Course: Transmission and Distribution– BEE402

Module-1:Introduction to power system

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Advantages of High Transmission Voltage

- Electrical energy is generated at a voltage about 11 kV using alternators.
- This voltage is then stepped up to 132, 220 or 400 kV for transmission purpose.

For transmission of electric power high voltage is preferred because of following advantages,

1) Reduction in the current

Power transmitted is given by,

$$P = \sqrt{3} V I \cos\phi$$

Where V = Transmission voltage, I = Load current, cos = Load power factor

Hence load current is given by,

$$I = \frac{P}{\sqrt{3} V \cos\phi}$$

- From the above expression it can be seen that for the constant power and power factor, the load current is inversely proportional to the transmission voltage.
- With increase in transmission voltage, load current gets reduced.
- As current gets reduced, size of conductor required also reduces for transmitting same amount of power.

2) Reduction in the losses

Power loss in a line is given by,

$$W = 3I^2R$$

$$W = 3\left[\frac{P}{\sqrt{3}\,V\cos\phi}\right]^2 R = \frac{P^2R}{V^2\cos^2\phi}$$

From the above expression it can be seen that power loss in a line is inversely proportional to square of transmission voltage i.e. greater the transmission voltage lesser is the loss in the line.

3) Reduction in volume of conductor material required.

4) Decrease in voltage drop and improvement of voltage regulation

5) Increase in transmission efficiency

6) Increased power handling capacity

Power transmitted over a transmission line is given by

$$P = \frac{V_S \cdot V_R}{X} \sin \delta$$

Thus if we assume that Vs=VR then power transmitted is proportional to square of voltage which increases power handling capacity of the line.

7) The number of circuits and the land requirement reduces as transmission voltage increases.

8) The total line cost per MW per km decreases considerably with the increase in line voltage.

9) The operation with HV A.C. voltage is simple and can be adopted easily and naturally to the synchronously operating a.c. systems.

10) The equipments used in HV A.C. system are simple and reliable without need of high technology.

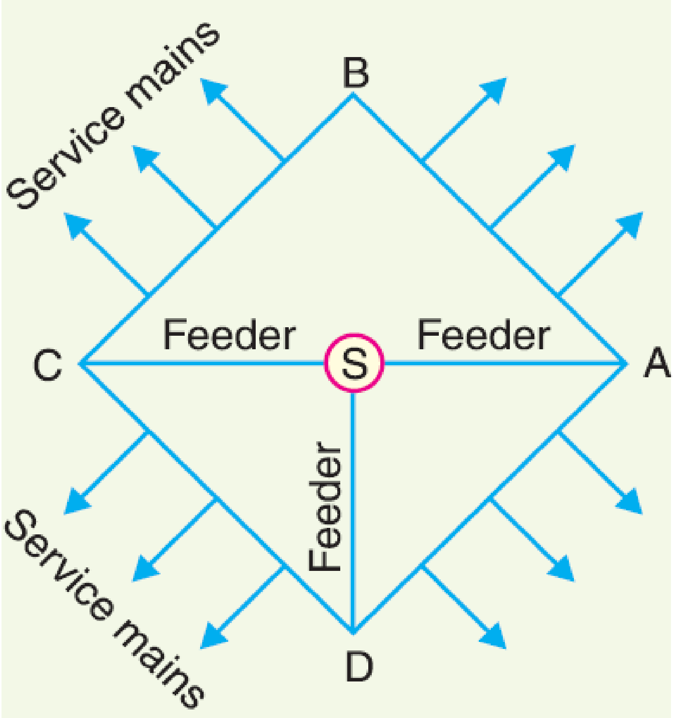
11) The lines can be easily tapped and extended with simple control of power flow in the network.

Distribution System

That part of power system which distributes electric power for local use is known as **distribution system**.

- In general, the distribution system is the electrical system between the sub-station fed by the transmission system and the consumers meters.

- It generally consists of feeders, distributors and the service mains. Fig.1 shows the single line diagram of a typical low tension distribution system.



i) Feeders: A feeder is a conductor which connects the sub-station (or localised generating station) to the area where power is to be distributed.

- Generally, no tappings are taken from the feeder so that current in it remains the same throughout.
- The main consideration in the design of a feeder is the current carrying capacity.

(ii) Distributor: A distributor is a conductor from which tappings are taken for supply to the consumers. In Fig.1, AB, BC, CD and DA are the distributors.

- The current through a distributor is not constant because tappings are taken at various places along its length.
- While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 6% of rated value at the consumers' terminals.

(iii) Service mains: A service mains is generally a small cable which connects the distributor to the consumers' terminals.

Overhead Transmission Lines

Main Components of Overhead Lines

An overhead line may be used to transmit or distribute electric power. The successful operation of an overhead line depends to a great extent upon the mechanical design of the line.

In general, the main components of an overhead line are:

(i) Conductors

which carry electric power from the sending end station to the receiving end station.

(ii) Supports

which may be poles or towers and keep the conductors at a suitable level above the ground.

(iii) Insulators

Which are attached to supports and insulate the conductors from the ground.

(iv) Cross arms

Which provide support to the insulators.

(v) Miscellaneous items

Such as phase plates, danger plates, lightning arrestors, anti-climbing wires etc.

Conductor Materials

- The conductor is one of the important items as most of the capital outlay is invested for it.
- Therefore, proper choice of material and size of the conductor is of considerable importance.

The conductor material used for transmission and distribution of electric power should have the following properties :

(*i*) High electrical conductivity.

(*ii*) High tensile strength in order to withstand mechanical stresses.

(*iii*) Low cost so that it can be used for long distances.

(*iv*) Low specific gravity so that weight per unit volume is small.

Commonly used conductor materials.

- The most commonly used conductor materials for overhead lines are *copper, aluminium, steel-cored aluminium, galvanized steel* and *cadmium copper*.
- The choice of a particular material will depend upon the cost, the required electrical and mechanical properties and the local conditions.

Line Supports

The supporting structures for overhead line conductors are various types of poles and towers called ***line supports***.

In general, the line supports should have the following properties :

(*i*) High mechanical strength to withstand the weight of conductors and wind loads etc.

(*ii*) Light in weight without the loss of mechanical strength.

(*iii*) Cheap in cost and economical to maintain.

(*iv*) Longer life.

(*v*) Easy accessibility of conductors for maintenance.

- The line supports used for transmission and distribution of electric power are of various types including *wooden poles, steel poles, R.C.C. poles* and *lattice steel towers.*
- The choice of supporting structure for a particular case depends upon the line span, X-sectional area, line voltage, cost and local conditions.

Wooden poles.

These are made of seasoned wood and are suitable for lines of moderate X-sectional area and of relatively shorter spans, say upto 50 metres.

Such supports are cheap, easily available, provide insulating properties and, therefore, are widely used for distribution purposes in rural areas as an economical proposition.

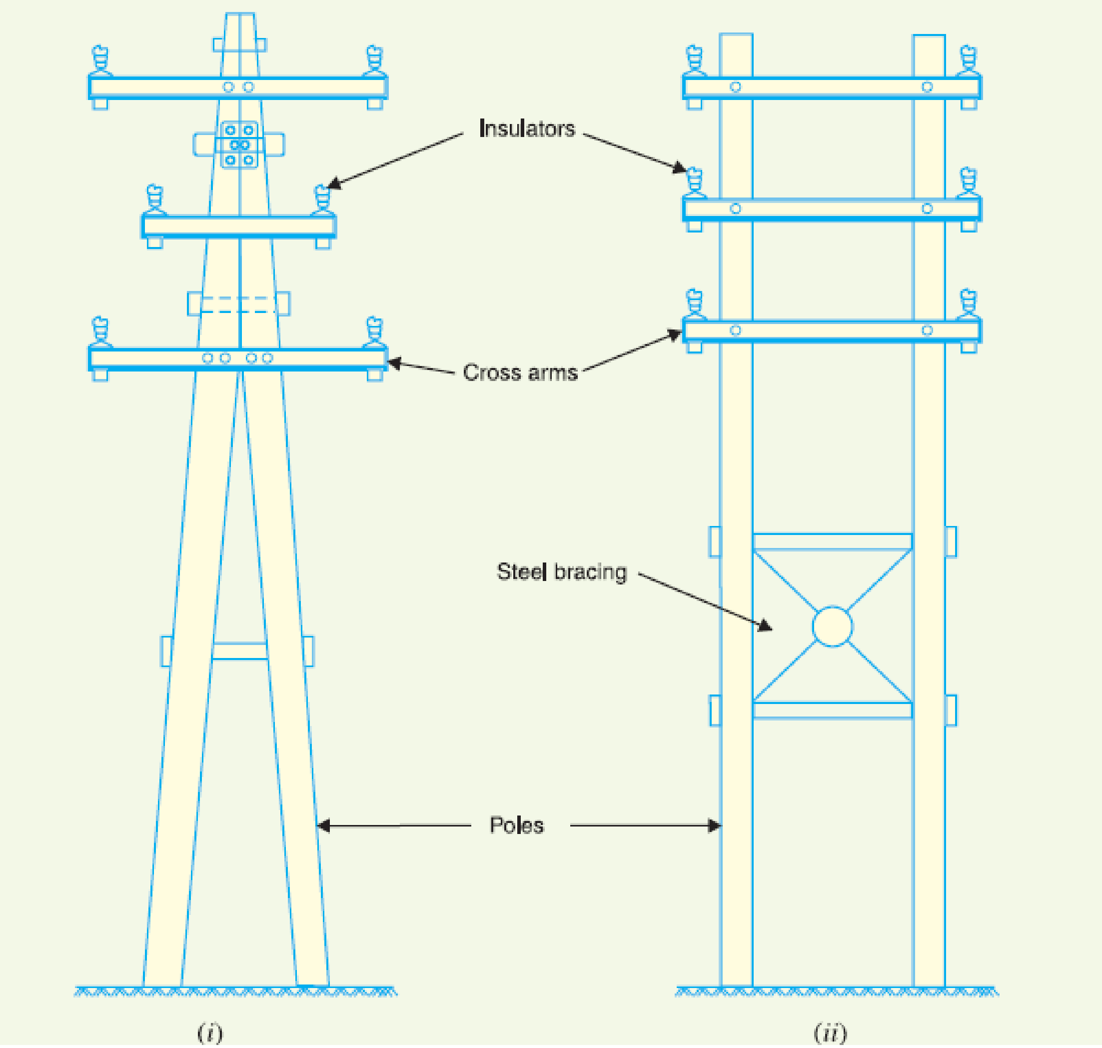


Fig 1.1 Wooden poles

2. Steel poles.

The steel poles are often used as a substitute for wooden poles. They possess greater mechanical strength, longer life and permit longer spans to be used. Such poles are generally used for distribution purposes in the cities. This type of supports need to be galvanized or painted in order to prolong its life.

