MODULE-4

Insulators

Definition of an electrical insulator:

The overhead line conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports *i.e.*, line conductors must be properly insulated from supports. This is achieved by securing line conductors to supports with the help of *insulators*.
The insulators provide necessary conductors and supports and thus prevent any leakage current from conductors to earth, and insulation between line

In general, the insulators should have the following desirable properties.

- High mechanical strength in order to withstand conductor load, wind load etc.
- High electrical resistance of insulator material in order to avoid leakage currents to earth.
- High relative permittivity of insulator material in order that dielectric strength is high.
- The insulator material should be non-porous, free from impurities and cracks otherwise the permittivity will be lowered.
- High ratio of puncture strength to flashover.

Materials Used in Electrical Insulators

- The most commonly used material for insulators of overhead line is porcelain but glass, steatite and special composition materials are also used to a limited extent.
- Porcelain is produced by firing at a high temperature a mixture of kaolin, feldspar and quartz.

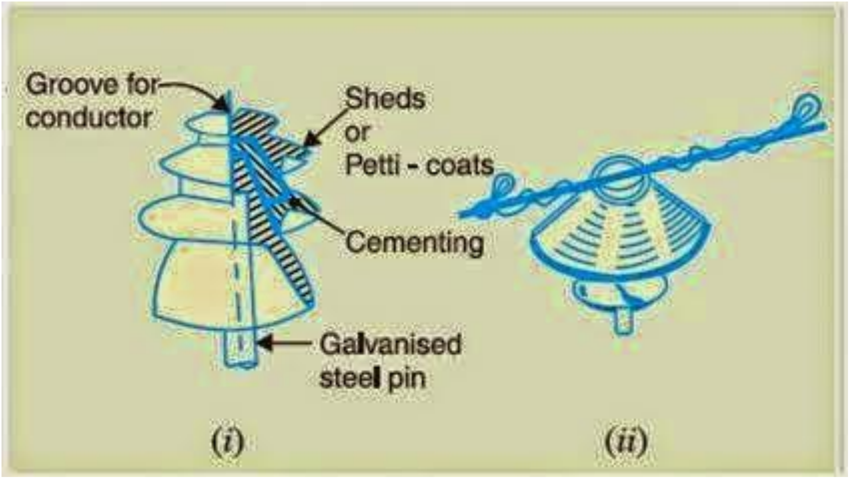
  - **Porcelain** – High durability and resistance
  - **Glass** – High dielectric strength and transparency for inspection
  - **Polymer/Composite** – Lightweight, flexible, and resistant to pollution

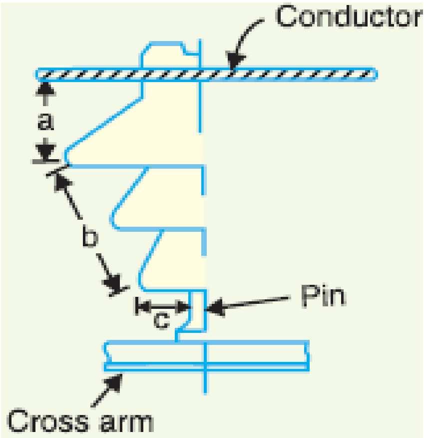
Types of Electrical Insulators

1. **Pin Type Insulator** - Used in distribution lines
2. **Suspension Insulator** - Used in high-voltage transmission lines
3. **Strain Insulator** - Used to support mechanical tension in power lines
4. **Shackle Insulator** - Used in low-voltage applications
5. **Post Insulator** - Used in substations and switchgear applications

PIN-TYPE INSULATORS

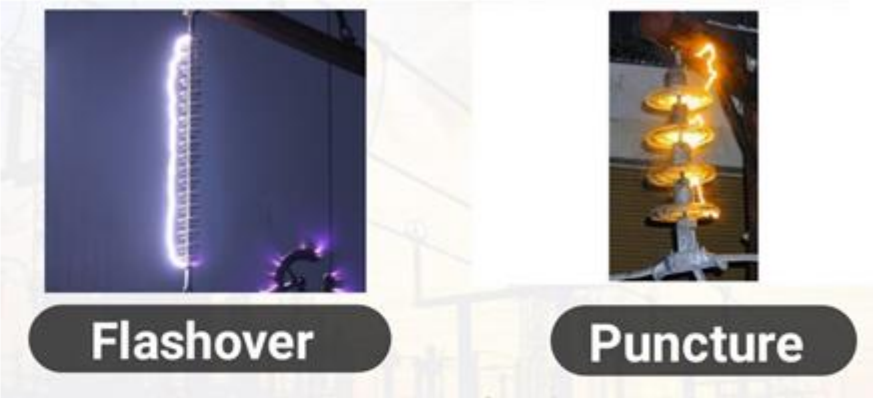
- The pin type insulator is secured to the cross-arm on the pole. There is a groove on the upper end of the insulator for housing the conductor.
- The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor
- Pin type insulators are used for transmission and distribution of electric power at voltages upto 33 kV.
- Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.





Causes of insulator failure

- The electrical breakdown of the insulator can occur either by *flash-over* or *puncture*.
- In flashover, an arc occurs between the line conductor and insulator pin (*i.e.*, earth) and the discharge jumps across the *air gaps, following shortest distance.
- In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat.



- In practice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flashover voltage is known as safety factor *i.e.*,

$$\text{Safety factor of insulator} = \frac{\text{Puncture strength}}{\text{Flash - over voltage}}$$

For pin type insulators, the value of safety factor is about 10.

Suspension type insulators

- The cost of pin type insulator increases rapidly as the working voltage is increased. Therefore, this type of insulator is not economical beyond 33 kV.
- For high voltages (>33 kV), it is a usual practice to use suspension type insulators.
- They consist of a number of porcelain discs connected in series by metal links in the form of a string.
- The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower.
- Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

Advantages

i. Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.
ii. Each unit or disc of suspension type insulator is designed for low voltage, usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in series.
iii. If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.
iv. The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.

v. In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.

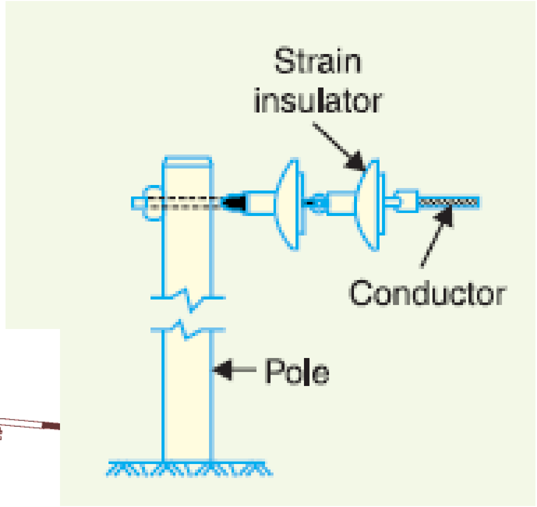
vi. The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

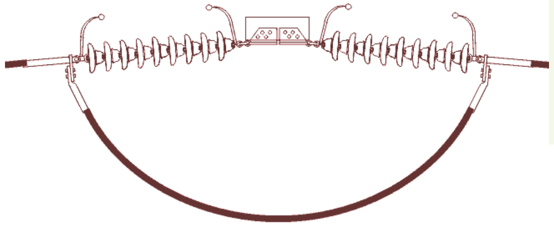
Shackle insulators

- In early days, the shackle insulators were used as strain insulators. But now a days, they are frequently used for low voltage distribution lines.
- Such insulators can be used either in a horizontal position or in a vertical position.
- They can be directly fixed to the pole with a bolt or to the cross arm. Fig. shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.

Strain insulators

- When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used.
- For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators
  - The discs of strain insulators are used in the vertical plane.
  - When the tension in lines is exceedingly high, as at long river spans, two or more strings are used in parallel.





