# UNIT-VI

**Various factors governing the performance of Transmission line:** Skin and Proximity effects, Ferranti effect, Charging Current.
**Corona:** Description of the phenomenon, Factors affecting corona, critical voltages and power loss, Radio Interference.
**Mechanical design of Overhead Transmission Line:** Calculation of sag for equal and unequal supports, loading on the conductors in an overhead line, variation of sag with load and temperature, string chart

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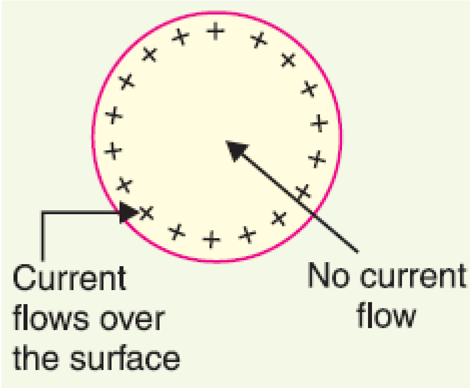
## Skin Effect ::

When a conductor is carrying steady direct current (d.c.), this current is uniformly distributed over the whole X-section of the conductor. However, an alternating current flowing through the conductor does not distribute uniformly, rather it has the tendency to concentrate near the surface of the conductor as shown in Fig

This is known as skin effect.



*The tendency of alternating current to concentrate near the surface of a conductor is known as* skin effect.

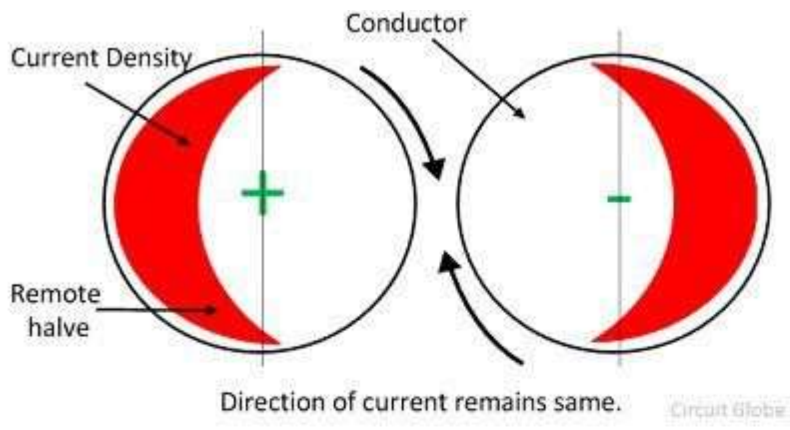
Due to skin effect, the effective area of cross-section of the conductor through which current flows is reduced. Consequently, the resistance of the conductor is slightly increased when carrying an alternating current.

The crowding of current near the conductor surface is the skin effect.
The skin effect depends upon the following factors :
(*i) Nature of material*
(*ii) Diameter of wire − increases with the diameter of wire.*
(*iii) Frequency − increases with the increase in frequency.*
(*iv) Shape of wire − less for stranded conductor than the solid conductor.*

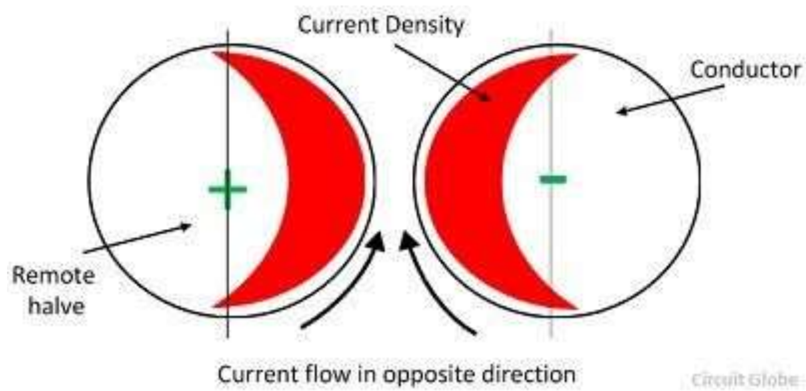
## Proximity effect::

When two or more conductors carrying alternating current are close to each other, then distribution of current in each conductor is affected due to the varying magnetic field of each other.
The proximity effect results in the increment of the apparent resistance of the conductor due to the presence of the other conductors carrying current in its vicinity.