The steel poles are of three types viz.,

(*i*) Rail poles **(*ii*)** Tubular poles and **(*iii*)** Rolled steel joints.

3. RCC poles. The reinforced concrete poles have become very popular as line supports in recent years. They have greater mechanical strength, longer life and permit longer spans than steel poles. Moreover, they give good outlook, require little maintenance and have good insulating properties.

Fig.1.2 shows R.C.C. poles for single and double circuit. The holes in the poles facilitate the climbing of poles and at the same time reduce the weight of line supports.

The main difficulty with the use of these poles is the high cost of transport owing to their heavy weight. Therefore, such poles are often manufactured at the site in order to avoid heavy cost of transportation.

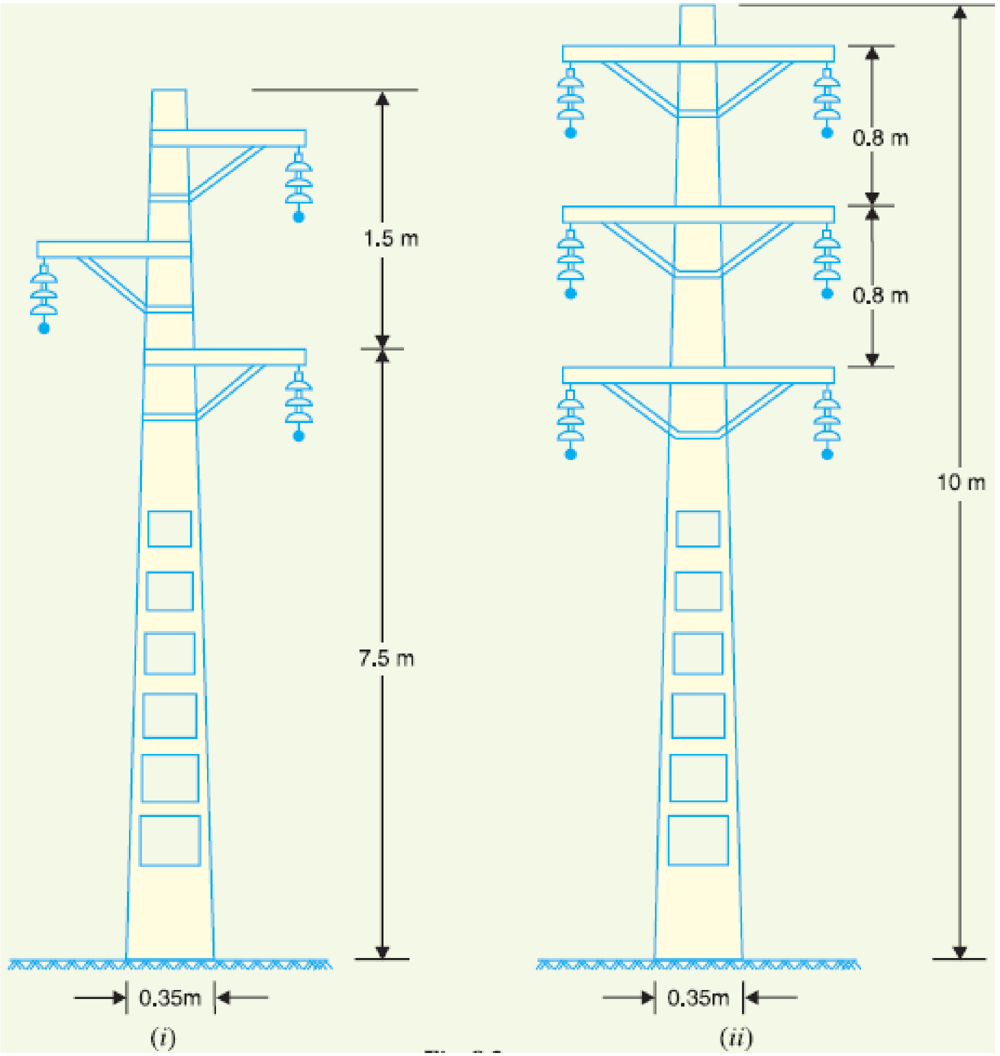


Fig.1.2 shows R.C.C. poles for single and double circuit

4. Steel towers.

- In practice, wooden, steel and reinforced concrete poles are used for distribution purposes at low voltages, say upto 11 kV.
- However, for long distance transmission at higher voltage, steel towers are invariably employed.
- Steel towers have greater mechanical strength, longer life, can withstand most severe climatic conditions and permit the use of longer spans.
- The risk of interrupted service due to broken or punctured insulation is considerably reduced owing to longer spans.
- Tower footings are usually grounded by driving rods into the earth. This minimizes the lightning troubles as each tower acts as a lightning conductor.

Fig. 1.3 (*i*) shows a single circuit tower. However, at a moderate additional cost, double circuit tower can be provided as shown in Fig. 1.3 (*ii*).

The double circuit has the advantage that it ensures continuity of supply. It case there is breakdown of one circuit, the continuity of supply can be maintained by the other circuit.