STRAIN INSULATOR

Number of Disc Required

Line voltage	Suspension type	Strain type
66kV	5	6
132kV	9	10
220kV	13-15	14-16
499kV	20-25	23-26
765kV	Approx.35	Approx.36

Voltage distribution in suspension type insulators

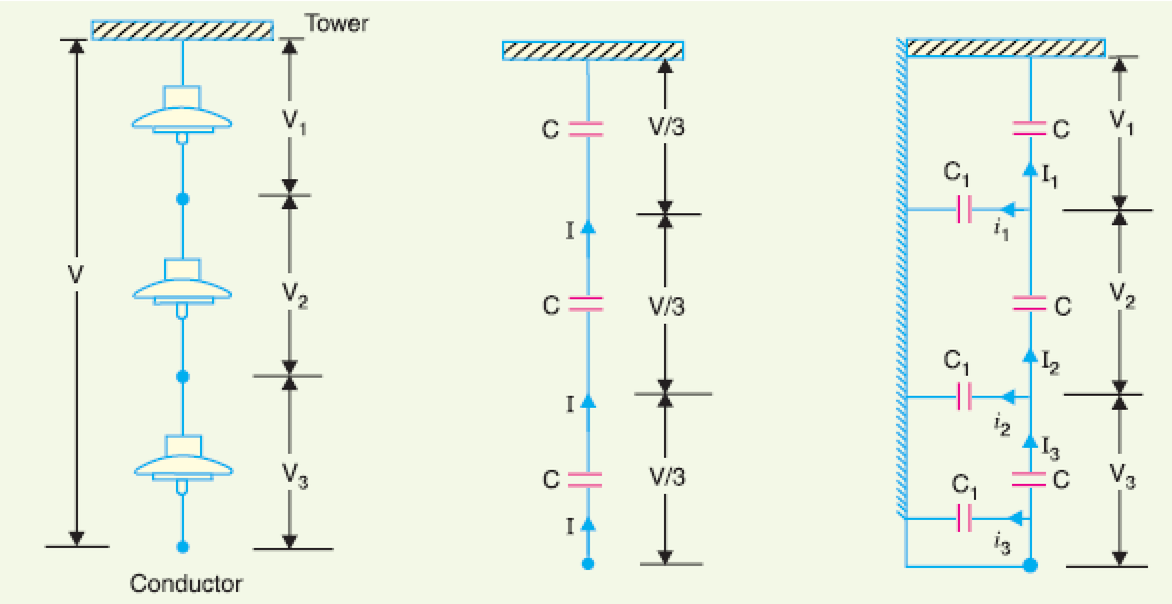
- A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links.

Let us consider a string consists of four insulators as shown in Fig.- operating at voltage

'V' (Line to Ground). Each insulator is represented by its capacitor.

'C'-The capacitance of each insulator

'KC' -The capacitance of insulator pin to ground



At node ' J ' using KCL we can write

$$I_{c2} = I_{c1} + I_1 \quad (5.1a)$$

$$\omega C V_2 = \omega C V_1 + \omega K C V_1 \quad (5.1b)$$

Which can be simplified to (5.2)

$$V_2 = (1 + K) V_1 \quad (5.2)$$

At node ' K ' using KCL we can write

$$I_{c3} = I_{c2} + I_2 \quad (5.3a)$$

$$\omega C V_3 = \omega C V_2 + \omega K C (V_1 + V_2) \quad (5.3b)$$

Which can be simplified to (5.4) by using (5.2)

$$V_3 = \left(1 + 3K + K^2\right) V_1 \quad (5.4)$$

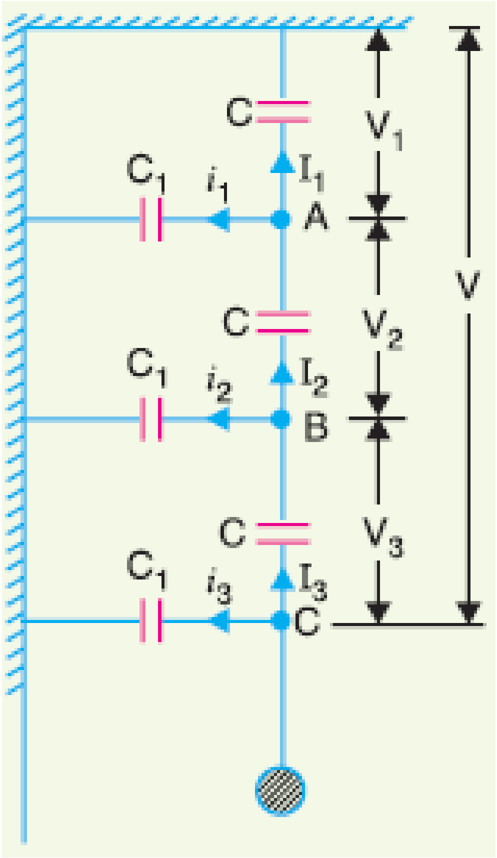
At node ' M ' using KCL we can write

$$I_{c4} = I_{c3} + I_3 \quad (5.5a)$$

$$\omega C V_4 = \omega C V_3 + \omega K C (V_1 + V_2 + V_3) \quad (5.5b)$$

Which can be simplified to (5.6) by using (5.2) and (5.4)

$$V_4 = \left(1 + 6K + 5K^2 + K^3\right) V_1 \quad (5.6)$$



Using the above equations we can determine the voltage across each insulator and it can be seen that they are not equal i.e. voltage distribution in the string is not uniform. At this point let us define string efficiency as follows:

$$\eta_{string} = \frac{\text{Votlage across string}}{\text{No.of Insulators X Voltage across the Insulator adjacent to the conductor}}$$

This efficiency is very low because of unequal voltage distribution. It can be increased by the following methods which is also known as grading of the insulators

LENGTH OF THE CROSS ARM

- As we can see the voltage distribution depends largely on the value of 'K' . Hence if the value of 'K' is reduced the distribution can be made equal and string efficiency can be improved.
- It can be done by increasing the length of the cross arm. However there is limitation to it because of mechanical strength of the supporting tower.

GRADING OF INSULATORS UNITS

- It is observed from the above derivation that the insulators having same capacitors have been used in the string.
- To make voltage distribution equal we can use insulators having different capacitance as shown in Fig.- such that we will result in the following equations.

$I_{c2} = I_{c1} + I_1$

$$\omega C_2 V = \omega C_1 V + \omega K C_1 V$$

Which can be simplified to

$$C_2 = (1 + K) C_1$$

Similarly we can use for the other nodes and can determine the capacitor of each insulators of the string. However this method is not practically feasible because of large no. of insulators in the string for very high voltage transmission line.

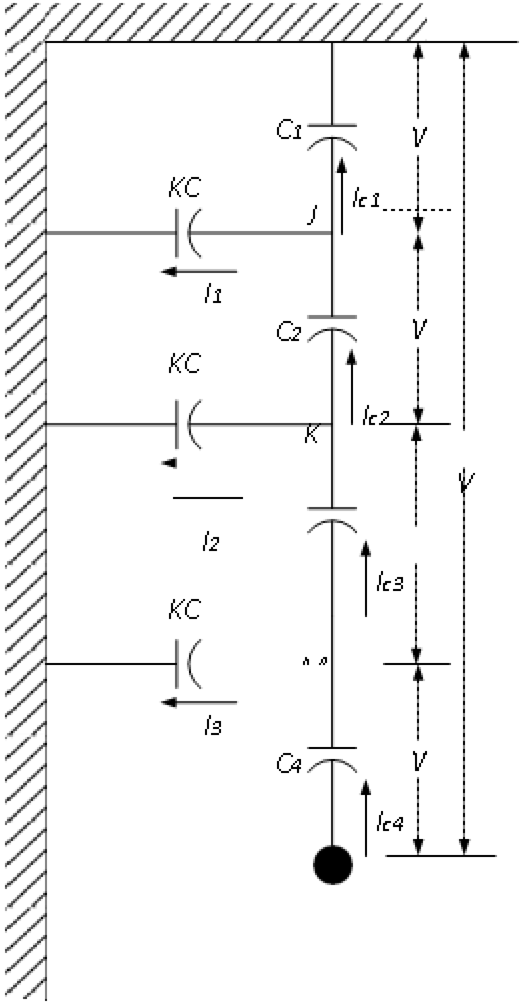


Fig.- Grading of String of Four Insulators

Method of equalizing

- It has been seen above that potential distribution in a string of suspension insulators is not uniform.
- The maximum voltage appears across the insulator nearest to the line conductor and decreases progressively as the crossarm is approached
- If the insulation of the highest stressed insulator (*i.e.* nearest to conductor) breaks down or flash over takes place, the breakdown of other units will take place in succession.
- This necessitates to equalise the potential across the various units of the string *i.e.* to improve the string efficiency.

