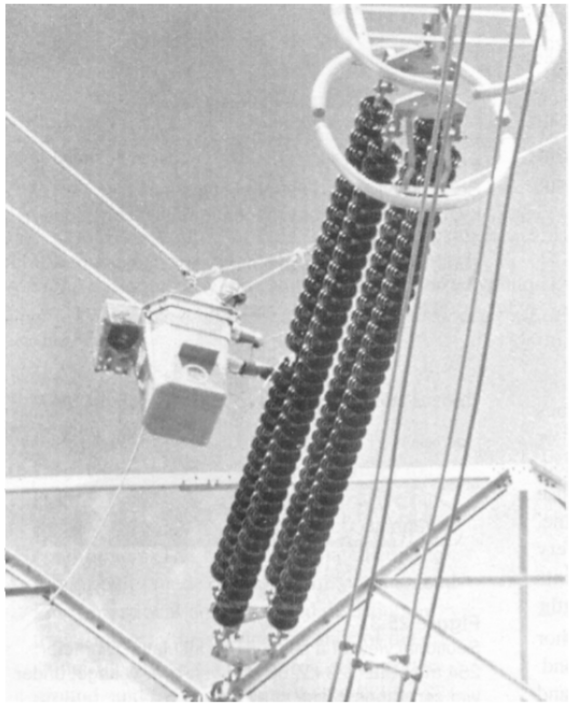
cross-bonding (usually >1.2km)

Power Lines/standard voltage/ components

- Conductor --- bare conductors, stranded copper, or steel-reinforced aluminum cable (ACSR), joints required when long lines are installed.
- Insulator --- support and anchor conductors and insulate them from ground/metal tower. Made of porcelain or toughened glass.
- Supporting structures --- single wooden pole with crossing arms, two pole H-frame, steel towers.

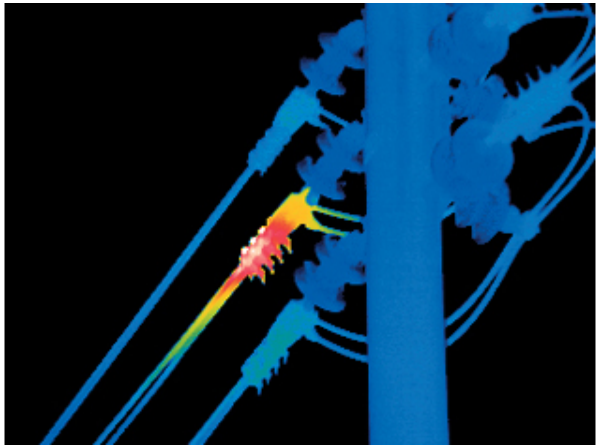


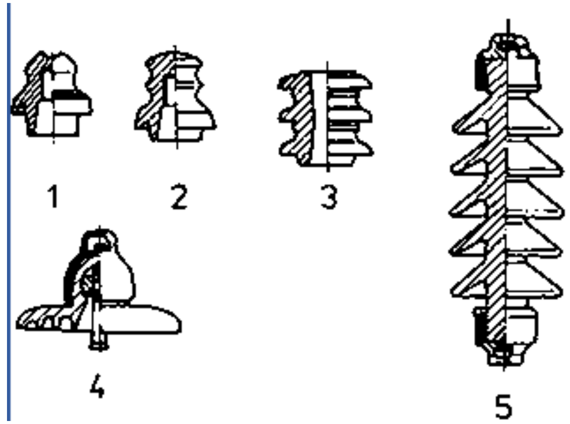




Overhead line Insulators

- Requirements:
  - Adequate size and shape to withstand the maximum working voltages and specified over-voltages
  - Perform under conditions of pollution
  - Withstand high mechanical loadings
  - Not give rise to high RFI due to corona.





Cap and Pin or String Insulators

- Cap and Pin insulators ---most popular.
  - A single unit support 11kV

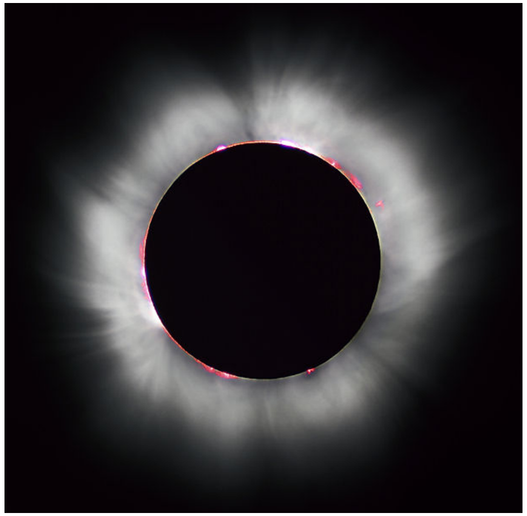
- Electrical properties for 400kV systems
  - Impulse withstand volt: 1425kV
  - Corona extinction volt: 320kV
  - 50Hz withstand volt: 800kV (dry) and 630kV (wet)
  - For suspension type (vertical)
    - Number of units: 24; String length 4.11m;
    - Min creepage distance: 12.7m; arc gap: 2.54m.

Insulator Design considerations

- Breakdown Voltage
  - Proportional to the distance between HV conductor and ground for both 50Hz a.c. and surge voltage.
  - Determines the “dry arcing distance” ---around the total insulator string length. The distance must be sufficient to support volts considerably higher than line volts.
  - Size of insulator is determined by the creepage distance required to prevent tracking failure.

