Chapter-8

Mechanical Design of Overhead Lines

Introduction

Electric power can be transmitted or distributed either by means of

1. Overhead lines (almost used in transmission system)
2. Underground cables (used in distribution system & rarely in transmission system)

Q. The underground cables are rarely used for power transmission

Firstly, power is generally transmitted over long distances to load centers. Obviously, the installation costs for underground transmission will be very heavy.

Secondly, electric power has to be transmitted at high voltages for economic reasons. It is very difficult to provide proper insulation to the cables to withstand such higher pressures.

8.1 Main Components of Overhead Lines

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.

Q. Name the important components of an overhead transmission line?

8.2 Insulators

The overhead lines conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports. The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth.

Q. Why are insulators used with overhead lines?

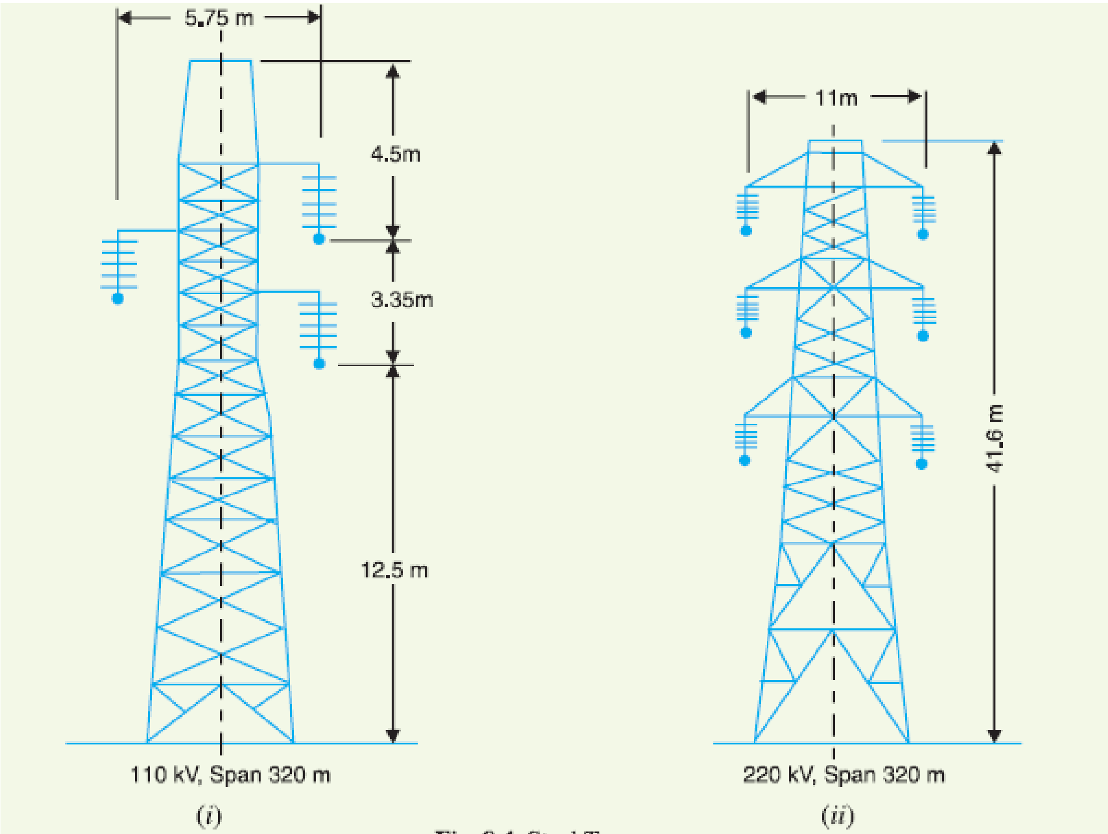


Fig. 8.4 Steel Towers

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

(i) High mechanical strength in order to withstand conductor weight, wind etc.
(ii) High electrical resistance of insulator material in order to avoid leakage currents to earth.
(iii) High relative permittivity of insulator material in order that dielectric strength is high.
(iv) The insulator material should be non-porous, free from impurities and cracks otherwise
the permittivity will be lowered.

(v) High ratio of puncture strength to flashover.

The most commonly used material for insulators of overhead line are porcelain and glass, Porcelain is stronger mechanically than glass, gives less trouble from leakage and is less affected by changes of temperature.

Q. Discuss the desirable properties of insulators.

8.3 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

1. pin type,
2. suspension type,
3. strain insulator and
4. shackle insulator.

1. ***Pin type insulators***. The part section of a pin type insulator is shown in Fig. 8.5 (i). As the name suggests, the pin type insulator is secured to the cross-arm on the pole.

Pin type insulator

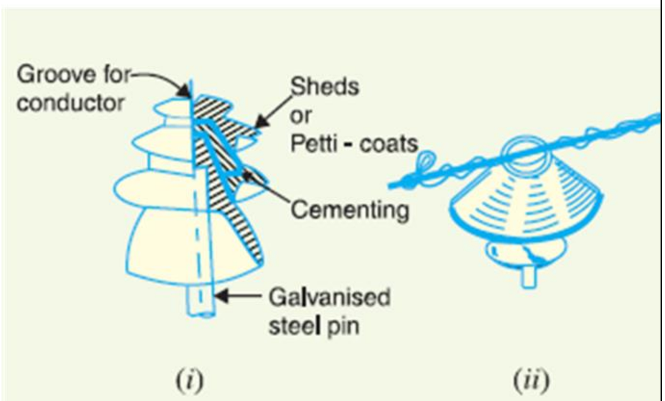


Fig. 8.5. Pin-type insulator

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 [See Fig. 8.5 (*ii*)].