The varying magnetic field produced by alternating current induces eddy currents in the adjacent conductors.
Due to this, when the near by conductors carrying current in the same direction, the current is concentrated at the farthest side of the conductors.



When the nearby conductors are carrying current in opposite direction to each other, the current is concentrated at the nearest parts of the conductors.




This effect is called as Proximity effect. The proximity effect also increases with increase in the frequency. Effective resistance of the conductor is increased due to the proximity effect.

The  proximity effect results in

- The overall capacity of current-carrying can be reduced.
- The resistance of AC can be increased.
- Eddy current which is induced can cause losses within this system.

The proximity effect depends on the following Factors::

1) The Material used in the Conductors
2) Structure of the Conductors
3) Frequency of the Conductors
4) The Diameter of the Conductors

To reduce the effect of proximity, the ACSR ( Aluminium Conductor Steel Reinforced) conductors can be used
in this type of conductor, the steel material can be arranged in the centre of the conductor & the Aluminium conductor can be used around steel material.

## Ferranti Effect::

The effect in which the voltage at the receiving end of the transmission line is more than the sending voltage is known as the Ferranti effect.
This effect mainly Occurs during light load or no load conditions

Ferranti effect is due to the charging current of the line. When an alternating voltage is applied, the current drawn by the capacitor is called charging current.
A charging current is also known as capacitive current.

This effect is negligible in short Transmission lines but significant in medium line and appreciable in long Transmission lines.
i.e. this phenomenon occurs in medium and long Transmission lines.

When the alternating voltage is applied at the sending end, the current drawn by the capacitance of the line is more than current associated with the load during light load or no load conditions. Thus, at no load or light load, the voltage at the receiving end is quite large as compared to the constant voltage at the sending end.