The various methods for this purpose are :

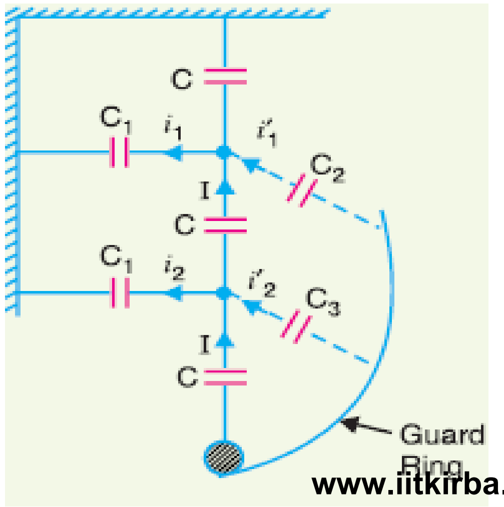
(*i*) *By using longer cross-arms.* The value of string efficiency depends upon the value of *K i.e.*, ratio of shunt capacitance to mutual capacitance. The lesser the value of *K*, the greater is the string efficiency and more uniform is the voltage distribution. The value of *K* can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased *i.e.*, longer cross-arms should be used. However, limitations of cost and strength of tower do not allow the use of very long cross-arms. In practice, $K = 0 \cdot 1$ is the limit that can be achieved by this method.

(*ii*) *By grading the insulators.* In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded *i.e.* they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (*i.e.*, nearest to conductor) is reached.

Since voltage is inversely proportional to capacitance, this method tends to equalise the potential distribution across the units in the string. This method has the disadvantage that a large number of different-sized insulators are required. However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line

conductor.

(*iii*) *By using a guard ring.* The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig. The guard ring introduces capacitance be tween metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents *i*1, *i*2 etc. are equal to metal fitting line capacitance currents *i*'1, *i*'2 etc. The result is that same charging current *I* flows through each unit of string. Consequently, there will be uniform potential distribution across the units.



Voltage Distribution

While solving problems relating to string efficiency, the following points must be kept in mind:

(*i*) The maximum voltage appears across the disc nearest to the conductror (*i.e.*, line conductor).

(*ii*) The voltage across the string is equal to phase voltage *i.e.*,

Voltage across string = Voltage between line and earth = Phase Voltage

(*iii*) Line Voltage = √3*Voltage across string

Economic Use of Insulators

Q-In a 33 kV overhead line, there are three units in the string of insulators. If the capacitance between each insulator pin and earth is 11% of self-capacitance of each insulator, find
(i) the distribution of voltage over 3 insulators and (ii) string efficiency.

Q-A 3-phase transmission line is being supported by three disc insulators. The potentials across top unit (i.e., near to the tower) and middle unit are 8 kV and 11 kV respectively. Calculate
(i) the ratio of capacitance between pin and earth to the self-capacitance of each unit
(ii)the line voltage and (iii) string efficiency

Q-A string of 5 insulators is connected across a 100 kV line. If the capacitance of each disc to earth is 0·1 of the capacitance of the insulator, calculate (i) the distribution of voltage on the insulator discs and (ii) the string efficiency.

Q-Each conductor of a 3-phase high-voltage transmission line is suspended by a string of 4 suspension type disc insulators. If the potential difference across the second unit from top is 13·2 kV and across the third from top is 18 kV, determine the voltage between conductors.

Q-The self capacitance of each unit in a string of three suspension insulators is C. The shunting capacitance of the connecting metal work of each insulator to earth is 0·15 C while for line it is 0·1 C. Calculate (i) the voltage across each insulator as a percentage of the line voltage to earth and (ii) string efficiency.

Mechanical Design of Overhead Transmission Line,

Sag and stress calculation

The difference in level between points of supports and the lowest point on the conductor is called **sag.**

Fig. 8.23. (*i*) shows a conductor suspended between two equilevel supports *A* and *B*. The conductor is not fully stretched but is allowed to have a dip. The lowest point on the conductor is *O* and the sag is *S*. The following points may be noted :

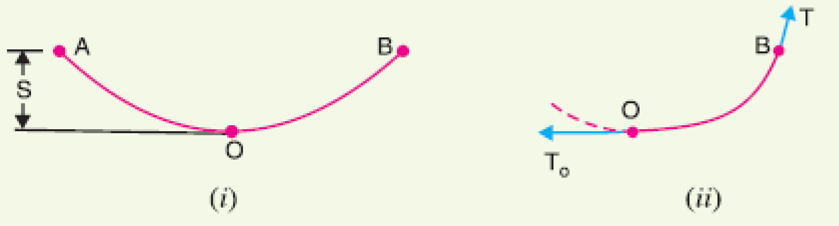


Fig. 8.23

Calculation of Sag

- In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits.
- The tension is governed by conductor weight, effects of wind, ice loading and temperature variations.
- It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength *i.e.*, minimum factor of safety in respect of conductor tension should be 2.
- We shall now calculate sag and tension of a conductor when (*i*) supports are at equal levels and (*ii*) supports are at unequal levels.

(*i*) When supports are at equal levels

Consider a conductor between two equilevel supports *A* and *B* with *O* as the lowest point as shown in Fig.8.24. It can be proved that lowest point will be at the mid-span.

Let

l = Length of span

w = Weight per unit length of conductor

T = Tension in the conductor.

Consider a point P on the conductor. Taking the lowest point O as the origin, let the co-ordinates of point P be x and y. Assuming that the curvature is so small that curved length is equal to its horizontal projection (*i.e.*, $OP = x$), the two forces acting on the portion OP of the conductor are :

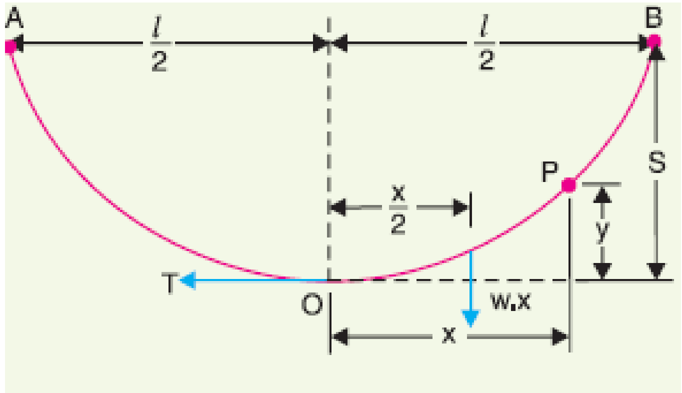


Fig. 8.24

(*a*) The weight wx of conductor acting at a distance $x/2$ from O.
(*b*) The tension T acting at O.

Equating the moments of above two forces about point O, we get,

$$Ty = wx \times \frac{x}{2}$$

$$y = \frac{wx^2}{2T}$$

The maximum dip (sag) is represented by the value of y at either of the supports A and B.

At support A,

$$x = \frac{l}{2} \quad and \quad y = S$$

$$Sag, \quad S = \frac{w\left(l/2\right)^2}{2T} = \frac{wl^2}{8T}$$

(*ii*) When supports are at unequal levels. In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig. 8.25 shows a conductor suspended between two supports *A* and *B* which are at different levels. The lowest point on the conductor is *O*.

