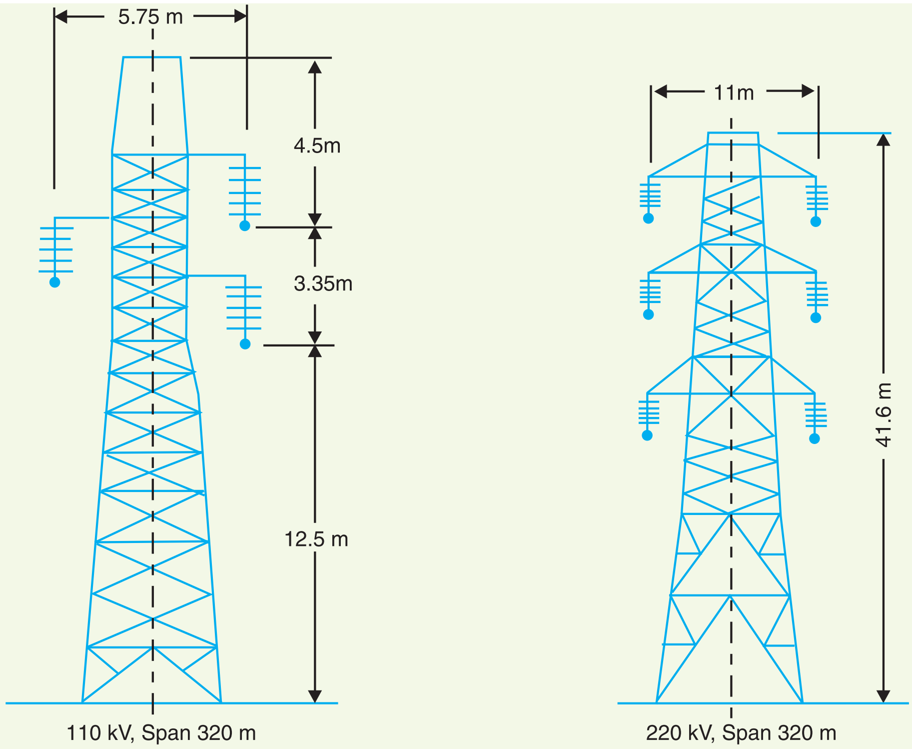

Fig. 8.4 Steel Towers

(i) High mechanical strength in order to withstand conductor load, wind load 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 is *porcelain* but glass, steatite and special composition materials are also used to a limited extent. Porcelain is produced by firing at a high temperature a mixture of kaolin, feldspar and quartz. It is stronger mechanically than glass, gives less trouble from leakage and is less effected by changes of temperature.

8.5 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.

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

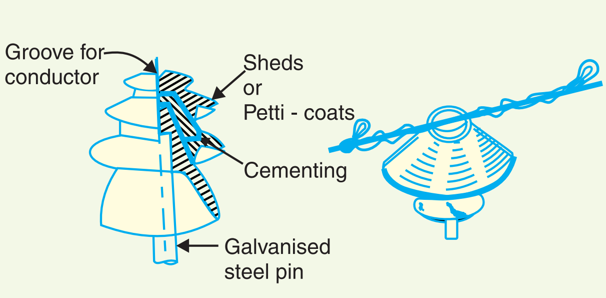

Fig. 8.5. Pin-type insulator

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

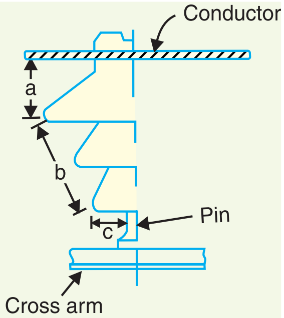

Fig. 8.6

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 pirmarily 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 flash-over, 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. 8.6 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.

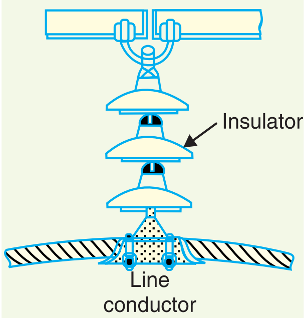

Fig. 8.7

In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat. In practice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flash-over voltage is known as safety factor *i.e.*,

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

Pin type insulator

Suspension insulator

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

* The insulator is generally dry and its surfaces have proper insulating properties. Therefore, arc can only occur through air gap between conductor and insulator pin.

consist of a number of porcelain discs connected in series by metal links in the form of a string. The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower. Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

Advantages

(*i*) Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.