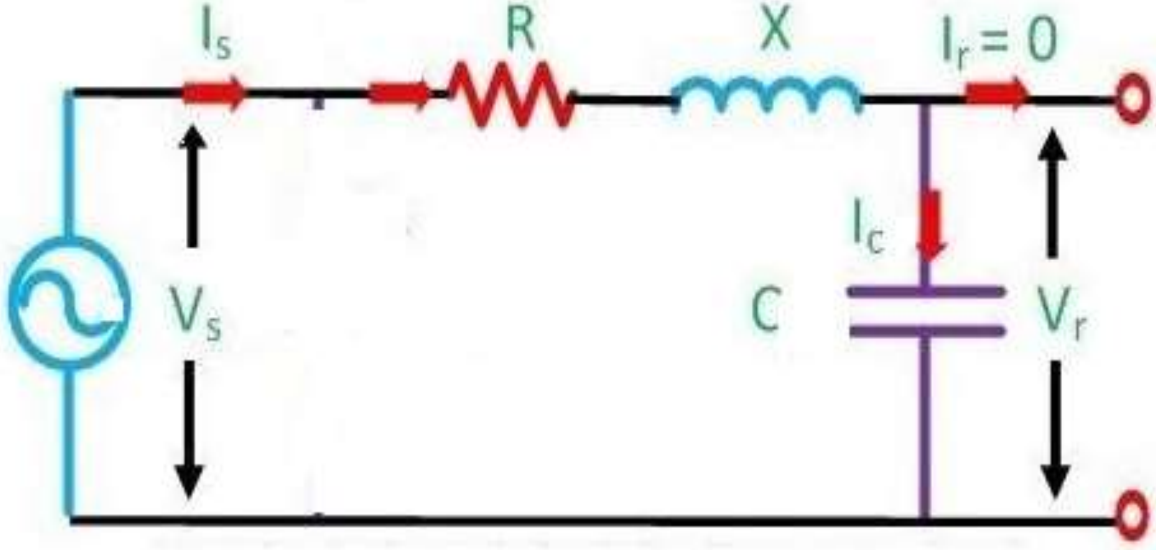



figure –a  Equivalent-circuit-of-long-transmission-line  at no-load

The  figure -a shows the equivalent circuit of a long transmission line

The  figure –b  shows the phasor diagram for the equivalent circuit.
Since we have assumed the line to be operating at no load, therefore $I_R$ =0 and $I_S$=$I_C$. And charging current $I_C$ will have drop across R and L given by $I_C$R and $I_C$X which are represented by QR and PR in the phasor diagram. Since charging current $I_C$ is leading with $V_R$ it is represented with OX in the phasor diagram.

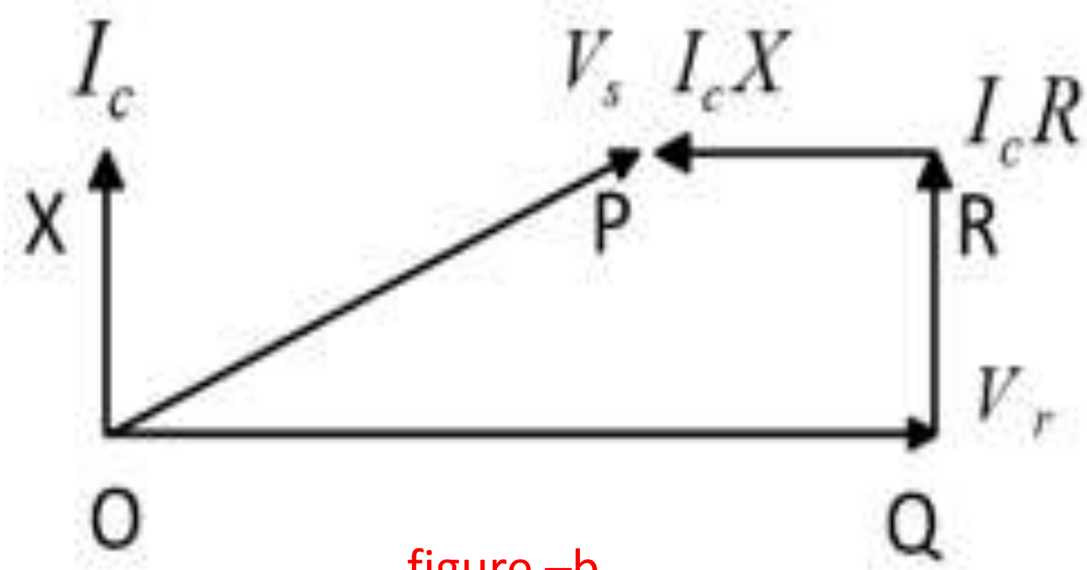



figure –b

OQ= receiving end voltage =$V_r$

OX = Current drawn by capacitance = $I_c$

QR  = Resistance drop

PR = voltage drop across inductance

OP = Sending end voltage at no load

From phasor diagram we can see that OQ > OP
In other words, voltage at the receiving end of the transmission line is more than the sending voltage

Like skin effect and proximity effect, Ferranti effects also have undesirable effect

Since the receiving end voltage becomes greater than sending end voltage, the loads at receiving end side which are designed to work at some particular voltages may get damaged
This increased voltage can be controlled by placing Shunt reactors at receiving end side

# Corona::

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called *critical disruptive voltage, the conductors are surrounded by a faint violet glow called* corona.
The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. The higher the voltage is raised, the larger and higher the luminous envelope becomes, and greater are the sound, the power loss and the radio noise.
If the applied voltage is increased to breakdown value, a flash-over will occur between the conductors due to the breakdown of air insulation.
*The phenomenon of violet glow, hissing noise and production of ozone gas in an overhead transmission line is known as **corona.***
If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductors, otherwise the rough points will appear brighter. With D.C. voltage, there is no corona.