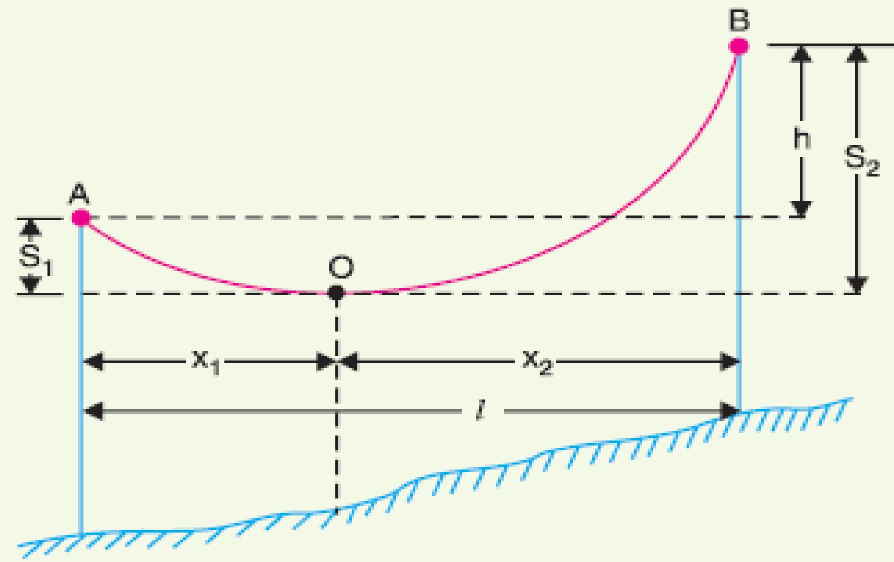


Fig. 8.25

Let

l = Span length

h = Difference in levels between two supports

$x1$ = Distance of support at lower level (*i.e.*, *A*) from *O*

$x2$ = Distance of support at higher level (*i.e. B*) from *O*

T = Tension in the conductor

If w is the weight per unit length of the conductor, then,

$$Sag\ S_1 = \frac{w x_1^{2*}}{2T}$$

$$and \quad S_2 = \frac{w x_2^2}{2T}$$

$$Also\ x_1 + x_2 = l$$

$$S_2 - S_1 = \frac{w}{2T}[x_2^2 - x_1^2] = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$S_2 - S_1 = \frac{wl}{2T}(x_2 - x_1)$$

$$S_2 - S_1 = h$$

$$h = \frac{wl}{2T}(x_2 - x_1)$$

$$(x_2 - x_1) = \frac{2Th}{wl}$$

$$x_1 = \frac{l}{2} - \frac{Th}{wl}$$

$$x_2 = \frac{l}{2} + \frac{Th}{wl}$$

Effect of wind and ice loading.

The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards *i.e.*, in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally *i.e.*, at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown in Fig.

Total weight of conductor per unit length is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

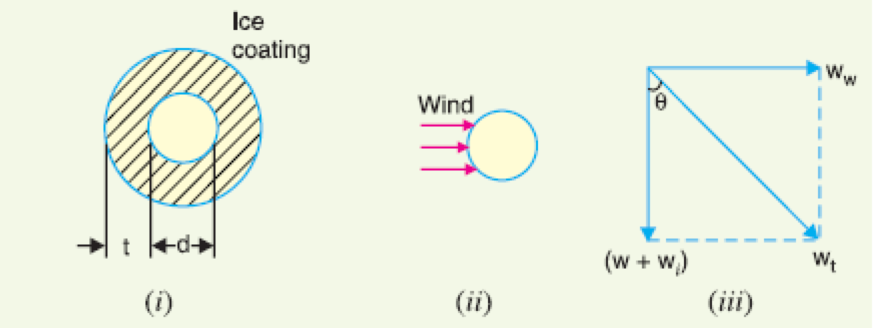


Fig. 8.26

w = weight of conductor per unit length
= conductor material density $*$ volume per unit length

w_i = weight of ice per unit length
= density of ice × volume of ice per unit length

$$= density\ of\ \ ice \times \frac{\pi}{4}\left[(d + 2t)^2 - d^2\right] \times 1$$

$$= density\ of\ \ ice \times \pi t (d + t)$$

$$W_w = wind\ \ pressure \times \left[(d + 2t) \times 1\right]$$

=wind force per unit length
= wind pressure per unit area · projected area per unit length

When the conductor has wind and ice loading also, the following points may be noted :

(i) The conductor sets itself in a plane at an angle θ to the vertical where

$$\tan\theta = \frac{w_w}{w + w_i}$$

(ii) The sag in the conductor is given by :

$$S = \frac{w_t l^2}{2T}$$

Hence S represents the slant sag in a direction making an angle θ to the vertical. *If no specific mention is made in the problem, then slant slag is calculated by using the above formula.*

(*iii*) The vertical sag $= S\cos\theta$

Q-An overhead line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm^2. The ultimate strength is 5000 kg/cm^2 and safety factor is 5. The specific gravity of the material is 8·9 gm/cc. The wind pressure is 1·5 kg/m. Calculate the height of the conductor above the ground level at which it should be supported if a minimum clearance of 7 m is to be left between the ground and the conductor.

Q-The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance betwen the towers is 500 m. If the tension in the conductor is 1600 kg, find the minimum clearance of the conductor and water and clearance mid-way between the supports. Weight of conductor is 1·5 kg/m. Bases of the towers can be considered to be at water level.

Q- An overhead transmission line at a river crossing is supported from two towers at heights of 40 m and 90 m above water level, the horizontal distance between the towers being 400 m. If the maximum allowable tension is 2000 kg, find the clearance between the conductor and water at a point mid-way between the towers. Weight of conductor is 1 kg/m.

Q-A transmission line over a hillside where the gradient is 1 : 20, is supported by two 22 m high towers with a distance of 300 m between them. The lowest conductor is fixed 2 m below the top of each tower. Find the clearance of the conductor from the ground. Given that conductor weighs 1 kg/m and the allowable tension is 1500 kg.

Some Mechanical Principles

We now discuss some important points in the mechanical design of overhead transmission lines.

(*i*) Tower height : Tower height depends upon the length of span. With long spans, relatively few towers are required but they must be tall and correspondingly costly. It is not usually possible to determine the tower height and span length on the basis of direct construction costs because the lightning hazards increase greatly as the height of the conductors above ground is increased. This is one reason that horizontal spacing is favoured inspite of the wider right of way required.

(*ii*) Conductor clearance to ground : The conductor clearance to ground at the time of greatest sag should not be less than some specified distance (usually between 6 and 12 m), depending on the voltage, on the nature of the country and on the local laws. The greatest sag may occur on the hottest day of summer on account of the expansion of the wire or it may occur in winter owing to the formation of a heavy coating of ice on the wires. Special provisions must be made for melting ice
from the power lines.

(*iii*) Sag and tension : When laying overhead transmission lines, it is necessary to allow a reasonable factor of safety in respect of the tension to which the conductor is subjected. The tension is governed by the effects of wind, ice loading and temperature variations. The relationship between tension and sag is dependent on the loading conditions and temperature variations. For example, the tension increases when the temperature decreases and there is a corresponding decrease in the sag. Icing-up of the line and wind loading will cause stretching of the conductor by an amount dependent on the line tension.

In planning the sag, tension and clearance to ground of a given span, a maximum stress is selected. It is then aimed to have this stress developed at the worst probable weather conditions (*i.e.* minimum expected temperature, maximum ice loading and maximum wind). Wind loading increases the sag in the direction of resultant loading but decreases the vertical component. Therefore, in clearance calculations, the effect of wind should not be included unless horizontal clearance is important.

(*iv*) Stringing charts : For use in the field work of stringing the conductors, temperature-sag and temperature tension charts are plotted for the given conductor and loading conditions. Such curves are called stringing charts (see Fig. 8.33). These charts are very helpful while stringing overhead lines.

(*v*) Conductor spacing : Spacing of conductors should be such so as to provide safety against flash-over when the wires are swinging in the wind. The proper spacing is a function of span length, voltage and weather conditions. The use of horizontal spacing eliminates the danger caused by unequal ice loading. Small wires or wires of light material are subjected to more swinging by the wind than heavy conductors. Therefore, light wires should be given greater spacings.

(*vi*) Conductor vibration : Wind exerts pressure on the exposed surface of the conductor. If the wind velocity is small, the swinging of conductors is harmless provided the clearance is sufficiently large so that conductors do not approach within the sparking distance of each other. A completely different type of vibration, called *dancing,* is caused by the action of fairly strong wind on a wire covered with ice, when the ice coating happens to take a form which makes a good air-foil section. Then the whole span may sail up like a kite until it reaches the limit of its slack, stops with a jerk and falls or sails back. The harmful effects of these vibrations occur at the clamps or supports where the conductor suffers fatigue and breaks eventually. In order to protect the conductors, dampers are used.