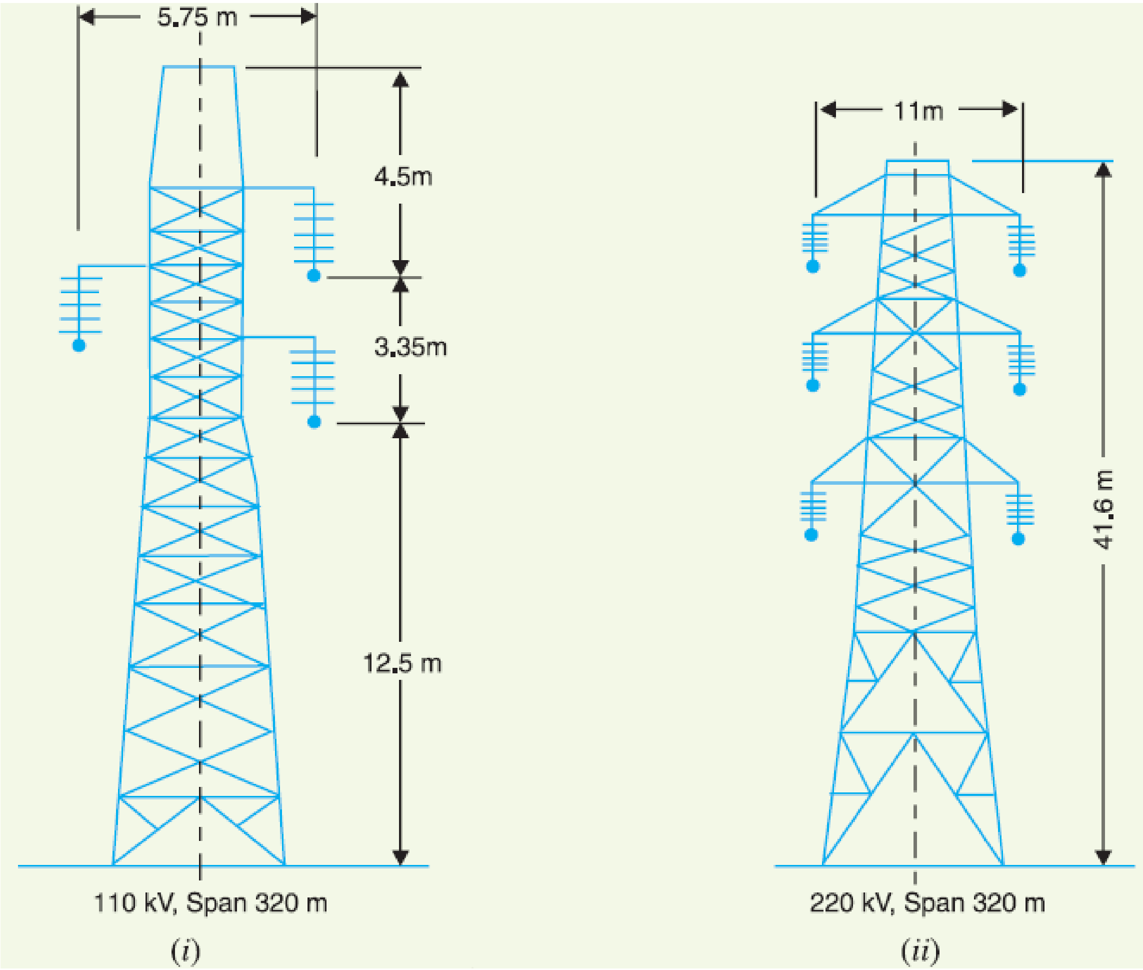


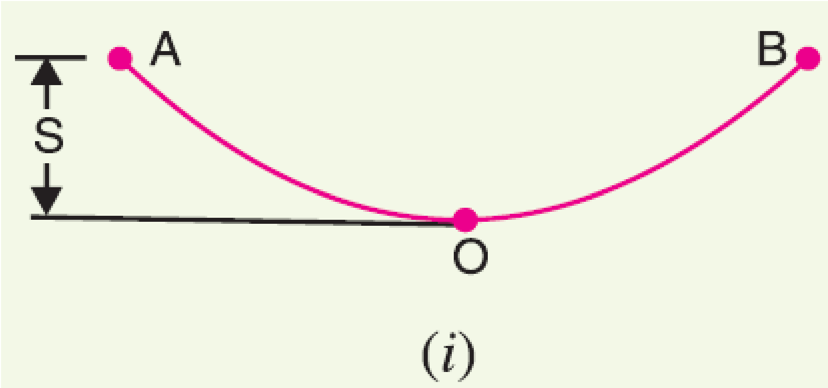
Fig 1.3 (i and ii) Single and Double Circuit Tower

Sag in Overhead Lines

- While erecting an overhead line, it is very important that conductors are under safe tension.
- If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases the conductor may break due to excessive tension.
- In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip or sag.

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

- Fig. 1.4 (*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*.



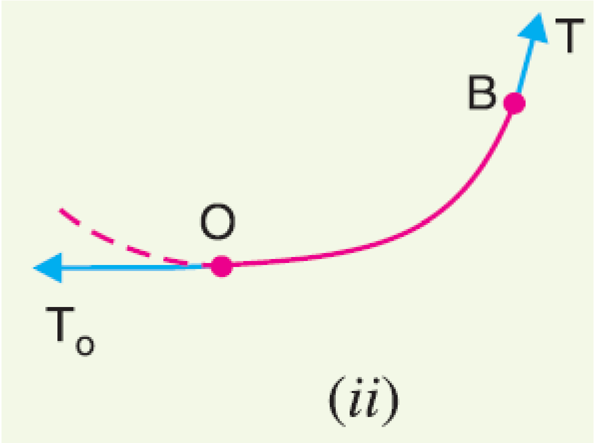


Fig 1.4

The following points may be noted :

(*i*) When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola.

(*ii*) The tension at any point on the conductor acts tangentially. Thus tension T_O at the lowest point *O* acts horizontally as shown in Fig. 1.4. (*ii*).

(*iii*) The horizontal component of tension is constant throughout the length of the wire.

(*iv*) The tension at supports is approximately equal to the horizontal tension acting at any point on the wire. Thus if *T* is the tension at the support *B*, then $T = T_O$.

Conductor Sag and Tension.

- This is an important consideration in the mechanical design of overhead lines.
- The conductor sag should be kept to a minimum in order to reduce the conductor material required and to avoid extra pole height for sufficient clearance above ground level.
- It is also desirable that tension in the conductor should be low to avoid the mechanical failure of conductor and to permit the use of less strong supports.
- However, low conductor tension and minimum sag are not possible.
- It is because low sag means a tight wire and high tension, whereas a low tension means a loose wire and increased sag.
- Therefore, in actual practice, a compromise in made between the two.

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. 1.5. 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.

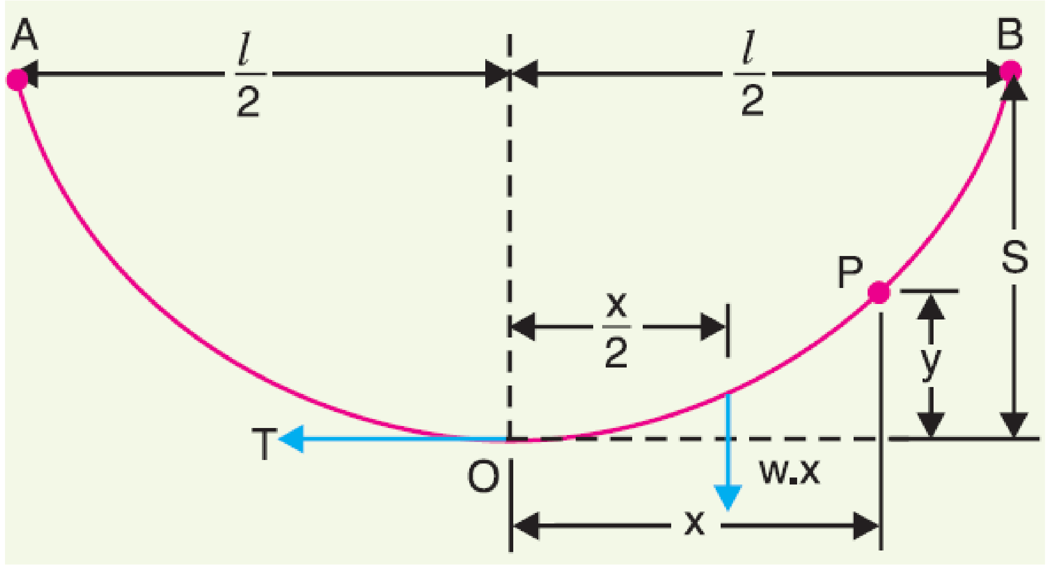
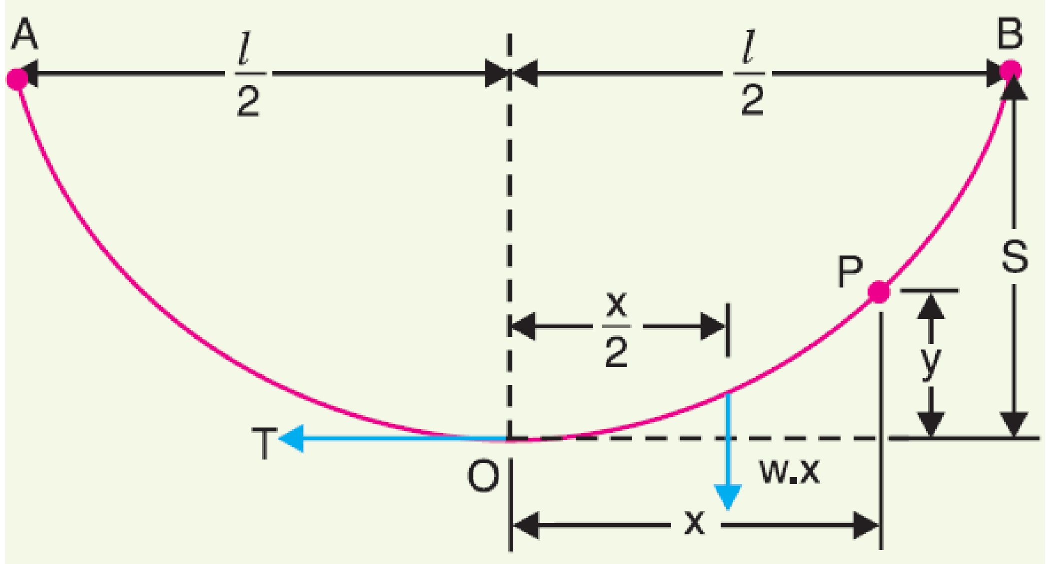


Fig 1.5

Consider a point *P* on the conductor. Taking the lowest point *O* as the origin, let the coordinates 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 :



(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,

$$Ty = wx \times \frac{x}{2} \quad \text{or} \quad y = \frac{wx^2}{2T}$$

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

At support *A*, $x = l/2$ and $y = S$

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

(*ii*) When supports are at unequal levels. In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig. 1.6 shows a conductor suspended between two supports *A* and *B* which are at different levels. The lowest point on the conductor is *O*.