# Theory of corona formation:

Some ionization is always present in air due to cosmic rays, ultraviolet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionized particles (*i.e., free electrons and +ve ions) and neutral molecules. When* potential difference is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons.

When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which is turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionization is cummulative. The result of this ionization is that either corona is formed or spark takes place between the conductors.

## Factors Affecting Corona::

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. The following are the factors upon which corona depends :

1) Atmosphere:

*As corona is formed due to ionization of air surrounding the conductors, therefore,* it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

*(ii) Conductor size.*

*The corona effect depends upon the shape and conditions of the conductors.* The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona that a solid conductor.

*(iii) Spacing between conductors.*

*If the spacing between the conductors is made very large as* compared to their diameters, there may not be any corona effect. It is because larger distance between conductors reduces the electro-static stresses ,thus avoiding corona formation.

*(iv) Line voltage::*

*The line voltage greatly affects corona. If it is low, there is no change in the* condition of air surrounding the conductors and hence no corona is formed. However, if the line voltage is high, electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

## Important Terms of corona::

The phenomenon of corona plays an important role in the design of an overhead transmission line. Therefore, it is profitable to consider the following terms much used in the analysis of corona effects:

***1) Critical disruptive voltage.***

It is the minimum phase-neutral voltage at which corona occurs.
Consider two conductors of radius r cm and spaced d cm apart. If V is the phase-neutral potential, then potential gradient at the conductor surface is given by:

$$g = \frac{V}{r \log_e \frac{d}{r}} \text{ volts / cm}$$

In order that corona is formed, the value of *g must be made equal to the breakdown strength of* air.

The breakdown strength of air at 76 cm pressure and temperature of $25^0$C is 30 kV/cm (max) or 21·2 kV/cm (r.m.s.) and is denoted by $g_o$.

If $V_c$ is the phase-neutral potential required under these conditions, then,

$$g_o = \frac{V_c}{r \log_e \frac{d}{r}}$$

where $g_o$ = breakdown strength of air at 76 cm of mercury and 25°C

= 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*)

$$\therefore \quad \text{Critical disruptive voltage, } V_c = g_o \, r \log_e \frac{d}{r}$$

The above expression for disruptive voltage is under standard conditions *i.e., at 76 cm of Hg and* $25^0$C.

However, if these conditions vary, the air density also changes, thus altering the value of $g_o$.

The value of $g_o$ *is directly proportional to air density. Thus the breakdown strength of air at a barometric* pressure of *b cm of mercury and temperature of* $t^0C$ *becomes* $\delta\, g_o$ *where*

$$\delta = \text{air density factor} = \frac{3 \cdot 92\, b}{273 + t}$$

Under standard conditions, the value of δ = 1.

∴ Critical disruptive voltage, $V_c = g_o \delta r \log_e \frac{d}{r}$

Correction must also be made for the surface condition of the conductor. This is accounted for by multiplying the above expression by irregularity factor $m_o$.

∴ Critical disruptive voltage, $V_c = m_o g_o \delta r \log_e \frac{d}{r}$ kV/phase

where $m_o$ = 1 for polished conductors
= 0·98 to 0·92 for dirty conductors
= 0·87 to 0·8 for stranded conductors

***(ii) Visual critical voltage ::***

*It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.*

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage $V_c$ *but at a higher voltage* $V_v$*, called visual critical voltage. The phase-neutral effective* value of visual critical voltage is given by the following formula

$$V_v = m_v g_o \delta r \left(1 + \frac{0 \cdot 3}{\sqrt{\delta r}}\right) \log_e \frac{d}{r} \text{ kV/phase}$$

## ***(iii) Power loss due to corona:***

*Formation of corona is always accompanied by energy loss* which is dissipated in the form of light, heat, sound and chemical action. When disruptive voltage is exceeded, the power loss due to corona is given by :

$$P = 242{\cdot}2\left(\frac{f+25}{\delta}\right)\sqrt{\frac{r}{d}}\,(V-V_c)^2 \times 10^{-5}\ \text{kW / km / phase}$$

where $f$ = supply frequency in Hz

$V$ = phase-neutral voltage (*r.m.s.*)

$V_c$ = disruptive voltage (*r.m.s.*) per phase

## Advantages and Disadvantages of Corona::

Corona has many advantages and disadvantages.