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.

Insulators are required to withstand both mechanical and electrical stresses. The latter type is primarily due to line voltage and may cause the breakdown of the insulator. 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. Fig. 8.6i shows the arcing distance (*i.e.* $a + b + c$) for the insulator.
In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced by the arc destroys the insulator.

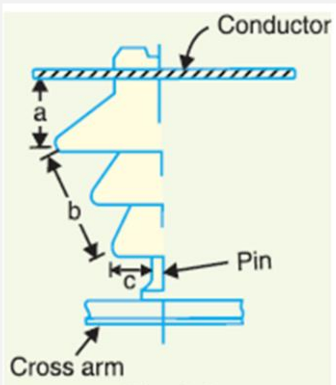


Fig 8.6i

In case of puncture, Fig. 8.6ii shows the discharge occurs from conductor to pin through the body of the insulator (red line). 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.*,

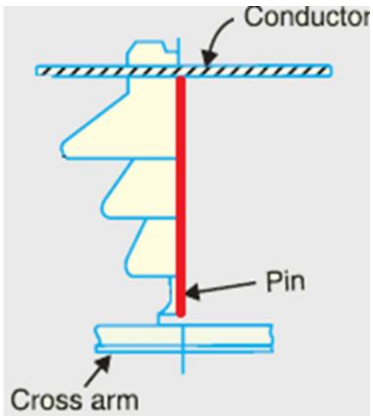


Fig 8.6ii

$$\textbf{Safety factor of insulator} == \frac{\textit{Puncture strength}}{\textbf{Flash over voltage}}$$

It is desirable that the value of safety factor is high so that flash-over takes place before the insulator gets punctured. For pin type insulators, the value of safety factor is about 10.

2. 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. 8.7.

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 g voltage is 66 kV, then six discs in series will be provided on the string.

Suspension insulator

Pin type insulators	Suspension type insulators
used for transmission and distribution of electric power at voltages up to 33 kV	used for transmission and distribution of electric power For high voltages (>33 kV)
The cost of pin type insulator increases rapidly as the working voltage is increased.	Cheaper than pin type insulators for voltages beyond 33 kV.
They consist of one porcelain disc.	They consist of a number of porcelain discs connected in series by metal links in the form of a string
If the disc is damaged, the Pin type insulators become useless.	If anyone disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.

Does not provides flexibility to the line	provides greater flexibility to the line
Cannot be used for higher voltages	It can be used for higher voltages by adding a new discs

Q. Compare between Pin & Suspension type insulators

8.4 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. 8.10 (*i*) shows 3-disc string of suspension insulators.

1. The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor *C* (**known as *mutual capacitance* or *self-capacitance***) 8.10 (*ii*).

2. 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. 8.10 (*ii*).

   $I_1 = I_2 = I_3 \dots \dots = I_N = I_{phase}$ Where N is the number of discs in suspension insulator

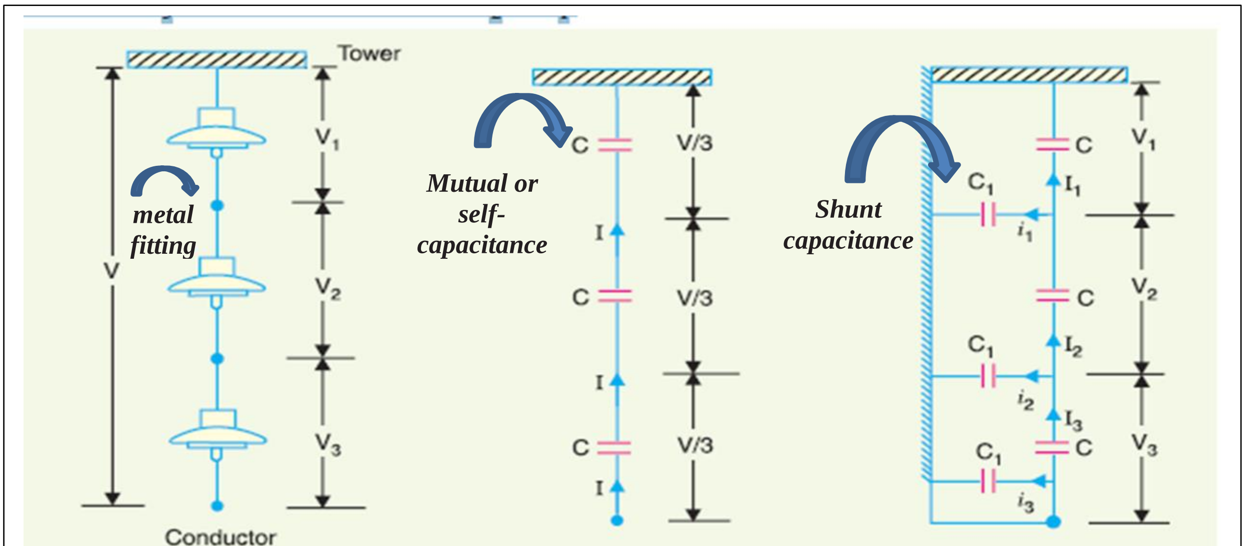
   $$V_1 = V_2 = V_3 \dots \dots V_N = \frac{V_{phase}}{3}$$