Let

l = Span length

h = Difference in levels between two supports

x_1 = Distance of support at lower level (*i.e.*, *A*) from *O*

x_2 = Distance of support at higher level (*i.e.* *B*) from *O*

T = Tension in the conductor

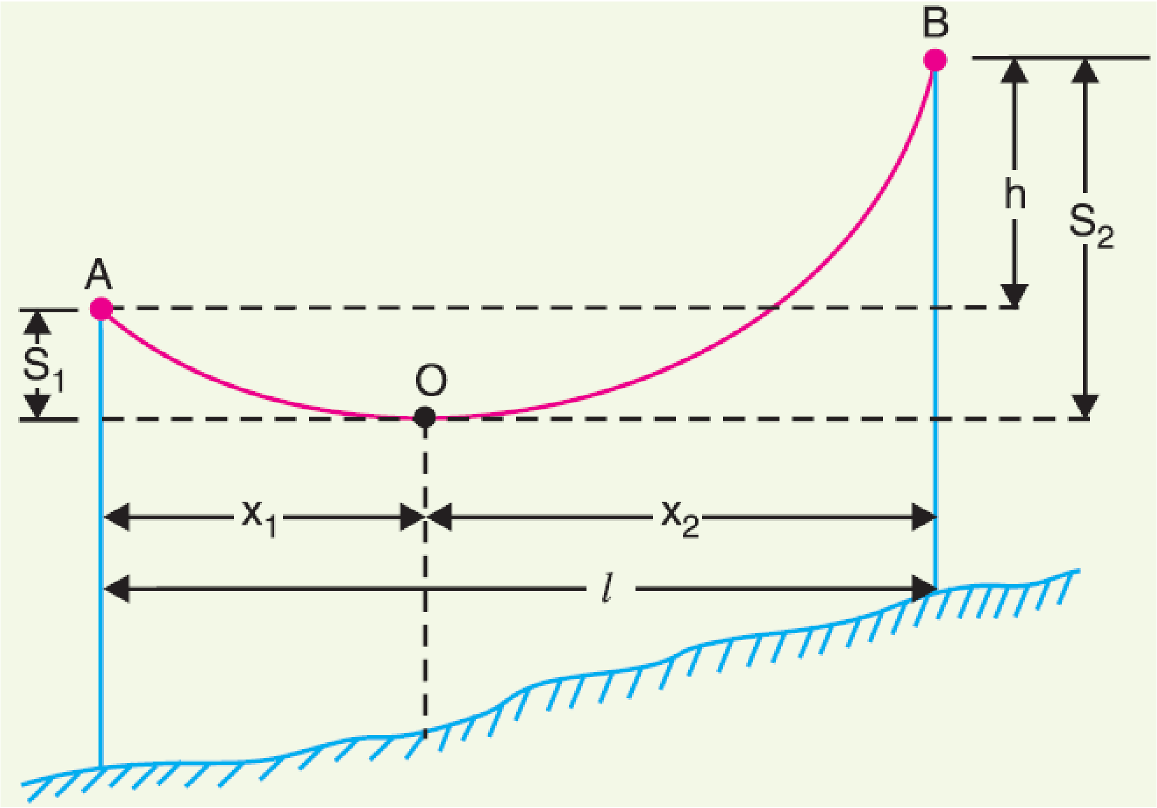


Fig 1.6

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

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

$$* \, y = \frac{w\,x^2}{2T}$$

At support A, $x = x_1$ and $y = S_1$.

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

$$\text{and} \qquad \text{Sag } S_2 = \frac{w\,x_2^2}{2T}$$

$$\text{Also} \qquad x_1 + x_2 = l \qquad \ldots(i)$$

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

$$S_2 - S_1 = \frac{w\,l}{2T}(x_2 - x_1) \qquad [\because x_1 + x_2 = l]$$

$$S_2 - S_1 = h$$

$$h = \frac{w\,l}{2T}(x_2 - x_1)$$

or $$x_2 - x_1 = \frac{2\,Th}{w\,l} \qquad \ldots(ii)$$

Solving exps. (i) and (ii), we get,

$$x_1 = \frac{l}{2} - \frac{T\,h}{w\,l} \qquad x_2 = \frac{l}{2} + \frac{T\,h}{w\,l}$$

Having found x_1 and x_2, values of S_1 and S_2 can be easily calculated.

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. 1.7 (*iii*).

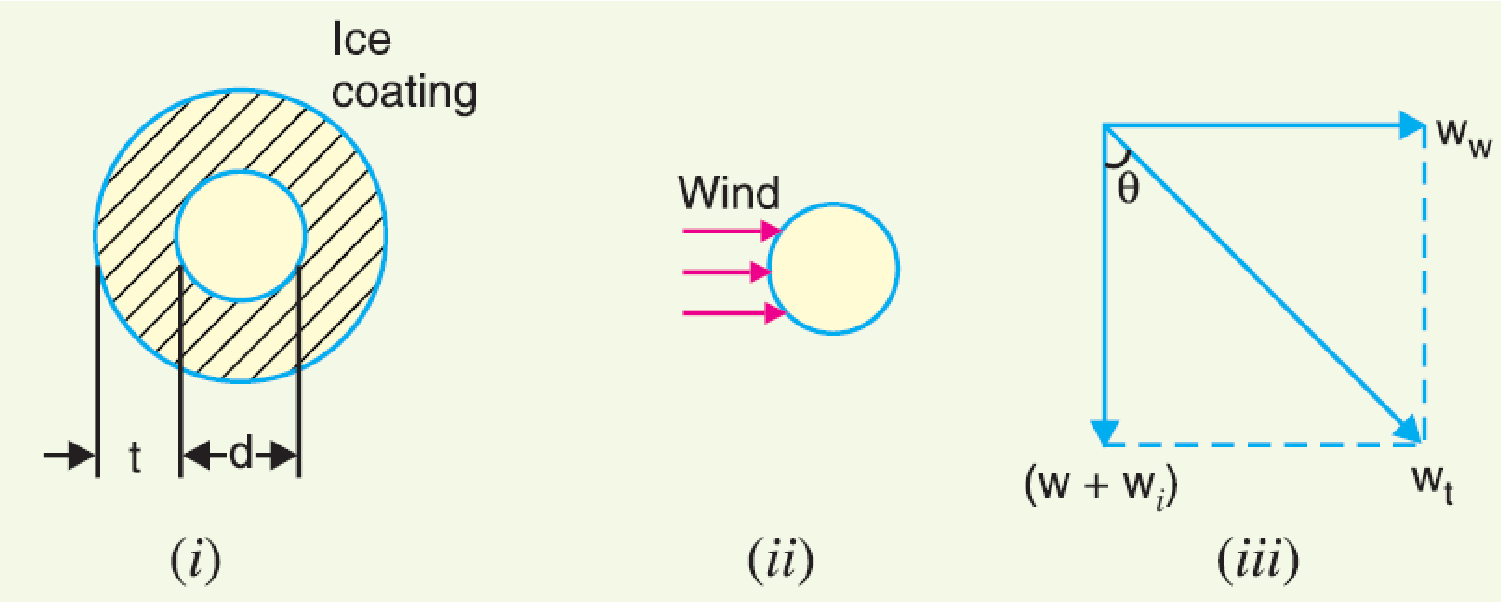


Fig 1.7

Total weight of conductor per unit length is

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

where 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 × $\frac{\pi}{4}[(d + 2t)^2 - d^2] \times 1$

= density of ice × $\pi\, t\,(d + t)$*

w_w = wind force per unit length

= wind pressure per unit area × projected area per unit length

= wind pressure × $[(d + 2t) \times 1]$

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 θ

Example 8.17. *A 132 kV transmission line has the following data :*

Wt. of conductor = 680 kg/km ; Length of span = 260 m

Ultimate strength = 3100 kg ; Safety factor = 2

Calculate the height above ground at which the conductor should be supported. Ground clearance required is 10 metres.

Solution.

Wt. of conductor/metre run, $w = 680/1000 = 0{\cdot}68$ kg

$$\text{Working tension, } T = \frac{\text{Ultimate strength}}{\text{Safety factor}} = \frac{3100}{2} = 1550 \text{ kg}$$

Span length, $l = 260$ m

$$\text{Sag} = \frac{w\,l^2}{8T} = \frac{0\cdot 68 \times (260)^2}{8 \times 1550} = 3{\cdot}7 \text{ m}$$

∴ Conductor should be supported at a height of $10 + 3{\cdot}7 =$ **13·7 m**

Example 8.18. *A transmission line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm^2. The tension in the conductor is 2000 kg. If the specific gravity of the conductor material is 9·9 gm/cm^3 and wind pressure is 1·5 kg/m length, calculate the sag. What is the vertical sag?*

Solution.

Span length, $l = 150$ m; Working tension, $T = 2000$ kg

Wind force/m length of conductor, $w_w = 1{\cdot}5$ kg

Wt. of conductor/m length, w = Sp. Gravity × Volume of 1 m conductor

$$= 9{\cdot}9 \times 2 \times 100 = 1980 \text{ gm} = 1{\cdot}98 \text{ kg}$$

Total weight of 1 m length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot 98)^2 + (1\cdot 5)^2} = 2{\cdot}48 \text{ kg}$$

$$\therefore \quad \text{Sag,} \quad S = \frac{w_t\, l^2}{8T} = \frac{2 \cdot 48 \times (150)^2}{8 \times 2000} = \mathbf{3 \cdot 48\ m}$$

This is the value of slant sag in a direction making an angle θ with the vertical. Referring to Fig. 1.8, the value of θ is given by ;

$$\tan\theta = w_w/w = 1 \cdot 5/1 \cdot 98 = 0 \cdot 76$$

$$\theta = \tan^{-1} 0 \cdot 76 = 37 \cdot 23^{\circ}$$

$$\therefore \quad \text{Vertical sag} = S\cos\theta$$

$$= 3 \cdot 48 \times \cos 37 \cdot 23^{\circ} = \mathbf{2 \cdot 77\ m}$$

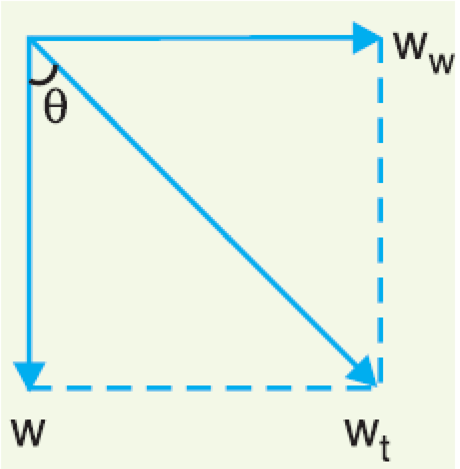


Fig 1.8

Types of Insulators

The successful operation of an overhead line depends to a considerable extent upon the proper selection of insulators. There are several types of insulators but the most commonly used are pin type, suspension type, strain insulator and shackle insulator.