Advantages

(i) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.

(ii) Corona reduces the effects of transients produced by surges.

**Disadvantages**

**(***i) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the* line.

(*ii) Ozone is produced by corona and may cause corrosion of the conductor due to chemical* action.

(*iii) The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal* voltage drop occurs in the line. This may cause inductive interference with neighboring communication lines.

## Methods of Reducing Corona Effect::

corona effects are observed at a working voltage of 33 kV or above.

Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33kV and higher voltages otherwise highly ionized air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment. The corona effects can be reduced by the following methods :

***i) By increasing conductor size:***

By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced. This is one of the reasons that ACSR conductors which have a larger cross-sectional area are used in transmission lines.

**(ii) By increasing conductor spacing.**

By increasing the spacing between conductors, the voltage at which corona occurs is raised and hence corona effects can be eliminated. However, spacing cannot be increased too much otherwise the cost of supporting structure (e.g., bigger cross arms and supports) may increase to a considerable extent.

1) *A 3-phase line has conductors 2 cm in diameter spaced equilaterally 1 m apart. If the dielectric strength of air is 30 kV (max) per cm, find the disruptive critical voltage for the line. Take air density factor δ = 0·952 and irregularity factor* $m_o = 0{\cdot}9$.

**Solution.**

Conductor radius, $r = 2/2 = 1$ cm

Conductor spacing, $d = 1$ m $= 100$ cm

Dielectric strength of air, $g_o = 30$ kV/cm (*max.*) $= 21{\cdot}2$ kV (*r.m.s.*) per cm

Disruptive critical voltage, $V_c = m_o\, g_o\, \delta\, r \log_e (d/r)$ kV*/phase (*r.m.s.* value)

$= 0{\cdot}9 \times 21{\cdot}2 \times 0{\cdot}952 \times 1 \times \log_e 100/1 = 83{\cdot}64$ kV/phase

∴ Line voltage (*r.m.s.*) $= \sqrt{3} \times 83{\cdot}64 =$ **144·8 kV**

2) *A 132 kV line with 1·956 cm dia. conductors is built so that corona takes place if the line voltage exceeds 210 kV (r.m.s.). If the value of potential gradient at which ionisation occurs can be taken as 30 kV per cm, find the spacing between the conductors.*

**Solution.**

Assume the line is 3-phase.

Conductor radius, $r = 1{\cdot}956/2 = 0{\cdot}978$ cm

Dielectric strength of air, $g_o = 30/\sqrt{2} = 21{\cdot}2$ kV (*r.m.s.*) per cm

Disruptive voltage/phase, $V_c = 210/\sqrt{3} = 121{\cdot}25$ kV

Assume smooth conductors (*i.e.*, irregularity factor $m_o = 1$) and standard pressure and temperature for which air density factor $\delta = 1$. Let $d$ cm be the spacing between the conductors.

∴ Disruptive voltage (*r.m.s.*) per phase is

$$V_c = m_o g_o \delta r \log_e (d/r) \text{ kV}$$

$$= 1 \times 21{\cdot}2 \times 1 \times 0{\cdot}978 \times \log_e (d/r)$$

or $$121{\cdot}25 = 20{\cdot}733 \log_e (d/r)$$

or $$\log_e \frac{d}{r} = \frac{121{\cdot}25}{20{\cdot}733} = 5{\cdot}848$$

or $$2{\cdot}3 \log_{10} d/r = 5{\cdot}848$$

or $$\log_{10} d/r = 5{\cdot}848/2{\cdot}3 = 2{\cdot}5426$$

or $$d/r = \text{Antilog } 2{\cdot}5426$$

or $$d/r = 348{\cdot}8$$

∴ Conductor spacing, $$d = 348{\cdot}8 \times r = 348{\cdot}8 \times 0{\cdot}978 = \mathbf{341 \text{ cm}}$$