Vibration dampers Under Ground

Cable:

An **underground cable** *essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.*

(*i*) The conductor used in cables should be tinned stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

(*ii*) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.

(*iii*) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

(*iv*) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.

(*v*) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

Type and construction

(*i*) *Cores or Conductors.* A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3-conductor cable shown in Fig. 11.1 is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

(*ii*) *Insulatian.* Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

(*iii*) *Metallic sheath.* In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig. 11.1.

(iv) *Bedding.* Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

(v) *Armouring.* Over the bedding, armouring is provided which consists of one or two layers of galvanised steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

(vi) *Serving.* In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as *serving.*

It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

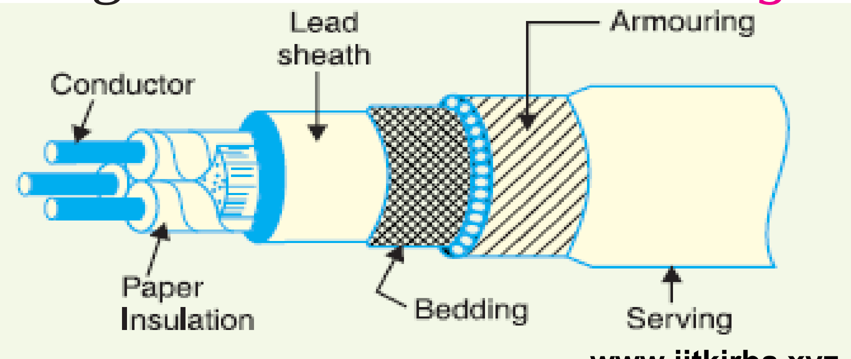


Fig. 11.1 Construction of a Cable

Grading of Cables

The process of achieving uniform electrostatic stress in the dielectric of cables is known as **grading of cables.**

- It has already been shown that electrostatic stress in a single core cable has a maximum value (g_{max}) at the conductor surface and goes on decreasing as we move towards the sheath
- The unequal stress distribution in a cable is undesirable for two reasons.
  - Firstly, insulation of greater thickness is required which increases the cable size.
  - Secondly, it may lead to the breakdown of insulation.
- In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables.

The following are the two main methods of grading of cables :

(*i*) Capacitance grading **(*ii*)** Intersheath grading

Capacitance Grading

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as **capacitance grading.**

- In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity ε_r of any layer is inversely proportional to its distance from the centre.
- Under such conditions, the value of potential gradient at any point in the dieletric is constant and is independent of its distance from the centre.
- There are three dielectrics of outer diameter d_1, d_2 and D and of relative permittivity ε_1, ε_2 and ε_3 respectively.
- If the permittivities are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and the three dielectrics are worked at the same maximum stress, then,

$$\frac{1}{\varepsilon_1 d} = \frac{1}{\varepsilon_2 d_1} = \frac{1}{\varepsilon_3 d_2}$$

$$\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

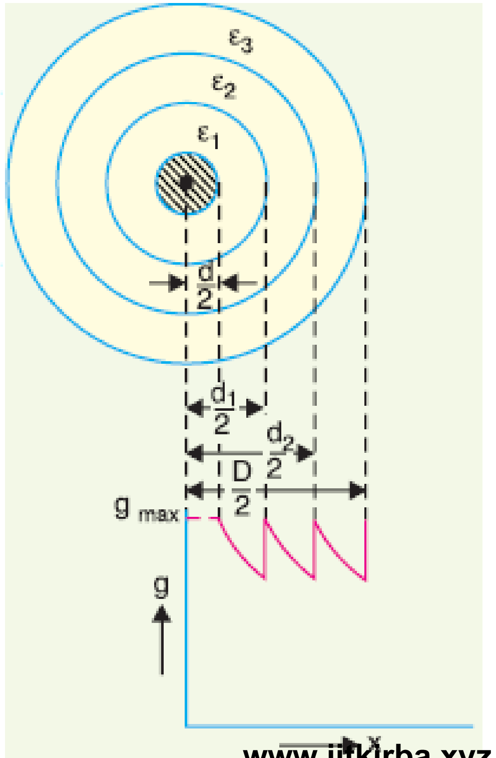


Fig. 11.15

Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g\, dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi\varepsilon_0\varepsilon_1 x}\, dx$$

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_1 x}\log_e \frac{d_1}{d} = \frac{g_{\max}}{2} d \log_e \frac{d_1}{d} \qquad \left[\because \frac{Q}{2\pi\varepsilon_0\varepsilon_1 x} = \frac{g_{\max}}{2} d\right]$$

Similarly, potential across second layer (V_2) and third layer (V_3) is given by

$$V_2 = \frac{g_{\max}}{2} d_1 \log_e \frac{d_2}{d_1}$$

$$V_3 = \frac{g_{\max}}{2} d_2 \log_e \frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$= \frac{g_{\max}}{2}\left[d \log_e \frac{d_1}{d} + d_1 \log_e \frac{d_2}{d_1} + d_2 \log_e \frac{D}{d_2} \right]$$

If the cable had homogeneous dielectric, then, for the same values of d, D and g_{max}, the permissible potential difference between core and earthed sheath would have been

$$V' = \frac{g_{max}}{2} d \log_e \frac{D}{d}$$

Obviously, $V > V'$ *i.e.,* for given dimensions of the cable, a graded cable can be worked at a greater potential than non-graded cable.
Alternatively, for the same safe potential, the size of graded cable will be less than that of non-graded cable. The following points may be noted :

(i) As the permissible values of g_{max} are peak values, therefore, all the voltages in above expressions should be taken as peak values and not the r.m.s. values.

(ii) If the maximum stress in the three dielectrics is not the same, then,

$$V = \frac{g_{1max}}{2} d \log_e \frac{d_1}{d} + \frac{g_{2max}}{2} d_1 \log_e \frac{d_2}{d_1} + \frac{g_{3max}}{2} d_2 \log_e \frac{D}{d_2}$$

Disadvantage - *there are a few high grade dielectrics of reasonable cost whose permittivities vary over the required range.*

Intersheath Grading

In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic intersheaths between the core and lead sheath. The intersheaths are held at suitable potentials which are inbetween the core potential and earth potential.

This arrangement improves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained

- Consider a cable of core diameter *d* and outer lead sheath of diameter *D*. Suppose that two intersheaths of diameters *d*1 and *d*2 are inserted into the homogeneous dielectric and maintained at some fixed potentials.
- Let V_1, V_2 and V_3 respectively be the voltage between core and intersheath 1, between intersheath 1 and 2 and between intersheath 2 and outer lead sheath.
- As there is a definite potential difference between the inner and outer layers of each intersheath, therefore, each sheath can be treated like a homogeneous single core cable.

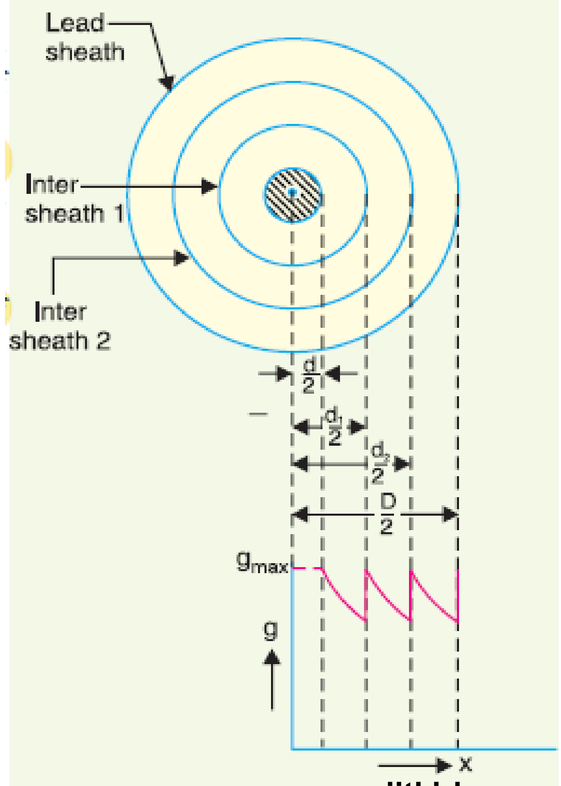


Fig. 11.17

Maximum stress between core and intersheath 1 is

$$g_{1\max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}}$$

$$g_{2\max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}}$$

$$g_{3\max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same *i.e.*,

$g_{1\max}$=$g_{1\max}$=$g_{1\max}$=$g_{\max}$

$$\frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase *i.e.* Voltage between conductor and earthed lead sheath is

$V = V_1 + V_2 + V_3$

Disadvantages.