Pin Type Insulators:

- The part section of a pin type insulator is shown in Fig.1.8(*i*).
- As the name suggests, 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 Fig.1.8 (*ii*).

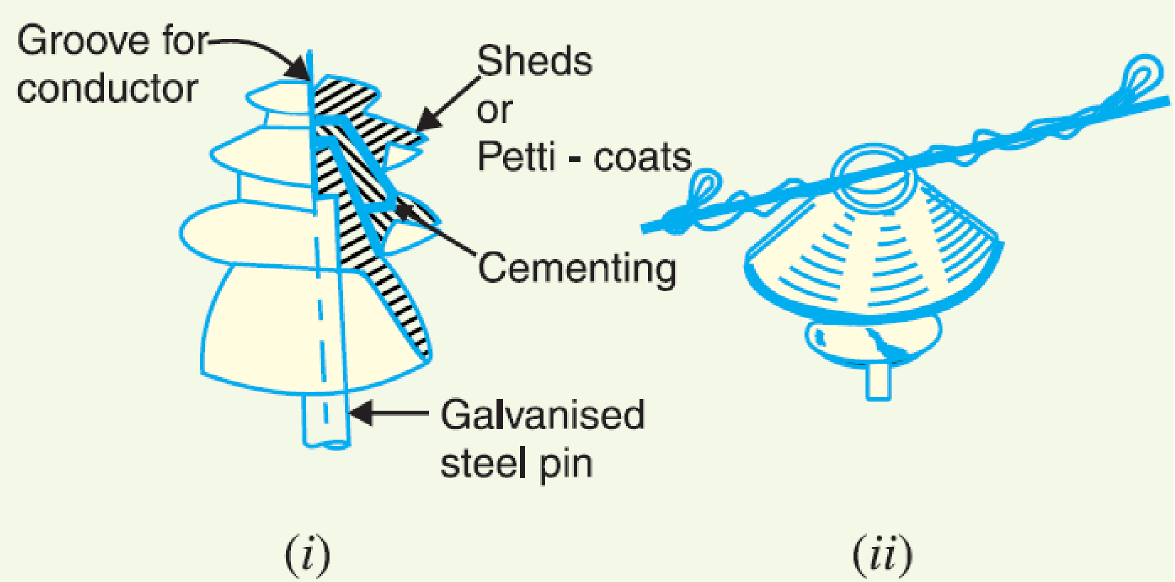


Fig 1.8

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 shown in Fig.1.9.
- 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.

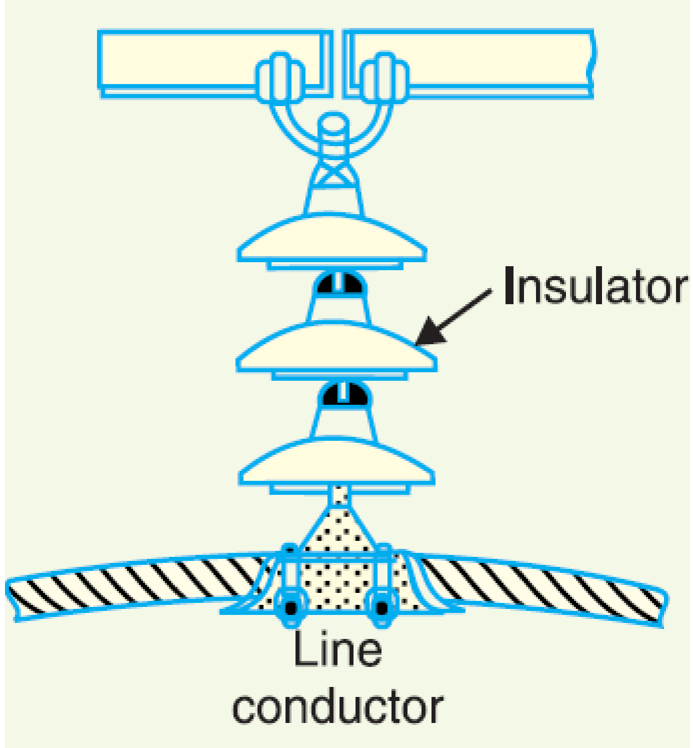


Fig 1.9

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 as shown in Fig. 1.10.
- 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.

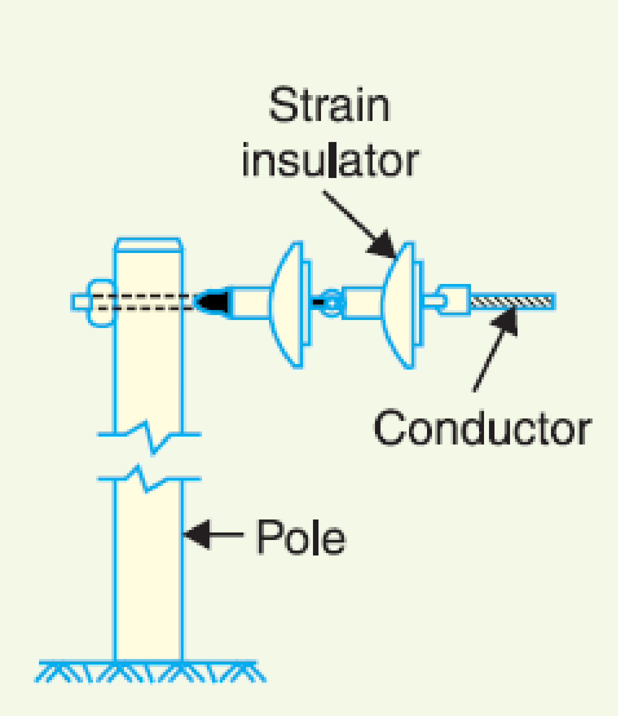


Fig 1.10

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. 1.11 shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.

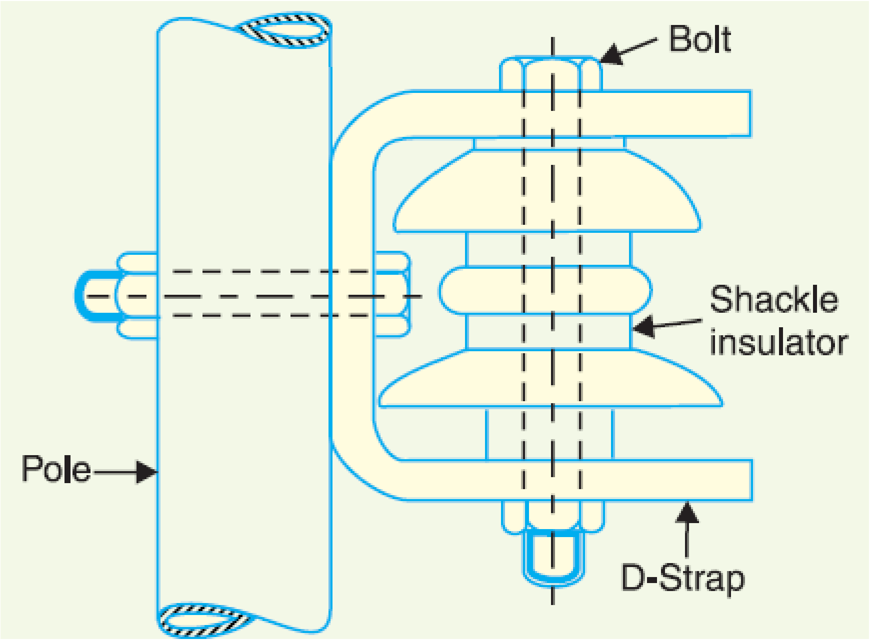


Fig 1.11

Potential Distribution over Suspension Insulator String

- A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links.
- Fig. 1.12 (*i*) shows 3-disc string of suspension insulators.
- The porcelain portion of each disc is in between two metal links.
- Therefore, each disc forms a capacitor *C* as shown in Fig. 1.12 (*ii*).
- This is known as ***mutual capacitance or self-capacitance.***
- If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same *i.e.*, *V*/3 as shown in Fig. 1.12 (*ii*).