3) *A 3-phase, 220 kV, 50 Hz transmission line consists of 1·5 cm radius conductor spaced 2 metres apart in equilateral triangular formation. If the temperature is 40°C and atmospheric pressure is 76 cm, calculate the corona loss per km of the line. Take $m_o$ = 0·85.*

**Solution.**

corona loss is given by :

$$P = \frac{242 \cdot 2}{\delta}(f+25)\sqrt{\frac{r}{d}}(V-V_c)^2 \times 10^{-5} \text{ kW/km/phase}$$

Now,
$$\delta = \frac{3 \cdot 92\, b}{273+t} = \frac{3 \cdot 92 \times 76}{273+40} = 0{\cdot}952$$

Assuming
$$g_o = 21{\cdot}2 \text{ kV/cm } (r.m.s.)$$

∴ Critical disruptive voltage per phase is

$$V_c = m_o g_o \delta r \log_e d/r \text{ kV}$$
$$= 0{\cdot}85 \times 21{\cdot}2 \times 0{\cdot}952 \times 1{\cdot}5 \times \log_e 200/1{\cdot}5 = 125{\cdot}9 \text{ kV}$$

Supply voltage per phase, $V = 220/\sqrt{3} = 127$ kV

Substituting the above values, we have corona loss as:

$$P = \frac{242 \cdot 2}{0 \cdot 952}(50+25) \times \sqrt{\frac{1 \cdot 5}{200}} \times (127 - 125 \cdot 9)^2 \times 10^{-5} \text{ kW/phase/km}$$

$$= \frac{242 \cdot 2}{0 \cdot 952} \times 75 \times 0 \cdot 0866 \times 1 \cdot 21 \times 10^{-5} \text{ kW/km/phase}$$

$$= 0{\cdot}01999 \text{ kW/km/phase}$$

∴ Total corona loss per km for three phases

$$= 3 \times 0{\cdot}01999 \text{ kW} = \mathbf{0{\cdot}05998 \text{ kW}}$$

4) *A certain 3-phase equilateral transmission line has a total corona loss of 53 kW at 106 kV and a loss of 98 kW at 110·9 kV. What is the disruptive critical voltage? What is the corona loss at 113 kV?*

**Solution.**

The power loss due to corona for 3 phases is given by :

$$P = 3 \times \frac{242 \cdot 2 (f + 25)}{\delta} \sqrt{\frac{r}{d}} (V - V_c)^2 \times 10^{-5} \text{ kW/km}$$

As $f$, $\delta$, $r$ and $d$ are the same for the two cases,

$$\therefore \quad P \propto (V - V_c)^2$$

For first case, $P = 53$ kW and $V = 106/\sqrt{3} = 61{\cdot}2$ kV

For second case, $P = 98$ kW and $V = 110 \cdot 9/\sqrt{3} = 64$ kV

$$\therefore \quad 53 \propto (61{\cdot}2 - V_c)^2 \quad \text{...}(i)$$

$$\text{and} \quad 98 \propto (64 - V_c)^2 \quad \text{...}(ii)$$

Dividing [(*ii*)/(*i*)], we get,

$$\frac{98}{53} = \frac{(64 - V_c)^2}{(61 \cdot 2 - V_c)^2}$$

$$\text{or} \quad V = \textbf{54 kV}$$

Let $W$ kilowatt be the power loss at 113 kV.

$$\therefore \quad W \propto \left(\frac{113}{\sqrt{3}} - V_c\right)^2$$

$$\propto (65{\cdot}2 - 54)^2 \qquad \ldots(iii)$$

Dividing [(*iii*)/(*i*)], we get,

$$\frac{W}{53} = \frac{(65\cdot 2 - 54)^2}{(61\cdot 2 - 54)^2}$$

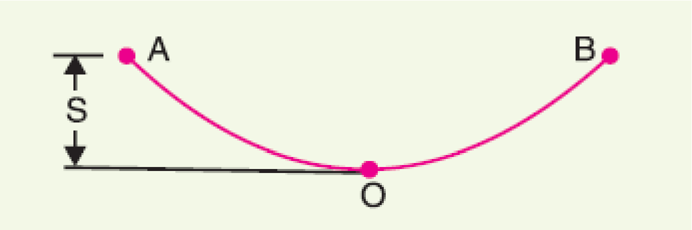
$$\therefore \quad W = (11{\cdot}2/7{\cdot}2)^2 \times 53 = \textbf{128 kW}$$

# 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. (*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.*



(*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.