Insulator Design considerations

- Corona ---careful design
  - RFI, EMI. Unavoidable in economic designs, sometimes.
- Voltage distribution
  - Non-uniform as seen in the example due to stray capacitance between metal work of each unit and tower.
  - Arcing horn/ring guard helpful with volt distribution



Insulator Design considerations---Materials

- Porcelain
  - Good electrical strength
  - Good mechanical strength
  - Easily shaped
  - Non-porous structure
  - Glazing facilitates cleaning

- Toughened Glass
  - Similar in size and shape as porcelain
  - Similar electrical and mechanical properties
  - Higher initial investment limits to high volume production.

- Others-composite materials—laboratory stage.

Process of Flash-over

- The process leading to pollution flashover:
- 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.

Remedy for Flashover

- 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

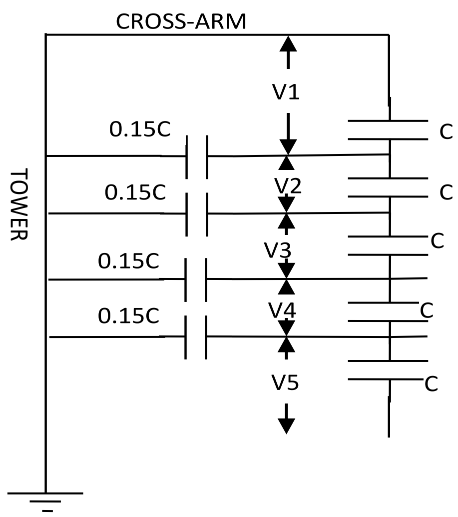
- surface treatment:
  - Mobile coating reduce the tendency for water to coalesce into a continuous film and to encapsulate particles of solid pollution. Mobile coating primarily consist of silicon pastes, petrolatum gels and hydrocarbon greases.
  - Hydrophobes used as surface treatment (PTFE coating) of poor chemical and discharge resistant properties.
  - Resistive glazes: use semi conductive glazes ---severe corrosion effect limits working life.

Example:

(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 0.15C. 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) Determine the string efficiency and discuss the significance of the string efficiency in insulator design.

(iii) Describe and explain the cause for the low string efficiency in the configuration provided and propose a solution to improve the efficiency.



$2\pi fCV2=2\pi f0.15CV1+2\pi fCV1$; $V2=1.15V1$

Similarly:

$V3=V2+0.15(V1+V2)=1.15V2+0.15V1$

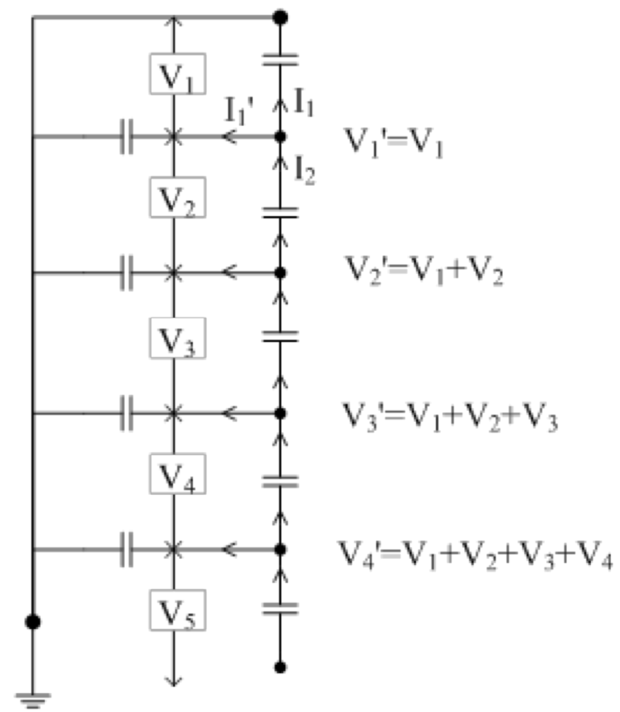
Substituting V2 for V1

$V3=1.4725V1$

Similarly:

$V4=V3+0.15(V1+V2+V3) = 2.016V1$

And $V5 =V4+0.15(V1+V2+V3+V4) = 2.8617V1$



$V1+V2+V3+V4+V5 =V1+ (1.15V1) + (1.47V1) + (2.016V1) + (2.86V1) = 250kV$.

Therefore, V1 = 29.43 kV

V2 = 33.84 kV, V3 = 43.26kV, V4 = 59.32kV, V5 = 84.16kV

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=2.24kV, V2=2.58kV, V3=3.30kV, V4=4.52kV, V5=6.86kV

String efficiency =Vtotal/(5xV5) = 19050/(5x6860) = 0.555

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. Equations can be used become

$V4+0.1(V4+V5)=V3+0.15(V1+V2+V3)$

and

$V5+0.2V5=V4+0.15(V1+V2+V3+V4)$;

Therefore, $V5=2.032V1$, $V4=1.648V1$

$V1 + V2 + V3 + V4 + V5 = 33kV/1.732 = 19.050kV$, ,$V5=5.505kV$

String efficiency $=Vtotal/(5xV5) = 19050/(5x5505) = 0.692$

The result of the solution is that string efficacy is improved significantly.