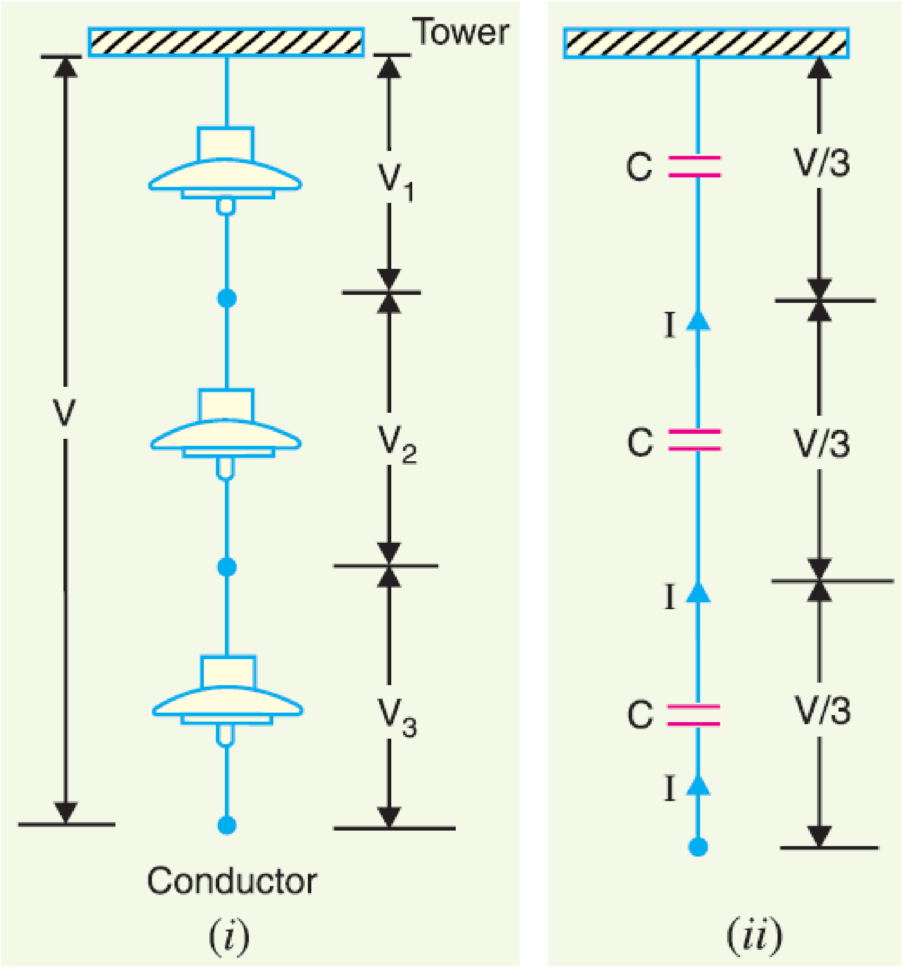
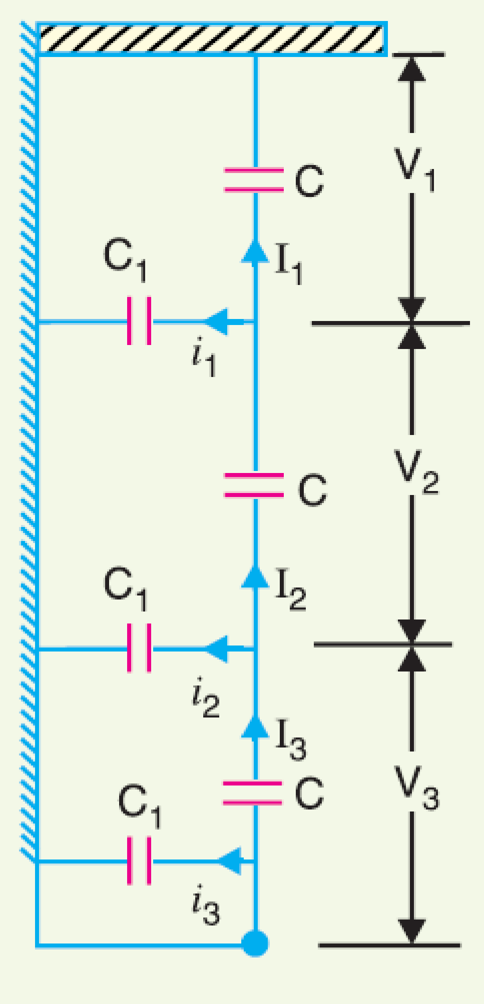


Fig 1.12

- However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth.
- This is known as ***shunt capacitance C1***. Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig. 1.12(*iii*)].
- Therefore, voltage across each disc will be different.
- Obviously, the disc nearest to the line conductor will have the maximum* voltage. Thus referring to Fig. 1.12 (*iii*), V_3 will be much more than V_2 or V_1.



(*iii*)

Fig 1.12

* Because charging current through the string has the maximum value at the disc nearest to the conductor.

The following points may be noted regarding the potential distribution over a string of suspension insulators :

(*i*) The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the presence of shunt capacitance.

(*ii*) The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.

(*iii*) The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured.

(*iv*) If the voltage impressed across the string were DC, then voltage across each unit would be the same. It is because insulator capacitances are ineffective for DC.

String Efficiency

- The voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs.
- The disc nearest to the conductor has much higher potential than the other discs.
- This unequal potential distribution is undesirable and is usually expressed in terms of string efficiency.

The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as **String efficiency** *i.e.,*

$$\text{String efficiency} = \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc nearest to conductor}}$$

where n = number of discs in the string.

- String efficiency is an important consideration since it decides the potential distribution along the string.
- The greater the string efficiency, the more uniform is the voltage distribution.
- Thus 100% string efficiency is an ideal case for which the voltage across each disc will be exactly the same.
- Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible.

Mathematical Expression:

Fig. 1.13 shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C_1 is some fraction K of self capacitance.

i.e., $C_1 = KC$

Starting from the cross-arm or tower, the voltage across each unit is V_1,V_2 and V_3 respectively as shown.

Applying Kirchhoff's current law to node A, we get,

$$I_2 = I_1 + i_1$$

$$V_2 \omega C^* = V_1 \omega C + V_1 \omega C_1$$

$$V_2 \omega C = V_1 \omega C + V_1 \omega K C$$

$$V_2 = V_1 (1 + K) \qquad ...(i)$$

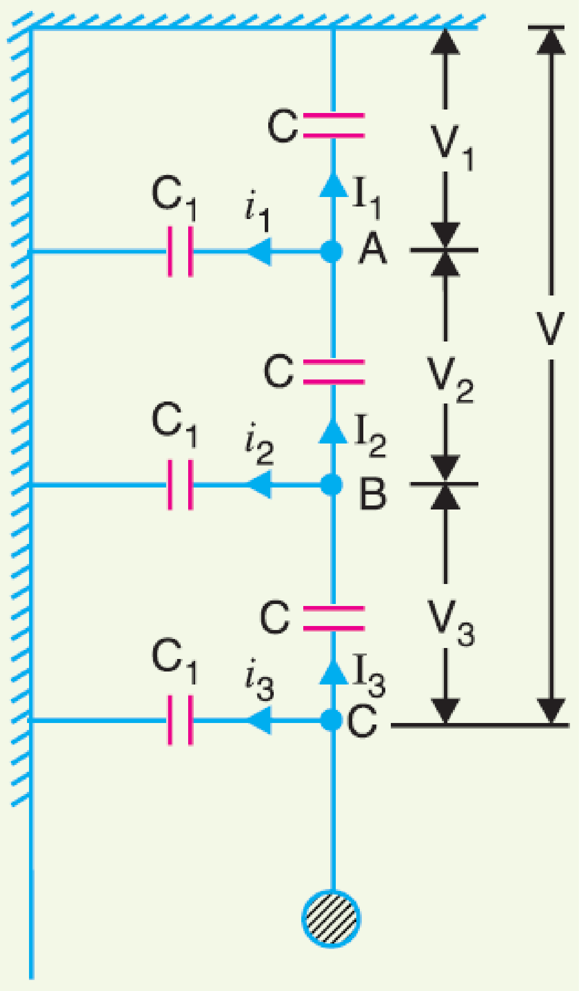


Fig 1.13

Applying Kirchhoff's current law to node B, we get,

$$I_3 = I_2 + i_2$$

$$V_3\,\omega\,C = V_2\omega\,C + (V_1 + V_2)\,\omega\,C_1$$

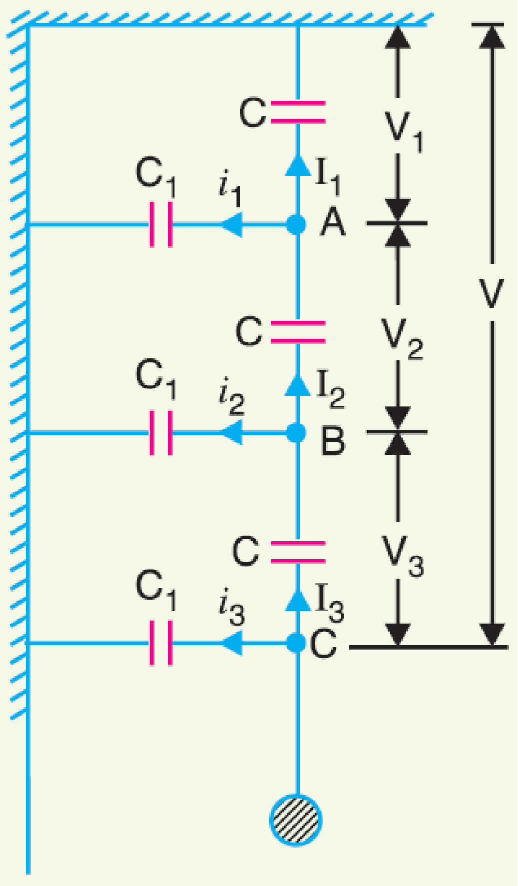
$$V_3\,\omega\,C = V_2\omega\,C + (V_1 + V_2)\,\omega\,K\,C$$

$$V_3 = V_2 + (V_1 + V_2)K$$

$$= KV_1 + V_2\,(1 + K) = KV_1 + V_1\,(1 + K)^2$$

$$= V_1\,[K + (1 + K)^2]$$

$$\therefore\ V_3 = V_1[1 + 3K + K^2] \qquad ...(ii)$$



Voltage between conductor and earth (i.e., tower) is

$$\therefore\ V = V_1 + V_2 + V_3 = V_1 + V_1(1 + K) + V_1\,(1 + 3K + K^2) = V_1\,(3 + 4K + K^2)$$

$$V = V_1(1 + K)\,(3 + K) \qquad ...(iii)$$

From expressions (i), (ii) and (iii), we get,

$$\frac{V_1}{1} = \frac{V_2}{1+K} = \frac{V_3}{1+3K+K^2} = \frac{V}{(1+K)(3+K)} \qquad \ldots(iv)$$

$$\therefore \text{Voltage across top unit,} \quad V_1 = \frac{V}{(1+K)(3+K)}$$

$$\text{Voltage across second unit from top,}\ V_2 = V_1\,(1+K)$$

$$\text{Voltage across third unit from top,}\ V_3 = V_1\,(1+3K+K^2)$$

$$\%\text{age String efficiency} = \frac{\text{Voltage across string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100$$

$$= \frac{V}{3 \times V_3} \times 100$$

Methods of Improving String Efficiency

- It has been seen 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 equalize the potential across the various units of the string *i.e.* to improve the string efficiency.