- Firstly, there are complications in fixing the sheath potentials.
- Secondly, the intersheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient.
- Thirdly, there are considerable losses in the intersheaths due to charging currents. For these reasons, intersheath grading is rarely used.

Capacitance of 3-Core Cables

- The capacitance of a cable system is much more important than that of overhead line because in cables

(i) conductors are nearer to each other and to the earthed sheath

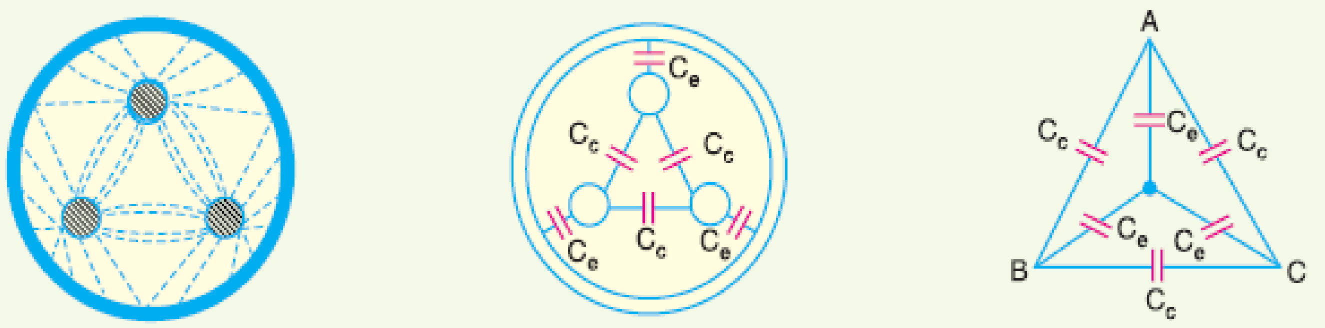
(ii) (*ii*) they are separated by a dielectric of permittivity much greater than that of air.

- Factors affecting capacitance: Dielectric material, conductor spacing, core arrangement

Types of Capacitances in 3-Core Cables

- Core-to-core capacitance
- Core-to-sheath capacitance
- Equivalent capacitance of the cable system

Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig. 11.18 (*i*). These electrostatic fields give rise to core-core capacitances *Cc* and conductor- earth capacitances *Ce* as shown in Fig. 11.18 (*ii*). The three *Cc* are delta connected whereas the three *Ce* are star connected, the sheath forming the star point [See Fig. 11.18 (*iii*)].



(*i*) (*ii*) (*iii*)

Fig. 11.18

They lay of a belted cable makes it reasonable to assume equality of each C_c and each C_e. The three delta connected capacitances C_c [See Fig. 11.19 (*i*)] can be converted into equivalent star connected capacitances as shown in Fig. 11.19 (*ii*). It can be easily *shown that equivalent star capacitance C_{eq} is equal to three times the delta capacitance C_c *i.e.* $C_{eq} = 3C_c$.

The system of capacitances shown in Fig. 11.18 (*iii*) reduces to the equivalent circuit shown in Fig. 11.20 (*i*). Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance [See Fig. 11.20 (*ii*)],

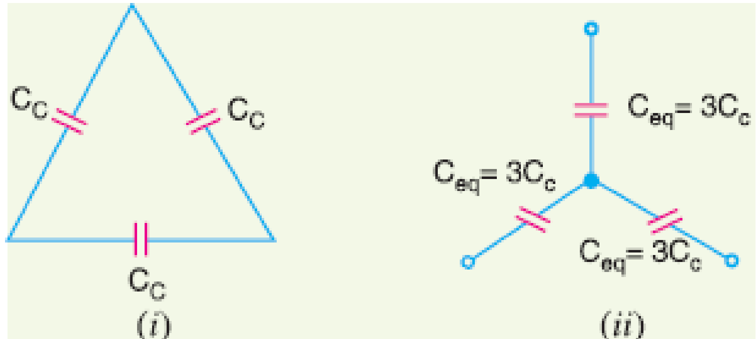


Fig. 11.19

$$C_N = C_e + C_{eq}$$
$$= C_e + 3C_c$$

If V_{ph} is the phase voltage, then charging current I_C is given by ;

$$I_C = \frac{V_{ph}}{capacitive\ reactance\ per\ phase}$$
$$= 2\pi f V_{ph} C_N$$
$$= 2\pi f V_{ph} \left(C_e + 3C_c \right)$$

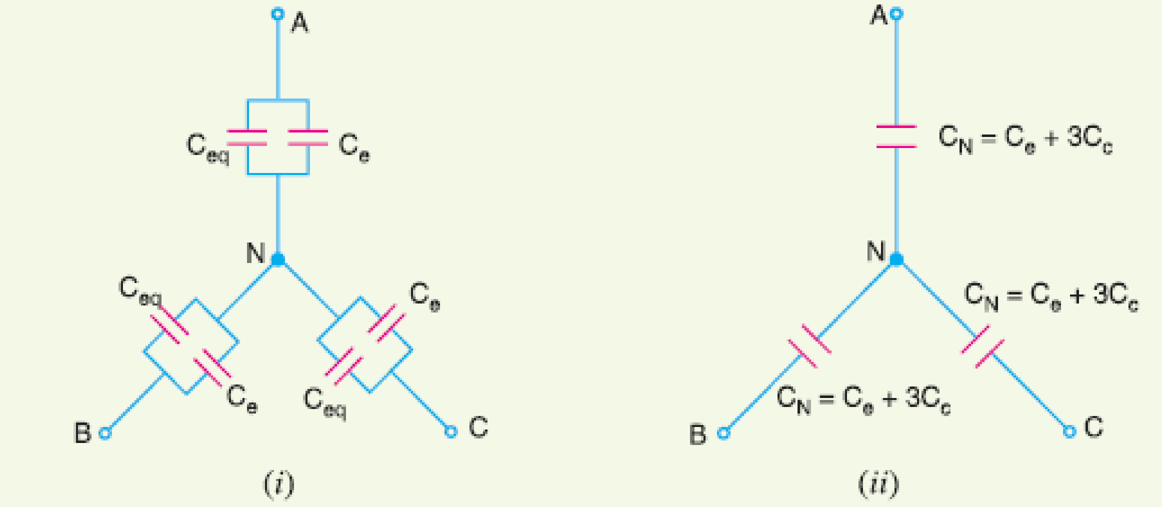


Fig. 11.20

Although core-core capacitance C_c and core-earth capacitance C_e can be obtained from the empirical formulas for belted cables, their values can also be determined by measurements. For this purpose, the following two measurements are required :

(*i*) In the first measurement, the three cores are bunched together (*i.e.* commoned) and the capacitance is measured between the bunched cores and the sheath. The bunching eliminates all the three capacitors *Cc*, leaving the three capacitors *Ce* in parallel. Therefore, if *C*1 is the measured capacitance, this test yields :

$$C_1 = 3C_e$$

$$C_e = \frac{C_1}{3}$$

Knowing the value of C_1, the value of C_e can be determined.

(*ii*) In the second measurement, two cores are bunched with the sheath and capacitance is measured between them and the third core. This test yields $2C_c + C_e$. If C_2 is the measured capacitance, then,

$C_2 = 2C_c + C_e$

As the value of C_e is known from first test and C_2 is found experminentally, therefore, value of C_c can be determined.