(*ii*) Each unit or disc of suspension type insulator is designed for low voltage,usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in series.

(*iii*) If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.

(*iv*) The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.

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

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

3. 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. 8.8. 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.

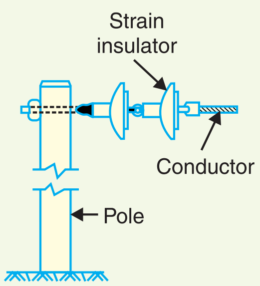

Fig. 8.8. Strain insulator.

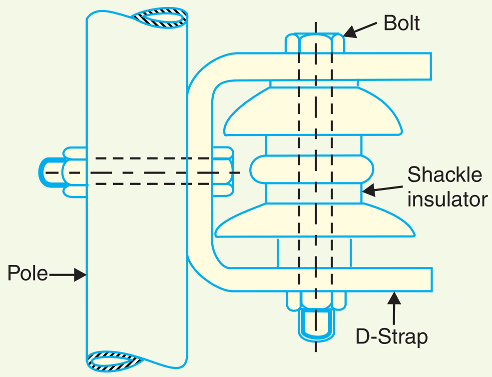

Fig. 8.9

4. 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. 8.9 shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.

8.6 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. The porcelain portion of each disc is inbetween two metal links. Therefore, each disc forms a capacitor *C* as shown in Fig. 8.10 (*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. 8.10 (*ii*). 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. 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.

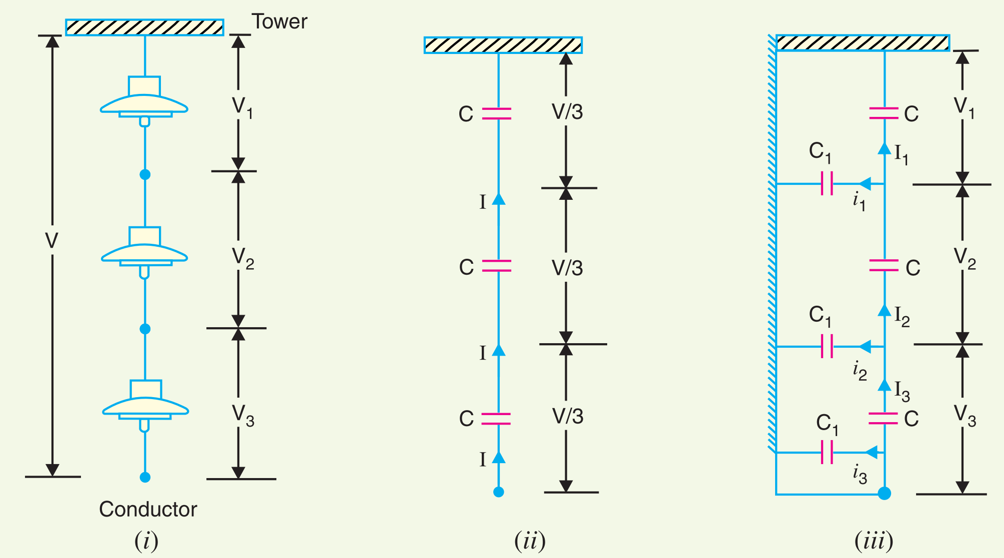

Fig. 8.10

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. Therefore, means must be provided to equalise the potential across each unit. This is fully discussed in Art. 8.8.

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

8.7 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

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

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 volatge 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. 8.11 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.