## **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

Calculation of sag and tension of a conductor can be done when
(i) supports are at equal levels (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.a
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. 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 :

(a) The weight wx of conductor acting at a distance x/2 from O.

(b) The tension T acting at O.

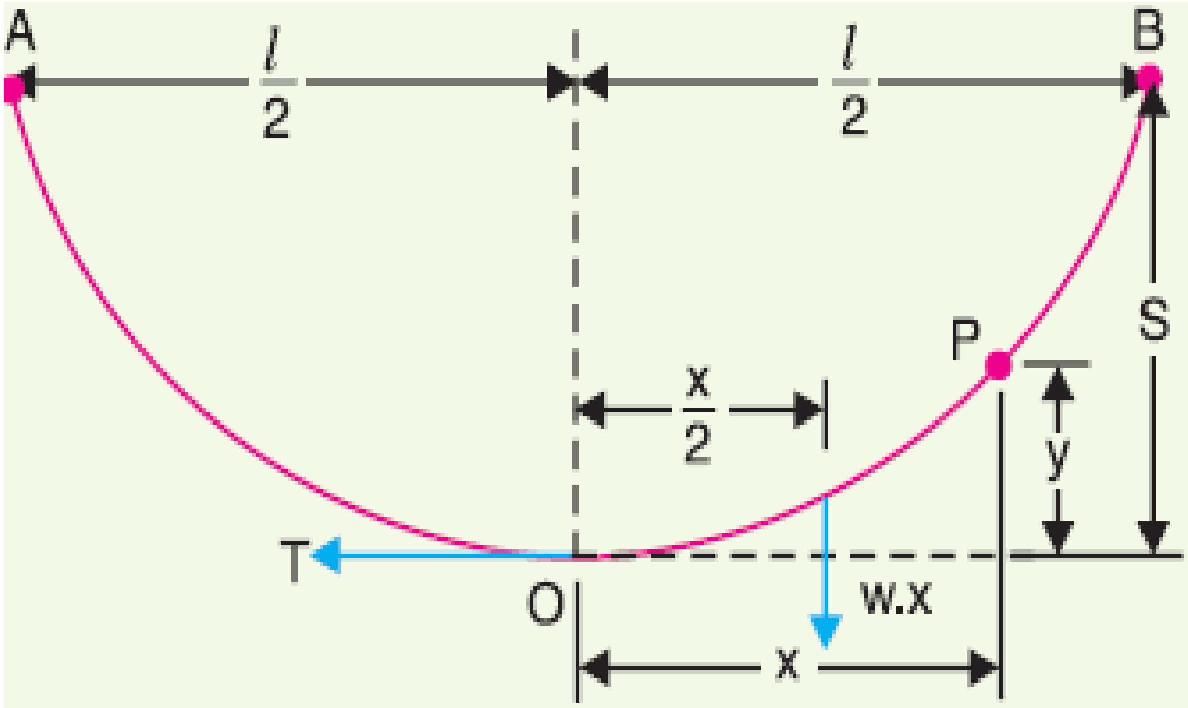



Fig.. a

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

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

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

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 $y = S$

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

## (ii) When supports are at unequal levels. ::

In hilly areas, we generally come across conductors suspended between supports at unequal levels.