It may be noted here that if value of CN (= Ce + 3Cc) is desired, it can be found directly by another test. In this test, the capacitance between two cores or lines is measured with the third core free or connected to the sheath. This eliminates one of the capacitors Ce so that if C3 is the measured capacitance, then,

$$C_3 = C_c + \frac{C_c}{2} + \frac{C_e}{2}$$

$$= \frac{1}{2}\left(C_e + 3C_c\right)$$

$$= \frac{1}{2}C_N$$

Current Ratings

The safe current-carrying capacity of an underground cable is determined by the maximum permissible temperature rise. The cause of temperature rise is the losses that occur in a cable which appear as heat. These losses are :

(*i*) Copper losses in the conductors

(*ii*) Hysteresis losses in the dielectric

(*iii*) Eddy current losses in the sheath

The safe working conductor temperature is 65ºC for armoured cables and 50ºC for lead-sheathed cables laid in ducts. The maximum steady temperature conditions prevail when the heat generated in the cable is equal to the heat dissipated. The heat dissipation of the conductor losses is by conduction through the insulation to the sheath from which the total losses (including dielectric and sheath losses) may be conducted to the earth. Therefore, in order to find permissible current loading, the thermal resistivities of the insulation, the protective

Thermal Resistance

The thermal resistance between two points in a medium (*e.g.* insulation) is equal to temperature difference between these points divided by the heat flowing between them in a unit time *i.e.*

$$\text{Thermal resistance, } S = \frac{\text{Temperature difference}}{\text{Heat flowing in a unit time}}$$

In SI units, heat flowing in a unit time is measured in watts.

$$\text{Thermal resistance, } S = \frac{\text{Temperature rise (t)}}{\text{Watts dissipated}(P)}$$

$$S = \frac{t}{P}$$

Clearly, the SI unit of thermal resistance is °C per watt. This is also called *thermal ohm*. Like electrical resistance, thermal resistance is directly proportional to length l in the direction of transmission of heat and inversely proportional to the cross-section area a at right angles to that direction.

$$S \,\alpha\, \frac{l}{a}$$

$$S = k\frac{l}{a}$$

where k is the constant of proportionality and is known as *thermal resistivity*.

$$k = \frac{S\,a}{l}$$

Thermal Resistance of Dielectric of a Single-Core Cable

Let us now find the thermal resistance of the dielectric of a single-core cable.

Let r = radius of the core in metre

r_1 = inside radius of the sheath in metre

k = thermal resistivity of the insulation (*i.e.* dielectric)

Consider1m length of the cable. The thermal resistance of small element of thickness dx at radius x is

$$dS = k \times \frac{dx}{2\pi x}$$

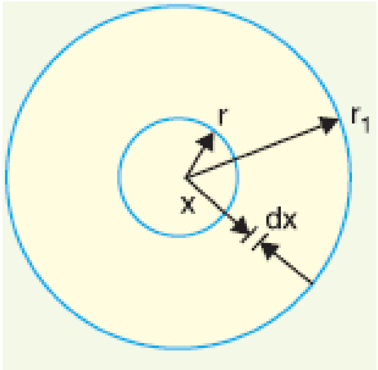


Fig. 11.21

Thermal resistance of the dielectric is

$$S = \int_r^{r_1} k \times \frac{dx}{2\pi x}$$

$$= \frac{k}{2\pi x} \int_r^{r_1} \frac{1}{x} dx$$

$$S = \frac{k}{2\pi} \log_e \frac{r_1}{r}$$

The thermal resistance of lead sheath is small and is generally neglected in calculations.

Permissible Current Loading

When considering heat dissipation in underground cables, the various thermal resistances providing a heat dissipation path are in series. Therefore, they add up like electrical resistances in series.

Consider a cable laid in soil

Let I = permissible current per conductor

n = number of conductors

R = electrical resistance per metre length of the conductor at the working temperature

S = total thermal resistance (*i.e.* sum of thermal resistances of dielectric and soil) per metre length

t = temperature difference (rise) between the conductor and the soil

Neglecting the dielectric and sheath losses, we have,

$$\text{Power dissipated} = nI^2R$$

$$\text{Now Power dissipated} = \frac{\text{Temperature rise}}{\text{Thermal resistance}}$$

$$nI^2R = \frac{t}{S}$$

Permissible current per conductor in given by;

$$I = \sqrt{\frac{t}{nRS}}$$

Classification of Cables

Cables for underground service may be classified in two ways according to

(*i*) the type of insulating material used in their manufacture

(*ii*) the voltage for which they are manufactured.

According to the voltage for which they are manufactured

(*i*) Low-tension (L.T.) cables — upto 1000 V

(*ii*) High-tension (H.T.) cables — upto 11,000 V

(*iii*) Super-tension (S.T.) cables — from 22 kV to 33 kV

(*iv*) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

(*v*) Extra super voltage cables — beyond 132 kV

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be (*i*) single-core (*ii*) two-core (*iii*) three-core (*iv*) four-core etc. For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.

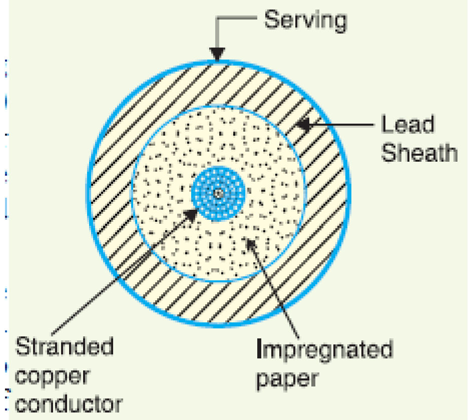


Fig. 11.2

Cables for 3-Phase Service

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or *three single core cables may be used. For voltages upto 66 kV, 3-core cable (*i.e.*, multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used. The following types of cables are generally used for 3-phase service :

1. Belted cables — upto 11 kV
2. Screened cables — from 22 kV to 66 kV
3. Pressure cables — beyond 66 kV.

Belted cables

- These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV
- The cores are insulated from each other by layers of impregnated paper.
- Another layer of impregnated paper tape, called *paper belt* is wound round the grouped insulated cores.
- The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable.
- The cores are generally stranded and may be of noncircular shape to make better use of available space.
- The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury.
- The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure).

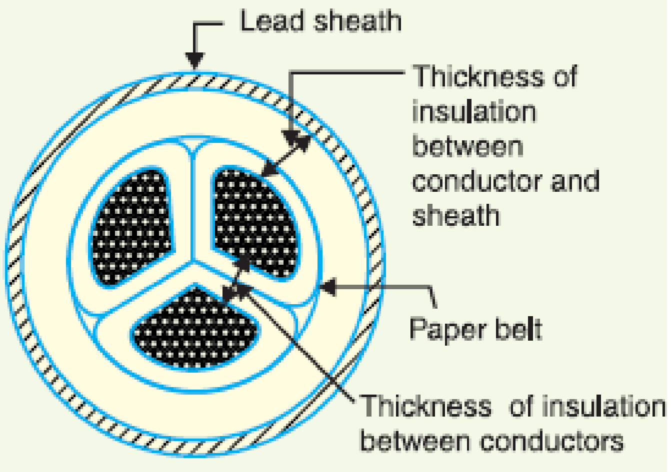


Fig. 11.3

- The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial *i.e.*, across the insulation.
- However, for high voltages (beyond 22 kV), the tangential stresses also become important.
- These stresses act along the layers of paper insulation.
- As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up leakage current along the layers of paper insulation.
- The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment. In order to overcome this difficulty, *screened cables* are used where leakage currents are conducted to earth through metallic screens

2. Screened cables.

These cables are meant for use upto 33 kV, but in particular cases their use may be extended to operating voltages upto 66 kV. Two principal types of screened cables are Htype cables and S.L. type cables.

(i) *H-type cables*

This type of cable was first designed by H. Hochstadter and hence the name. Fig. 11.4 shows the constructional details of a typical 3-core, *H*-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminium foil. The cores are laid in such a way that metallic screens make contact with one another. An additional conducting belt (copper woven fabric tape) is

wrapped round the three cores. The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at †earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced.

Two principal advantages are claimed for *H*-type cables.