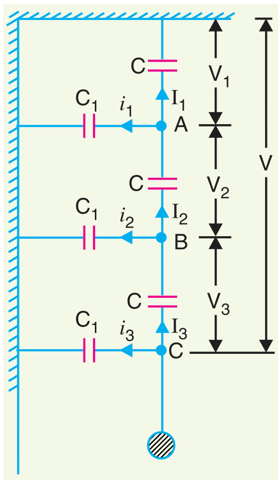

Fig. 8.11

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

$\therefore$ $$V_2 = V_1 (1 + K) \quad \text{...}(i)$$

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
$$\begin{aligned} V_3 &= V_2 + (V_1 + V_2)K \\ &= KV_1 + V_2 (1 + K) \\ &= KV_1 + V_1 (1 + K)^2 \qquad [\because V_2 = V_1 (1 + K)] \\ &= V_1 [K + (1 + K)^2] \end{aligned}$$

$\therefore$ $$V_3 = V_1[1 + 3K + K^2] \quad \text{...}(ii)$$

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

$$\begin{aligned} V &= V_1 + V_2 + V_3 \\ &= V_1 + V_1(1 + K) + V_1 (1 + 3K + K^2) \\ &= V_1 (3 + 4K + K^2) \end{aligned}$$

$\therefore$ $$V = V_1(1 + K)(3 + K) \quad \text{...}(iii)$$

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

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

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

---

* Note that current through capacitor = $\dfrac{\text{Voltage}}{\text{Capacitive reactance}}$

† Voltage across second shunt capacitance C_1 from top = $V_1 + V_2$. It is because one point of it is connected to B and the other point to the tower.

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

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

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

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

The following points may be noted from the above mathematical analysis :

(*i*) If $K = 0{\cdot}2$ (Say), then from exp. (*iv*), we get, $V_2 = 1{\cdot}2\ V_1$ and $V_3 = 1{\cdot}64\ V_1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(*ii*) The greater the value of K ($= C_1/C$), the more non-uniform is the potential across the discs and lesser is the string efficiency.

(*iii*) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one.

8.8 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 to equalise the potential across the various units of the string *i.e.* to improve the string efficiency. The various methods for this purpose are :

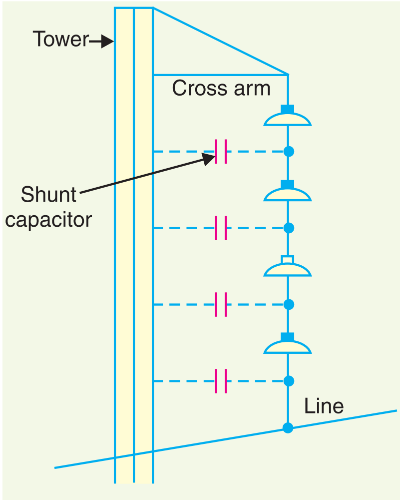

Fig. 8.12

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

(*ii*) *By grading the insulators.* In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded *i.e.* they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (*i.e.*, nearest to conductor) is reached. Since voltage is inversely proportional to capacitance, this method tends to equalise the potential distribution across the units in the string. This method has the disadvantage that a large number of different-sized insulators are required. However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line conductor.

(*iii*) *By using a guard ring.* The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig. 8.13. 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.

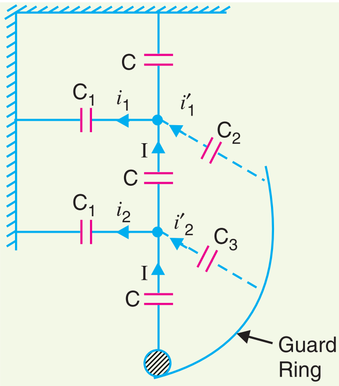

Fig. 8.13

8.9 Important Points

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

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

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

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

(iii) Line Voltage = $\sqrt{3}$ × Voltage across string

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.

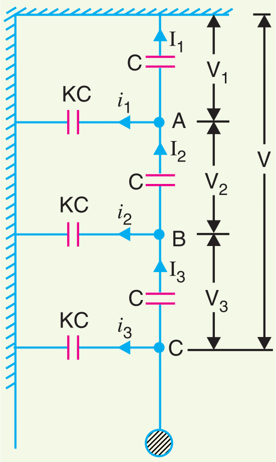

Fig. 8.14

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

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

At Junction A

$$I_2 = I_1 + i_1$$

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

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

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

∴ $$V_3 = 1{\cdot}342\,V_1$$

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

Example 8.2. *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 $$V_2 = V_1 (1 + K)$$

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

(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 $= \sqrt{3} \times 37{\cdot}12 = \mathbf{64{\cdot}28 \text{ kV}}$