3. However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as ***shunt capacitance C*1**. Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig. 8.10 (*iii*)]. Therefore, voltage across each disc will be different.

   $$I_1 \neq I_2 \neq I_3 \dots \dots \neq I_N \neq I_{phase}$$
   $$V_1 \neq V_2 \neq V_3 \dots \dots V_N \neq \frac{V_{phase}}{3}$$

4. Obviously, the disc nearest to the line conductor will have the maximum* voltage. Thus referring to Fig. 8.10 (*iii*), *V*3 will be much more than *V*2 or *V*1.

   $i.e.\ \ V_3 > V_2 > V_1$



Q. Give the reasons for unequal potential distribution over a string insulators.

8.5 String Efficiency

As stated above, 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.

Q. under any condition the efficiency of suspension insulator reach to100%?

$$V_1 = V_2 = V_3 \ldots \ldots V_N = \frac{V_{phase}}{3}$$

$$\eta = \frac{V_{phase}}{n * Vn} * 100\% \qquad = \frac{V_{phase}}{V_{phase}} * 100\% \quad = 100\%$$

8.6 Mathematical expression.

Fig. 8.11 shows the equivalent circuit for a 3-disc string.

Let us suppose that self-capacitance of each disc is *C*.

And shunt capacitance is *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.

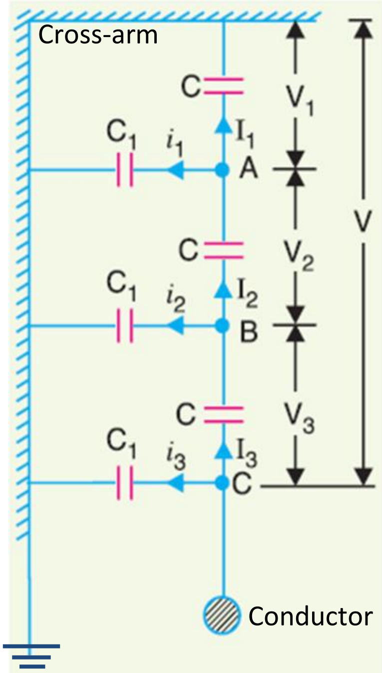


Fig. 8.11

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

$$I_2 = I_1 + i_1$$

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

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

∴ $$V_2 = V_1 (1 + K) \qquad ...(i)$$

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

$$I_3 = I_2 + i_2$$

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

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

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

$$= KV_1 + V_2 (1 + K)$$

$$= KV_1 + V_1 (1 + K)^2 \qquad [\because V_2 = V_1 (1 + K)]$$

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

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

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

$$V = V_1 + V_2 + V_3$$

$$= V_1 + V_1(1 + K) + V_1 (1 + 3K + K^2)$$

$$= V_1 (3 + 4K + K^2)$$

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

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

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

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

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

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

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

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

8.7 Methods of Improving String Efficiency

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 cross arm 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 equalizing 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

Longer cross-arms

⇩

increased the distance of conductor from tower

⇩

Lesser C_1

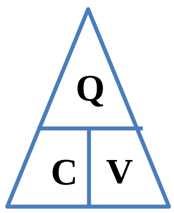
⇩

Lesser K

⇩

Improving String Efficiency

(ii) *By grading the insulators.*



From triangle $Q = C * V$

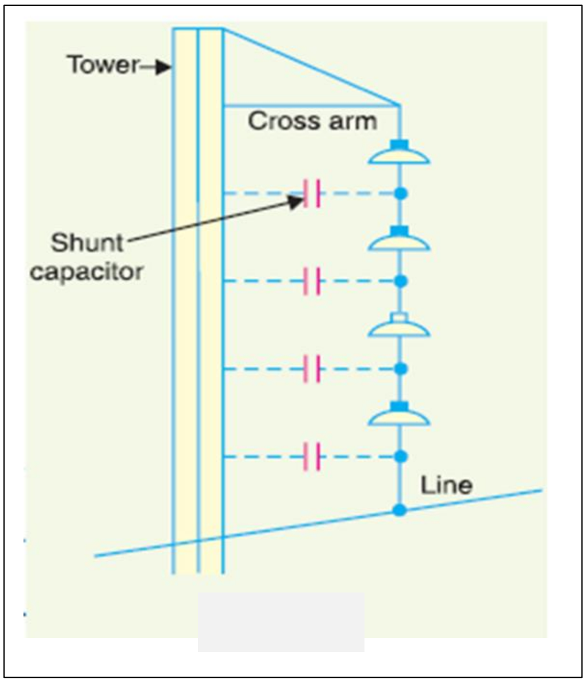
If Q is constant, voltage is inversely proportional to capacitance