Fig. (b) 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

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

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

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

Also $$x_1 + x_2 = l$$

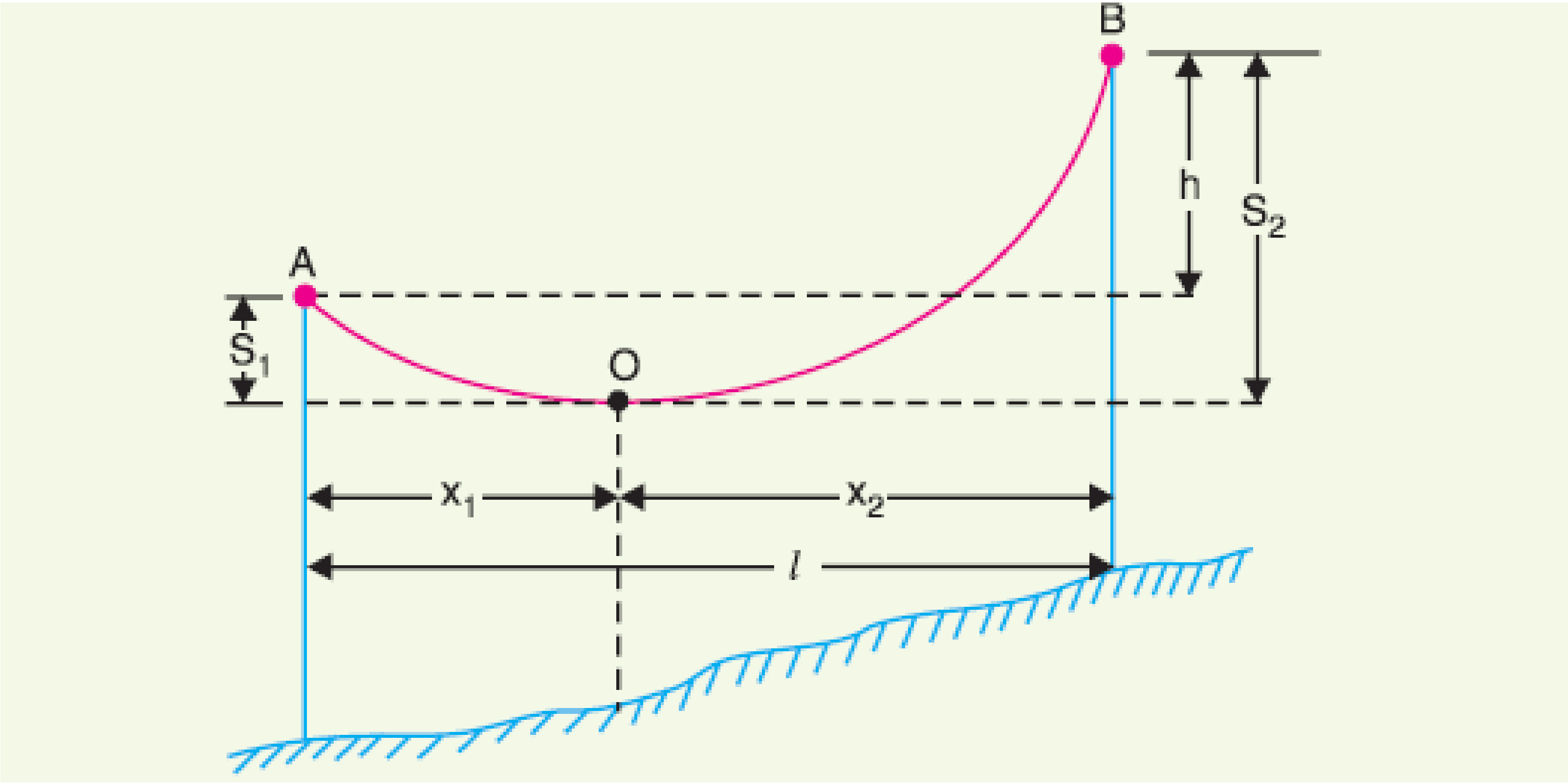



Fig..b

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

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

But $$S_2 - S_1 = h$$

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

or $$x_2 - x_1 = \frac{2\,Th}{w\,l}$$

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

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

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

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