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

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

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

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

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

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

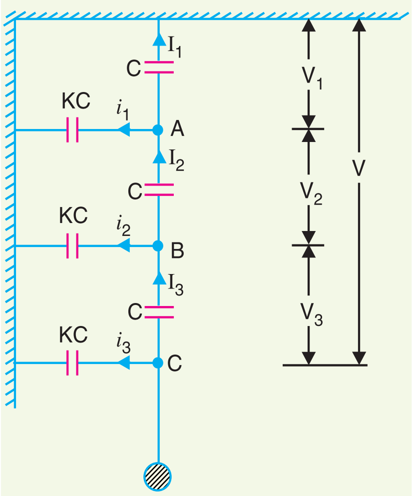

Fig. 8.15

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

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

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 $$V_3 (1 + K) = V_2 (1 + K) + [V_2 + V_2 (1 + K)]\, K$$

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

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

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

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

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

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

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

$\therefore$ Voltage between bus-bars (*i.e.*, line voltage)

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

Example 8.5. *An insulator string consists of three units, each having a safe working voltage of 15 kV. The ratio of self-capacitance to shunt capacitance of each unit is 8 : 1. Find the maximum safe working voltage of the string. Also find the string efficiency.*

Solution. The equivalent circuit of string insulators is the same as shown in Fig. 8.15. The maximum voltage will appear across the lowest unit in the string.

$\therefore$ $V_3 = 15$ kV ; $K = 1/8 = 0{\cdot}125$

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

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

or $$V_1 = V_2/(1 + K) = V_2/(1 + 0{\cdot}125) = 0{\cdot}89\, V_2 \qquad ...(i)$$

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

$$V_3 = V_2 + (V_1 + V_2) K = V_2 + (0.89\, V_2 + V_2) \times 0.125$$

$\therefore \quad V_3 = 1.236\ V_2$ ...(*ii*)

$\therefore$ Voltage across middle unit, $V_2 = V_3/1.236 = 15/1{\cdot}236 = 12{\cdot}13$ kV

Voltage across top unit, $V_1 = 0{\cdot}89\ V_2 = 0{\cdot}89 \times 12{\cdot}13 = 10{\cdot}79$ kV

Voltage across the String $= V_1 + V_2 + V_3 = 10{\cdot}79 + 12{\cdot}13 + 15 =$ **37·92 kV**

String efficiency $= \dfrac{37{\cdot}92}{3 \times 15} \times 100 =$ **84·26 %**

Example 8.6. *A string of 4 insulators has a self-capacitance equal to 10 times the pin to earth capacitance. Find (i) the voltage distribution across various units expressed as a percentage of total voltage across the string and (ii) string efficiency.*

Solution. When the number of insulators in a string exceeds 3, the nodal equation method becomes laborious. Under such circumstances, there is a simple method to solve the problem. In this method*, shunt capacitance (C_1) and self capacitance (C) of each insulator are represented by their equivalent reactances. As it is only the ratio of capacitances which determines the voltage distribution, therefore, the problem can be simplified by assigning unity value to X_C *i.e.*, assuming $X_C = 1\ \Omega$. If ratio of $C/C_1 = 10$, then we have $X_C = 1\ \Omega$ and $X_{C1} = 10\ \Omega$.

(*i*) Suppose $X_C = 1\ \Omega$. As the ratio of self-capacitance to shunt capacitance (*i.e.*, C/C_1) is 10, therefore, $X_{C1} = 10\ \Omega$ as shown in Fig. 8·16 (*i*). Suppose that potential V across the string is such that 1 A current flows in the top insulator. Now the potential across each insulator can be easily determined. Thus :

Voltage across top unit, $V_1 = 1\ \Omega \times 1\ \text{A} = 1$ volt

Voltage across **2nd unit, $V_2 = 1\ \Omega \times 1{\cdot}1\ \text{A} = 1{\cdot}1$ volts

Voltage across †3rd unit, $V_3 = 1\ \Omega \times 1{\cdot}31\ \text{A} = 1{\cdot}31$ volts

Voltage across 4th unit, $V_4 = 1\ \Omega \times 1{\cdot}65\ \text{A} = 1{\cdot}65$ volts