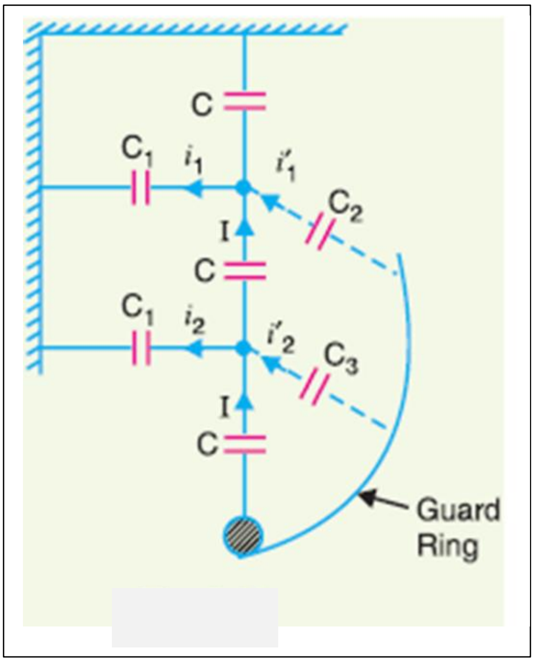
The insulators of capacitance graded *i.e.* they are assembled in the string in such a way that

$$C1 < C2 < C3 \quad \text{then, } V1 > V2 > V3 >$$

This method tends to equalize the potential distribution across the units in the string and improve string efficiency.

(iii) *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. 8.13.





The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring 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.

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. 8.14. 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.

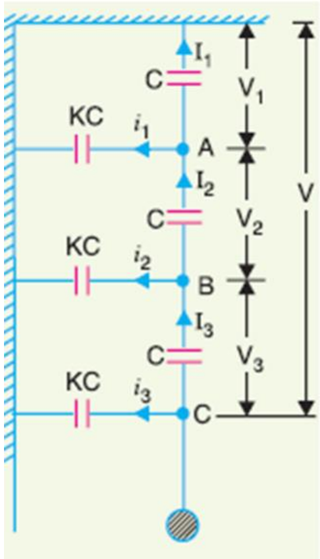


Fig. 8.14

Since KC=0.11C , then $K = \dfrac{\text{Shunt Capacitance}}{\text{Self - capacitance}} = 0.11$

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

At Junction A

$$I_2 = I_1 + i_1$$

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

or $$V_2 = V_1 (1 + K) = V_1 (1 + 0{\cdot}11)$$

or $$V_2 = 1{\cdot}11\, V_1 \qquad \text{...}(i)$$

At Junction B

$$I_3 = I_2 + i_2$$

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

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

$$= 1{\cdot}11 V_1 + (V_1 + 1{\cdot}11\, V_1)\, 0{\cdot}11$$

∴ $$V_3 = 1{\cdot}342\, V_1$$

(*i*) Voltage across the whole string is

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

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

∴ Voltage across top unit, $V_1 = 19{\cdot}05/3{\cdot}452 =$ **5·52 kV**

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

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

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

Example 8.2. *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.*

Solution. The equivalent circuit of string insulators is the same as shown in Fig. 8.14. It is given that $V_1 = 8$ kV and $V_2 = 11$ kV.

(*i*) Let K be the ratio of capacitance between pin and earth to self capacitance. If C farad is the self capacitance of each unit, then capacitance between pin and earth = KC.

Applying Kirchoff's current law to Junction A,

$$I_2 = I_1 + i_1$$

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

or $$V_2 = V_1 (1 + K)$$

$\therefore$ $$K = \frac{V_2 - V_1}{V_1} = \frac{11-8}{8} = \mathbf{0{\cdot}375}$$

(*ii*) Applying Kirchoff's current law to Junction B,

$$I_3 = I_2 + i_2$$

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

or $$V_3 = V_2 + (V_1 + V_2) K = 11 + (8 + 11) \times 0{\cdot}375 = 18{\cdot}12 \text{ kV}$$

Voltage between line and earth $= V_1 + V_2 + V_3 = 8 + 11 + 18{\cdot}12 = 37{\cdot}12$ kV

$\therefore$ Line Voltage $= \sqrt{3} \times 37{\cdot}12 = \mathbf{64{\cdot}28\ kV}$

(*iii*) String efficiency $$= \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{37{\cdot}12}{3 \times 18{\cdot}12} \times 100 = \mathbf{68.28\%}$$

Example 8.3. *Each line of a 3-phase system is suspended by a string of 3 similar insulators. If the voltage across the line unit is 17·5 kV, calculate the line to neutral voltage. Assume that the shunt capacitance betwen each insulator and earth is 1/8th of the capacitance of the insulator itself. Also find the string efficiency.*

Solution. Fig. 8·15 shows the equivalent circuit of string insulators. If C is the self capacitance of each unit, then KC will be the shunt capacitance where $K = 1/8 = 0{\cdot}125$.