- Firstly, the perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation.
- Secondly, the metallic screens increase the heat dissipating power of the cable.

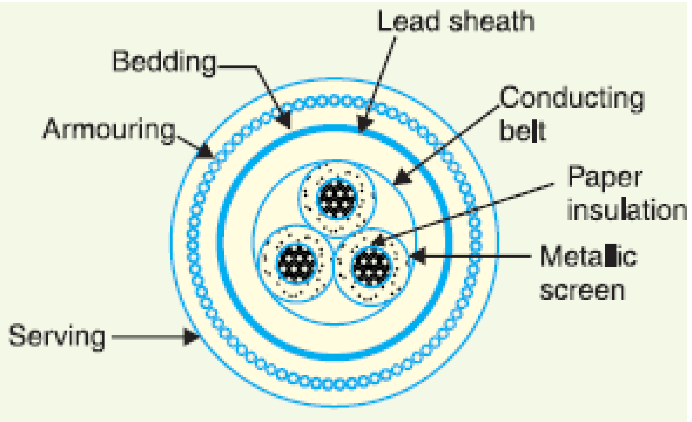


Fig. 11.4

(*ii*) *S.L. type cables.*

- It is basically *H*-type cable but the screen round each core insulation is covered by its own lead sheath.
- There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over *H*-type cables.
- Firstly, the separate sheaths minimise the possibility of core-to-core breakdown. Secondly, bending of cables becomes easy due to the elimination of overall lead sheath.
- However, the disadvantage is that the three lead sheaths of S.L. cable are much thinner than the single sheath of *H*-cable and, therefore, call for greater care in manufacture.

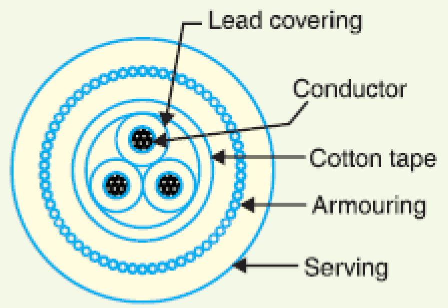


Fig. 11.5

Limitations of solid type cables. All the cables of above construction are referred to as solid type cables because solid insulation is used and no gas or oil circulates in the cable sheath. The voltage limit for solid type cables is 66 kV due to the following

reasons :

(*a*) As a solid cable carries the load, its conductor temperature increases and the cable com-pound (*i.e.*, insulating compound over paper) expands. This action stretches the lead sheath which may be damaged.

(*b*) When the load on the cable decreases, the conductor cools and a partial vacuum is formed within the cable sheath. If the pinholes are present in the lead sheath, moist air may be drawn into the cable. The moisture reduces the dielectric strength of insulation and may eventually cause the breakdown of the cable.

(*c*) In practice, †voids are always present in the insulation of a cable. Modern techniques of manufacturing have resulted in void free cables. However, under operating conditions, the voids are formed as a result of the differential expansion and contraction of the sheath and impregnated compound. The breakdown strength of voids is considerably less than that of the insulation. If the void is small enough, the electrostatic stress across it may cause its breakdown. The voids nearest to the conductor are the first to break down, the chemical and thermal effects of ionisation causing permanent damage to the paper insulation.

3. Pressure cables For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids. When the operating voltages are greater than 66 kV, *pressure cables* are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables *viz* oil-filled cables and gas pressure cables are commonly used.

(i) Oil-filled cables.

- In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the cable.
- Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers.

- Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV upto 230 kV.
- Oil-filled cables are of three types *viz.*, single-core conductor channel, single-core sheath channel and three-core filler-space channels.
- Fig. 11.6 shows the constructional details of a single-core conductor channel, oil filled cable.
- The oil channel is formed at the centre by stranding the conductor wire around a hollow cylindrical steel spiral tape.
- The oil under pressure is supplied to the channel by means of external reservoir.
- As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation.
- The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation.

- The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir. However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel.

- Disadvantage of this type of cable is that the channel is at the middle of the cable and is at full voltage *w.r.t.* earth, so that a very complicated system of joints is necessary.

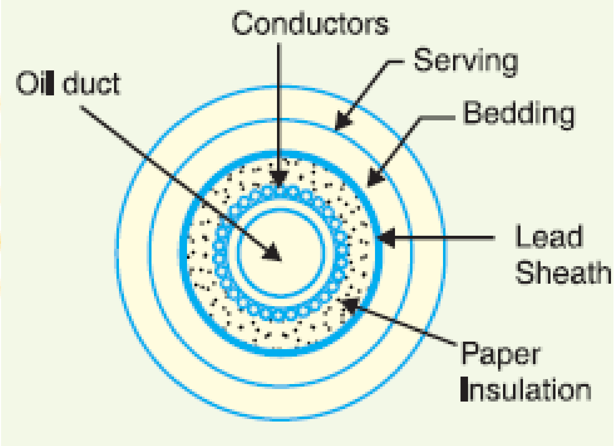


Fig. 11.6 Single-core conductor channel, oil-filled cable

- Fig. 11.7 shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown.
- In the 3-core oil-filler cable shown in Fig. 11.8, the oil ducts are located in the filler spaces. These channels are composed of perforated metal-ribbon tubing and are at earth potential.

Advantages

- Firstly, formation of voids and ionisation are avoided.
- Secondly, allowable temperature range and dielectric strength are increased.
- Thirdly, if there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased.

Disadvantages

- High initial cost
- Complicated system of laying.

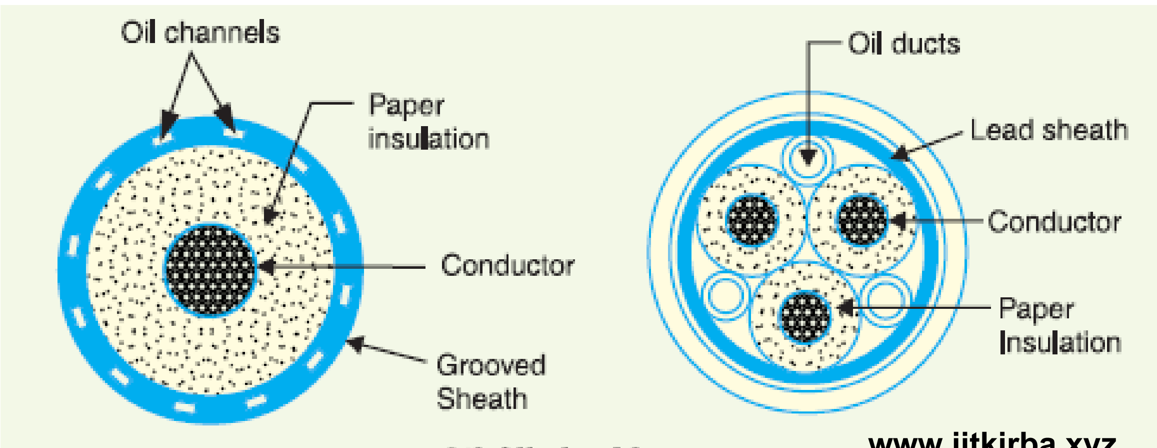


Fig. 11.7 *Oil-filled cables* Fig. 11.8

(*ii*) *Gas pressure cables.*

- The voltage required to set up ionisation inside a void increases as the pressure is increased.
- Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionisation can be altogether eliminated.
- At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.

- The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable.
- The triangular section reduces the weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane.
- The sheath is protected by a thin metal tape.

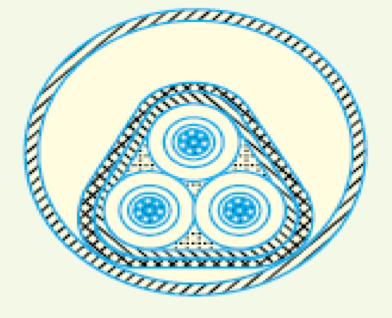


Fig. 11.9

- The cable is laid in a gas-tight steel pipe. The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres.
- The gas pressure produces radial compression and closes the voids that may have formed between the layers of paper insulation. Such cables can carry more load current and operate at higher voltages than a normal cable.
- Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. Disadvantage -overall cost is very high.