The various methods for this purpose are :

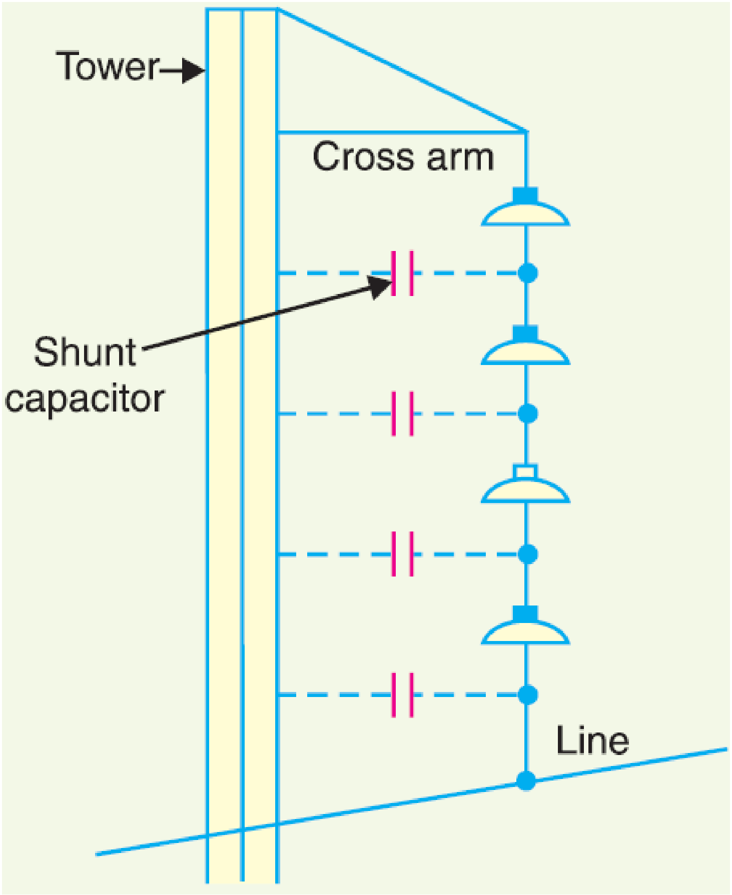
(i) By using longer cross-arms.

(ii) By grading the insulators.

(iii) By using a guard ring.

1. 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.



2. 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 equalize 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.

3. By using a guard ring:

- The potential across each unit in a string can be equalized 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.1.14.
- The guard ring introduces capacitance between 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.

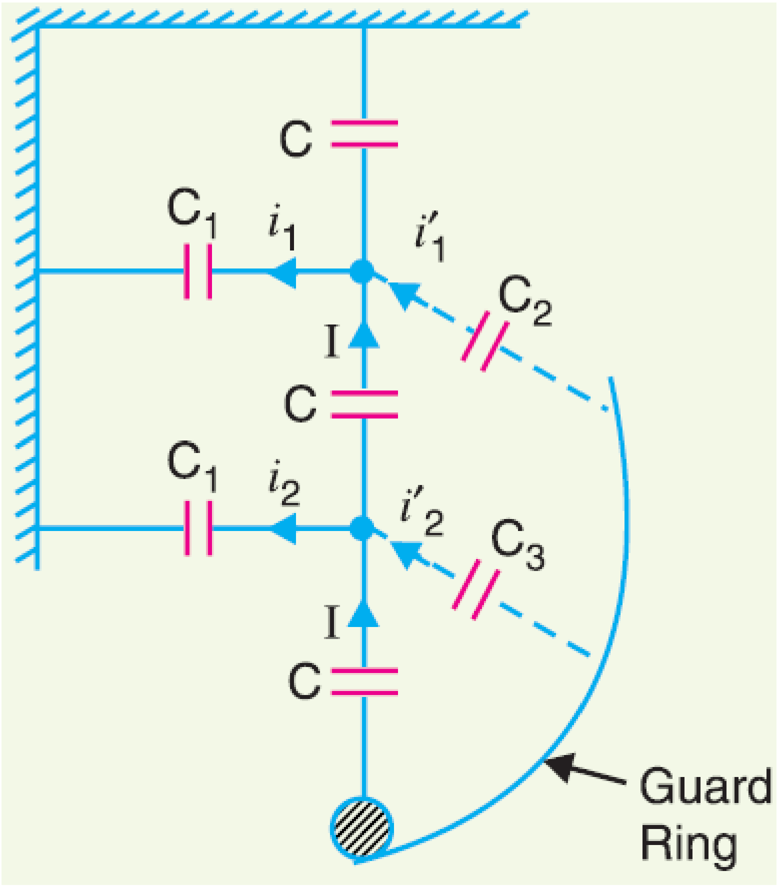


Fig 1.14

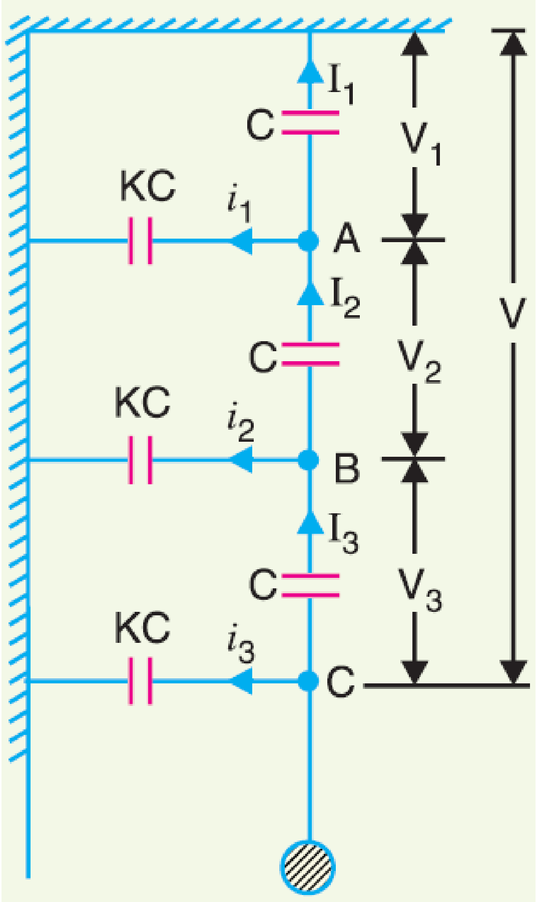
Example 8.1. *In a 33 kV overhead line, there are three units in the string of insulators. If the capacitance between each insulator pin and earth is 11% of self-capacitance of each insulator, find (i) the distribution of voltage over 3 insulators and (ii) string efficiency.*

Solution.

- Fig shows the equivalent circuit of string insulators.
- Let V_1, V_2 and V_3 be the voltage across top, middle and bottom unit respectively.
- If C is the self-capacitance of each unit, then KC will be the shunt capacitance.

$$K = \frac{\text{Shunt Capacitance}}{\text{Self-capacitance}} = 0.11$$

$$\text{Voltage across string, } V = 33/\sqrt{3} = 19{\cdot}05 \text{ kV}$$



At Junction A

$$
\begin{aligned}
I_2 &= I_1 + i_1 \\
V_2\,\omega\,C &= V_1\,\omega\,C + V_1 K\,\omega\,C \\
V_2 &= V_1\,(1+K) = V_1\,(1+0{\cdot}11) \\
V_2 &= 1{\cdot}11\;V_1 \quad \ldots(i)
\end{aligned}
$$

At Junction B

$$
\begin{aligned}
I_3 &= I_2 + i_2 \\
V_3\,\omega\,C &= V_2\,\omega\,C + (V_1 + V_2)\,K\,\omega\,C \\
V_3 &= V_2 + (V_1 + V_2)\,K = 1{\cdot}11 V_1 + (V_1 + 1{\cdot}11\;V_1)\,0{\cdot}11 \\
\therefore \quad V_3 &= 1{\cdot}342\;V_1
\end{aligned}
$$

(*i*) Voltage across the whole string is

$$V = V_1 + V_2 + V_3 = V_1 + 1{\cdot}11\ V_1 + 1{\cdot}342\ V_1 = 3{\cdot}452\ V_1$$

$$19{\cdot}05 = 3{\cdot}452\ V_1$$

$$\therefore \quad \text{Voltage across top unit}, V_1 = 19{\cdot}05/3{\cdot}452 = \mathbf{5{\cdot}52\ kV}$$

$$\text{Voltage across middle unit}, V_2 = 1{\cdot}11\ V_1 = 1{\cdot}11 \times 5{\cdot}52 = \mathbf{6.13\ kV}$$

$$\text{Voltage across bottom unit}, V_3 = 1{\cdot}342\ V_1 = 1{\cdot}342 \times 5{\cdot}52 = \mathbf{7.4\ kV}$$

(*ii*) $$\text{String efficiency} = \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{19 \cdot 05}{3 \times 7 \cdot 4} \times 100 = \mathbf{85.8\%}$$

Example 8.23. *The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance between 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.*

Solution. Figure shows the conductor suspended between two supports *A* and *B* at different levels with *O* as the lowest point on the conductor.