Voltage across line unit, $V_3 = 17{\cdot}5$ kV

At Junction A

$$I_2 = I_1 + i_1$$

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

or $$V_2 = V_1(1+K) = V_1(1 + 0.125)$$

$\therefore$ $$V_2 = 1{\cdot}125\,V_1$$

At Junction B

$$I_3 = I_2 + i_2$$

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

or $$V_3 = V_2 + (V_1+V_2)K$$
$$= 1{\cdot}125\,V_1 + (V_1 + 1{\cdot}125\,V_1)\times 0.125$$

$\therefore$ $$V_3 = 1{\cdot}39\,V_1$$

Voltage across top unit, $V_1 = V_3/1{\cdot}39 = 17{\cdot}5/1{\cdot}39$
$= 12{\cdot}59$ kV

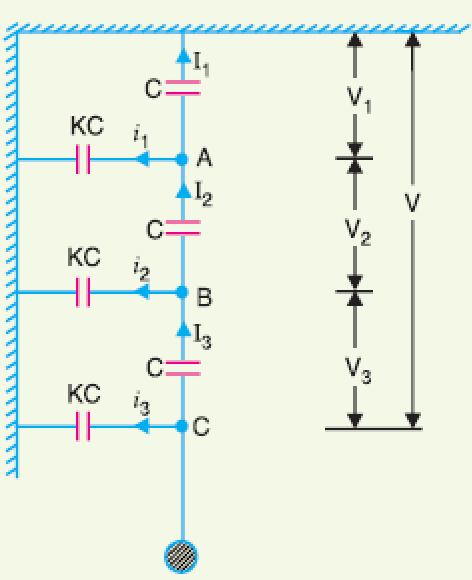


Fig. 8.15

Voltage across middle unit, $V_2 = 1{\cdot}125\,V_1 = 1{\cdot}125 \times 12{\cdot}59 = 14{\cdot}16$ kV

$\therefore$ Voltage between line and earth (*i.e.,* line to neutral)

$$= V_1 + V_2 + V_3 = 12{\cdot}59 + 14{\cdot}16 + 17{\cdot}5 = \mathbf{44.25\ kV}$$

$$\text{String efficiency} = \frac{44\cdot 25}{3\times 17\cdot 5}\times 100 = \mathbf{84{\cdot}28\%}$$

Example 8.4. *The three bus-bar conductors in an outdoor substation are supported by units of post type insulators. Each unit consists of a stack of 3 pin type insulators fixed one on the top of the other. The voltage across the lowest insulator is 13·1 kV and that across the next unit is 11 kV. Find the bus-bar voltage of the station.*

Solution. The equivalent circuit of insulators is the same as shown in Fig. 8.15. It is given that $V_3 = 13{\cdot}1$ kV and $V_2 = 11$ kV. Let K be the ratio of shunt capacitance to self capacitance of each unit. Applying Kirchhoff's current law to Junctions A and B, we can easily derive the following equations (See example 8.3) :

$$V_2 = V_1 (1 + K)$$

or $$V_1 = \frac{V_2}{1+K} \quad ...(i)$$

and $$V_3 = V_2 + (V_1 + V_2)\,K \quad ...(ii)$$

Putting the value of $V_1 = V_2/(1 + K)$ in eq. (*ii*), we get,

$$V_3 = V_2 + \left[\frac{V_2}{1+K} + V_2\right] K$$

or $$V_3 (1 + K) = V_2 (1 + K) + [V_2 + V_2 (1 + K)]\,\mathrm{K}$$

$$= V_2 [(1 + K) + K + (K + K^2)]$$

$$= V_2 (1 + 3K + K^2)$$

∴ $$13{\cdot}1\,(1 + K) = 11[1 + 3K + K^2]$$

or $$11K^2 + 19{\cdot}9\,K - 2{\cdot}1 = 0$$

Solving this equation, we get, $K = 0.1$.

∴ $$V_1 = \frac{V_2}{1+K} = \frac{11}{1+0{\cdot}1} = 10 \text{ kV}$$

Voltage between line and earth = $V_1 + V_2 + V_3 = 10 + 11 + 13{\cdot}1 = 34{\cdot}1$ kV

∴ Voltage between bus-bars (*i.e.,* line voltage)

$$= 34{\cdot}1 \times \sqrt{3} = \mathbf{59\ kV}$$

Example 8.10. *The self capacitance of each unit in a string of three suspension insulators is C.The shunting capacitance of the connecting metal fitting 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 toearth and (ii) string efficiency.*

Solution. In an actual string of insulators, three capacitances exist *viz.*, self-capacitance of each insulator, shunt capacitance and capacitance of each unit to line as shown in Fig. 8.20 (*i*). However, capacitance of each unit to line is very small and is usually neglected. Fig. 8.20 (*ii*) shows the equivalent circuit of string insulators.

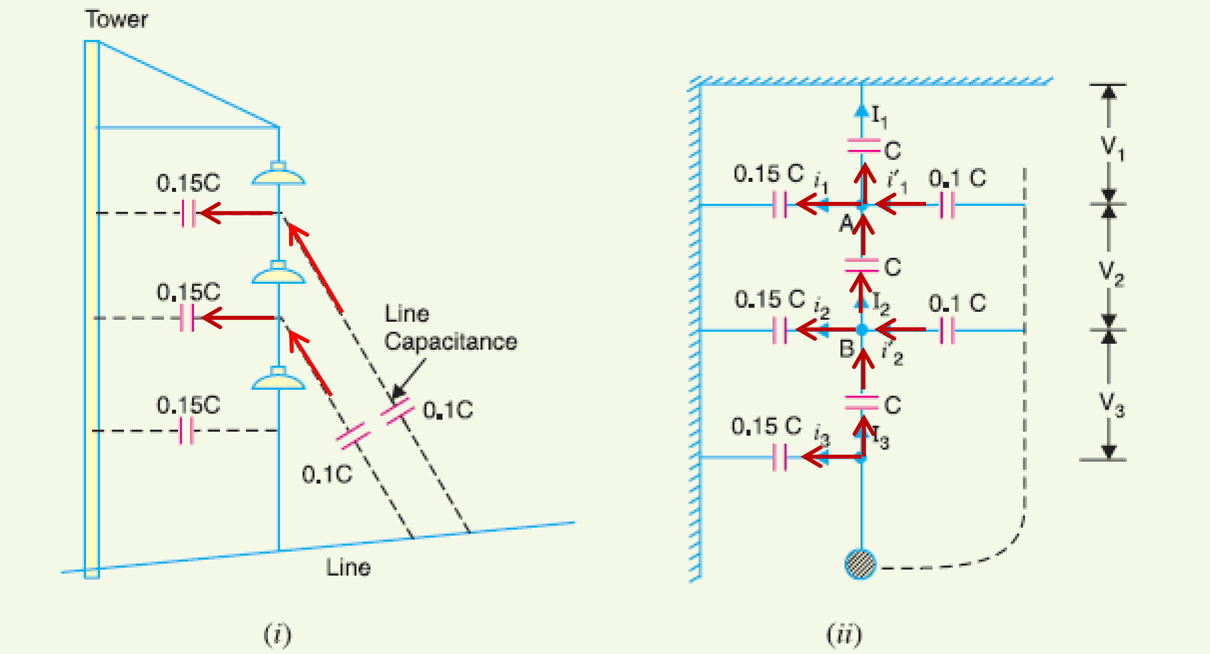


Fig. 8.20

At Junction A

$$I_2 + i'_1 = I_1 + i_1$$

or $$V_2 \omega C + (V_2 + V_3)\, 0{\cdot}1 \omega C = V_1 \omega C + 0{\cdot}15\, C V_1 \omega$$

or $$0{\cdot}1\, V_3 = 1{\cdot}15\, V_1 - 1{\cdot}1\, V_2$$

or $$V_3 = 11{\cdot}5\, V_1 - 11\, V_2 \quad \ldots(i)$$

At Junction B

$$I_3 + i'_2 = I_2 + i_2$$

or $$V_3 \omega C + V_3 \times 0{\cdot}1\, C \times \omega = V_2 \omega C + (V_1 + V_2)\, \omega \times 0{\cdot}15\, C$$

or $$1{\cdot}1\, V_3 = 1{\cdot}15\, V_2 + 0{\cdot}15\, V_1 \quad \ldots(ii)$$

Putting the value of V_3 from exp (*i*). into exp. (*ii*), we get,

$$1{\cdot}1\,(11{\cdot}5\, V_1 - 11\, V_2) = 1{\cdot}15\, V_2 + 0{\cdot}15\, V_1$$

or $$13{\cdot}25\, V_2 = 12{\cdot}5\, V_1$$

or $$V_2 = \frac{12{\cdot}5}{13{\cdot}25} V_1 \quad \ldots(iii)$$

Putting the value of V_2 from exp. (*iii*) into exp. (*i*), we get,

$$V_3 = 11{\cdot}5\; V_1 - 11\left(\frac{12{\cdot}5\, V_1}{13{\cdot}25}\right) = \left(\frac{14{\cdot}8}{13{\cdot}25}\right) V_1$$

Now voltage between conductor and earth is

$$V = V_1 + V_2 + V_3 = V_1\left(1 + \frac{12{\cdot}5}{13{\cdot}25} + \frac{14{\cdot}8}{13{\cdot}25}\right) = \left(\frac{40{\cdot}55\, V_1}{13{\cdot}25}\right) \text{volts}$$

$$\therefore \quad V_1 = 13{\cdot}25\, V/40{\cdot}55 = 0{\cdot}326\, V \text{ volts}$$

$$V_2 = 12{\cdot}5 \times 0{\cdot}326\, V/13{\cdot}25 = 0{\cdot}307\, V \text{ volts}$$

$$V_3 = 14{\cdot}8 \times 0{\cdot}326\, V/13{\cdot}25 = 0{\cdot}364\, V \text{ volts}$$

(*i*) The voltage across each unit expressed as a percentage of V becomes:

Top unit $= V_1 \times 100/V = 0{\cdot}326 \times 100 =$ **32·6%**

Second from top $= V_2 \times 100/V = 0{\cdot}307 \times 100 =$ **30·7%**

Third from top $= V_3 \times 100/V = 0{\cdot}364 \times 100 =$ **36·4%**

(*ii*) String efficiency $= \dfrac{V}{3 \times 0{\cdot}364\, V} \times 100 =$ **91·5 %**

Example 8.11. *Each line of a 3-phase system is suspended by a string of 3 indentical insulators of self-capacitance C farad. The shunt capacitance of connecting metal work of each insulator is 0·2 C to earth and 0·1 C to line. Calculate the string efficiency of the system if a guard ring increases the capacitance to the line of metal work of the lowest insulator to 0·3 C.*

Solution. The capacitance between each unit and line is artificially increased by using a guard ring as shown in Fig. 8.21. This arrangement tends to equalise the potential across various units and hence leads to improved string efficiency. It is given that with the use of guard ring, capacitance of the insulator link-pin to the line of the lowest unit is increased from 0·1 C to 0·3 C.