Here, l = 500 m ; w = 1·5 kg ; T = 1600 kg.

Difference in levels between supports, $h = 90 - 30 = 60$ m.

Let the lowest point *O* of the conductor be at a distance x_1 from the support at lower level (*i.e.*, support *A*) and at a distance x_2 from the support at higher level (*i.e.*, support *B*).

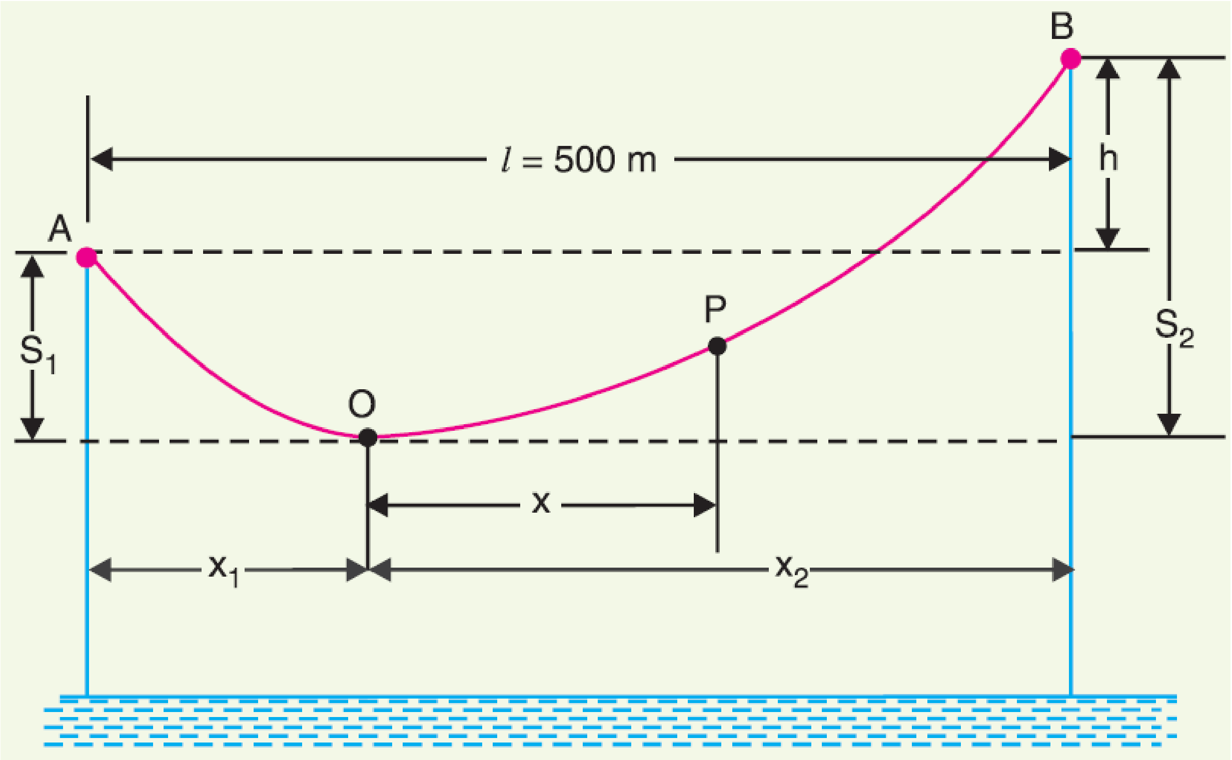
Obviously, $x_1 + x_2 = 500 \text{ m}$ ...(*i*)

$$\text{Sag } S_1 = \frac{w\,x_1^2}{2T} \quad \text{and} \quad \text{Sag } S_2 = \frac{w\,x_2^2}{2T}$$

$$h = S_2 - S_1 = \frac{w\,x_2^2}{2T} - \frac{w\,x_1^2}{2T}$$

$$60 = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$x_2 - x_1 = \frac{60 \times 2 \times 1600}{1 \cdot 5 \times 500} = 256 \text{ m} \quad ...(ii)$$



Solving exps. (i) and (ii), we get, $x_1 = 122$ m; $x_2 = 378$ m

$$\text{Now,} \quad S_1 = \frac{w\,x_1^2}{2T} = \frac{1 \cdot 5 \times (122)^2}{2 \times 1600} = 7 \text{ m}$$

Clearance of the lowest point O from water level

$$= 30 - 7 = \mathbf{23\ m}$$

Let the mid-point P be at a distance x from the lowest point O.

Clearly, $x = 250 - x_1 = 250 - 122 = 128$ m

Sag at mid-point P, $S_{mid} = \dfrac{w\,x^2}{2T} = \dfrac{1 \cdot 5 \times (128)^2}{2 \times 1600} = 7 \cdot 68$ m

Clearance of mid-point P from water level $= 23 + 7 \cdot 68 = \mathbf{30 \cdot 68\ m}$

Example 8.25. *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.*

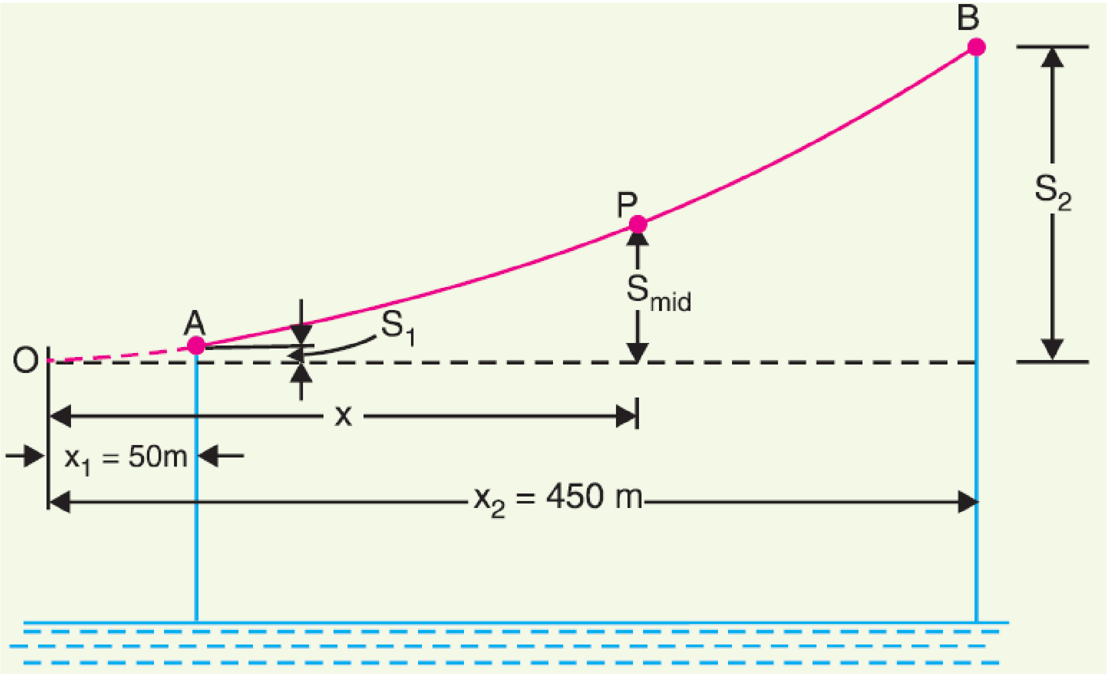
Solution. Figure shows the whole arrangement.

$$h = 90 - 40 = 50 \text{ m}; \quad l = 400 \text{ m}$$

$$T = 2000 \text{ kg}; \quad w = 1 \text{ kg/m}$$

$$\text{Obviously,} \quad x_1 + x_2 = 400 \text{ m}$$

$$\text{Now} \quad h = S_2 - S_1 = \frac{wx_2^2}{2T} - \frac{wx_1^2}{2T}$$



$$\text{or} \qquad 50 = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \qquad x_2 - x_1 = \frac{50 \times 2 \times 2000}{400} = 500 \text{ m}$$

Solving exps. (*i*) and (*ii*), we get, $x_2 = 450$ m and $x_1 = -50$ m

Now $x2$ is the distance of higher support *B* from the lowest point *O* on the conductor, whereas $x1$ is that of lower support *A*. As the span is 400 m, therefore, point *A* lies on the same side of *O* as *B*.

Horizontal distance of mid-point *P* from lowest point *O* is

$$x = \text{Distance of } A \text{ from } O + 400/2 = 50 + 200 = 250 \text{ m}$$

$\therefore$ Sag at point P, $S_{mid} = \dfrac{w\,x^2}{2T} = \dfrac{1 \times (250)^2}{2 \times 2000} = 15{\cdot}6 \text{ m}$

Sag $S_2 = \dfrac{w\,x_2^2}{2T} = \dfrac{1 \times (450)^2}{2 \times 2000} = 50{\cdot}6 \text{ m}$

Height of point B above mid-point P $= S_2 - S_{mid}$

$= 50{\cdot}6 - 15{\cdot}6 = 35 \text{ m}$

$\therefore$ Clearance of mid-point P above water level

$= 90 - 35 =$ **55 m**

Thank You