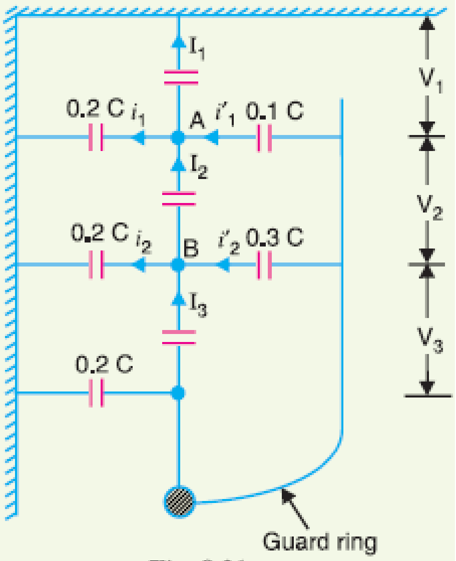


Fig. 8.21

At Junction A

$$I_2 + i'_1 = I_1 + i_1$$

or $$V_2\,\omega\,C + (V_2 + V_3)\,\omega \times 0{\cdot}1\,C = V_1\,\omega\,C + V_1 \times 0{\cdot}2\,C\,\omega$$

$$V_3 = 12\,V_1 - 11\,V_2 \qquad ...(i)$$

At Junction B

$$I_3 + i'_2 = I_2 + i_2$$

or $$V_3\,\omega\,C + V_3 \times 0{\cdot}3\,C \times \omega = V_2\,\omega\,C + (V_1 + V_2)\,\omega \times 0{\cdot}2\,C$$

or $$1{\cdot}3\,V_3 = 1{\cdot}2\,V_2 + 0{\cdot}2\,V_1 \qquad ...(ii)$$

Substituting the value of V_3 from exp. (*i*) into exp. (*ii*), we get,

$$1{\cdot}3\,(12\,V_1 - 11V_2) = 1{\cdot}2\,V_2 + 0{\cdot}2\,V_1$$

or $$15{\cdot}5\,V_2 = 15{\cdot}4\,V_1$$

$\therefore$ $$V_2 = 15{\cdot}4\,V_1/15{\cdot}5 = 0{\cdot}993\,V_1 \qquad ...(iii)$$

Substituting the value of V_2 from exp. (*iii*) into exp. (*i*), we get,

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Substituting the value of V_2 from exp. (*iii*) into exp. (*i*), we get,

$$V_3 = 12\,V_1 - 11 \times 0{\cdot}993\,V_1 = 1{\cdot}077\,V_1$$

Voltage between conductor and earth (*i.e.* phase voltage)

$$= V_1 + V_2 + V_3 = V_1 + 0{\cdot}993\,V_1 + 1{\cdot}077\,V_1 = 3{\cdot}07\,V_1$$

$$\text{String efficiency} = \frac{3\cdot 07\,V_1}{3 \times 1\cdot 077\,V_1} \times 100 = \mathbf{95\%}$$

Example 8.12. *It is required to grade a string having seven suspension insulators. If the pin to earth capacitance are all equal to C, determine the line to pin capacitance that would give the same voltage across each insulator of the string.*

Solution. Let C_1, C_2... C_6 respectively be the required line to pin capacitances of the units as shown in Fig. 8.22. As the voltage across each insulator has to be the same, therefore,

$$I_1 = I_2 = I_3 = I_4 = I_5 = I_6 = I_7$$

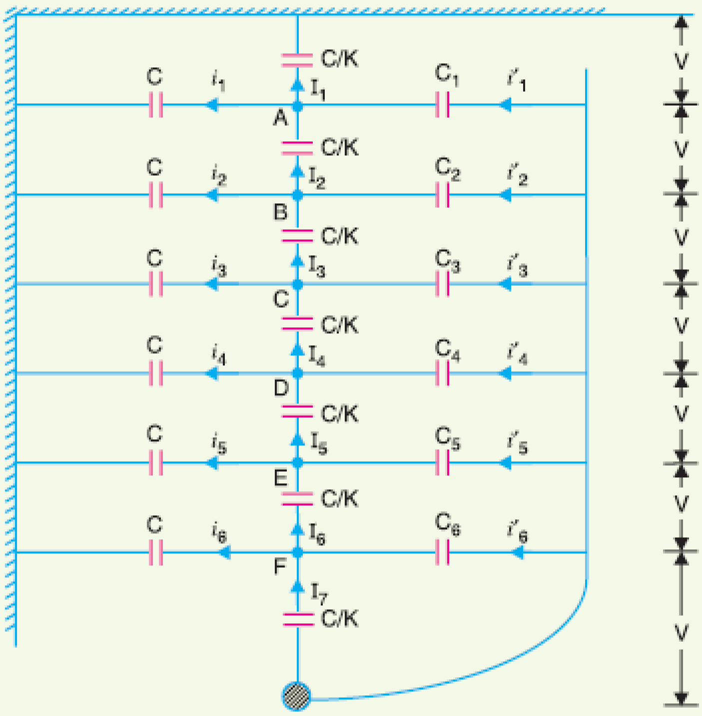

Fig. 8.22

At Junction A

$$i_1' + I_2 = i_1 + I_1$$

or $$i'_1 = i_1 \qquad (\because I_1 = I_2)$$

or $$\omega C_1 (6V) = \omega CV \qquad (\because \text{Voltage across } C_1 = 6V)$$

$\therefore$ $$C_1 = C/6 = \mathbf{0 \cdot 167\ C}$$

At Junction B

$$i_2' = i_2$$

or $$\omega C_2 (5V) = \omega C (2V)$$

$\therefore$ $$C_2 = \frac{2C}{5} = \mathbf{0 \cdot 4\ C}$$

At Junction C

$$i_3' = i_3$$

or $$\omega C_3 (4V) = \omega C (3V)$$

$$\therefore \quad C_3 = 3C/4 = \mathbf{0 \cdot 75\ C}$$

At Junction D

$$i_4' = i_4$$

or $$\omega C_4 (3V) = \omega C (4V)$$

$$\therefore \quad C_4 = 4C/3 = \mathbf{1 \cdot 33\ C}$$

At Junction E

$$i_5' = i_5$$

or $$\omega C_5 (2V) = \omega C (5V)$$

$$\therefore \quad C_5 = 5C/2 = \mathbf{2 \cdot 5\ C}$$

At Junction F

$$i_6' = i_6$$

or $$\omega C_6 V = \omega C (6V)$$

$$\therefore \quad C_6 = \mathbf{6\ C}$$

TUTORIAL PROBLEMS

1. In a 3-phase overhead system, each line is suspended by a string of 3 insulators. The voltage across the top unit (*i.e.* near the tower) and middle unit are 10 kV and 11 kV respectively. Calculate (*i*) the ratio of shunt capacitance to self capacitance of each insulator, (*ii*) the string efficiency and (*iii*) line voltage.

[(*i*) 0·1 (*ii*) 86·76% (*iii*) 59 kV]

2. Each line of a 3-phase system is suspended by a string of 3 similar insulators. If the voltage across the line unit is 17·5 kV, calculate the line to neutral voltage and string efficiency. Assume that shunt capacitance between each insulator and earthed metal work of tower to be 1/10th of the capacitance of the insulator. **[52 kV, 86·67%]**

3. The three bus-bar conductors in an outdoor sub-station are supplied by units of post insulators. Each unit consists of a stack of 3-pin insulators fixed one on the top of the other. The voltage across the lowest insulator is 8·45 kV and that across the next is 7·25 kV. Find the bus-bar voltage of the station. **[38·8 kV]**

4. A string of suspension insulators consists of three units. The capacitance between each link pin and earth is one-sixth of the self-capacitance of each unit. If the maximum voltage per unit is not to exceed 35 kV, determine the maximum voltage that the string can withstand. Also calculate the string efficiency. **[84·7 kV; 80·67%]**

5. A string of 4 insulators has self-capacitance equal to 4 times the pin-to-earth capacitance. Calculate (*i*) the voltage distribution across various units as a percentage of total voltage across the string and (*ii*) string efficiency. **[(*i*) 14·5%, 18·1%, 26·2% and 40·9% (*ii*) 61·2 %]**

6. A string of four suspension insulators is connected across a 285 kV line. The self-capacitance of each unit is equal to 5 times pin to earth capacitance. Calculate :

   (*i*) the potential difference across each unit, (*ii*) the string efficiency. **[(*i*) 27·65 kV, 33·04 kV, 43·85 kV, 60 kV (*ii*) 68·5%]**

7. Each of three insulators forming a string has self-capacitance of "*C*" farad. The shunt capacitance of each cap of insulator is 0·25 C to earth and 0·15 C to line. Calculate the voltage distribution across each insulator as a pecentage of line voltage to earth and the string efficiency. **[31·7%, 29·4%, 38·9%; 85·7%]**

8. Each of the three insulators forming a string has a self capacitance of *C* farad. The shunt capacitance of each insulator is 0·2 C to earth and 0·1 C to line. A guard-ring increases the capacitance of line of the metal work of the lowest insulator to 0·3 C. Calculate the string efficiency of the arrangement :

   (*i*) with the guard ring, (*ii*) without guard ring. **[(*i*) 95% (*ii*) 86·13%]**

9. A three-phase overhead transmission line is being supported by three-disc suspension insulators; the potentials across the first and second insulator from the top are 8 kV and 11 kV respectively. Calcualte (*i*) the line voltage (*ii*) the ratio of capacitance between pin and earth to self capacitance of each unit (*iii*) the string efficiency. **[(*i*) 64·28 V (*ii*) 0·375 (*iii*) 68·28%]**

10. A 3-phase overhead transmission line is supported on 4-disc suspension insulators. The voltage across the second and third discs are 13·2 kV and 18 kV respectively. Calculate the line voltage and mention the nearest standard voltage. **[118·75 kV; 120 kV]**