Voltage obtained across the string, $V = 1 + 1{\cdot}1 + 1{\cdot}31 + 1{\cdot}65 = 5{\cdot}06$ volts

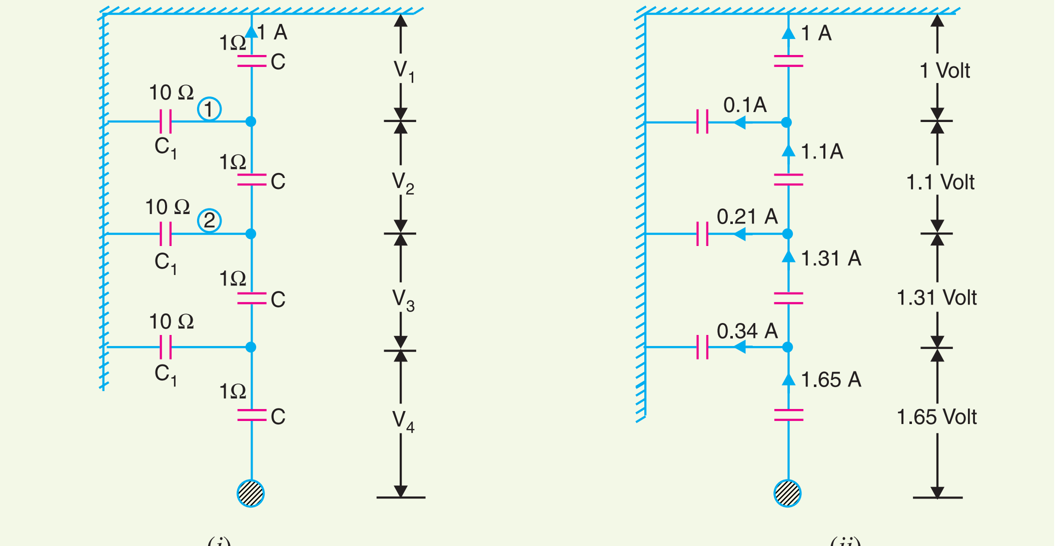

Fig. 8.16

* This method is equally applicable for a string having 3 or less than 3 insulators.

** Current through first shunt capacitance [marked 1, see Fig. 8·16] is $V_1/10 = 1/10 = 0{\cdot}1$ A. Therefore, the current through second unit from top is $= 1 + 0{\cdot}1 = 1{\cdot}1$ A and voltage across it is $= 1\Omega \times 1{\cdot}1\ \text{A} = 1{\cdot}1$ volts.

† Current through second shunt capacitance [marked 2 in Fig. 8·16] is $(V_1 + V_2)/10 = (1 + 1{\cdot}1)/10 = 0{\cdot}21$ A. Therefore, current thro' 3rd unit from top $= 1{\cdot}1 + 0{\cdot}21 = 1{\cdot}31$ A and voltage across it is $1\Omega \times 1{\cdot}31\ \text{A} = 1{\cdot}31$ volts.

The voltage across each unit expressed as a percentage of V (*i.e.*, 5·06 volts) becomes :

Top unit	$= (1/5{\cdot}06) \times 100 =$ **19·76%**
Second from top	$= (1{\cdot}1/5{\cdot}06) \times 100 =$ **21·74%**
Third from top	$= (1{\cdot}31/5{\cdot}06) \times 100 =$ **25·9%**
Fourth from top	$= (1{\cdot}65/5{\cdot}06) \times 100 =$ **32·6%**

(*ii*) String efficiency $= \dfrac{V}{4 \times V_4} \times 100 = \dfrac{5 \cdot 06}{4 \times 1 \cdot 65} \times 100 =$ **76·6%**

Example 8.7. *A string of 5 insulators is connected across a 100 kV line. If the capacitance of each disc to earth is 0·1 of the capacitance of the insulator, calculate (i) the distribution of voltage on the insulator discs and (ii) the string efficiency.*

Solution. Suppose $X_C = 1\ \Omega$. As the ratio of self capacitance to shunt capacitance is 10, therefore, $X_{C1} = 10\ \Omega$ as shown in Fig. 8·17 (*i*). Suppose that potential V across the string is such that 1A current flows in the top insulator. Then potential across each insulator will be as shown in Fig. 8·17 (*ii*).

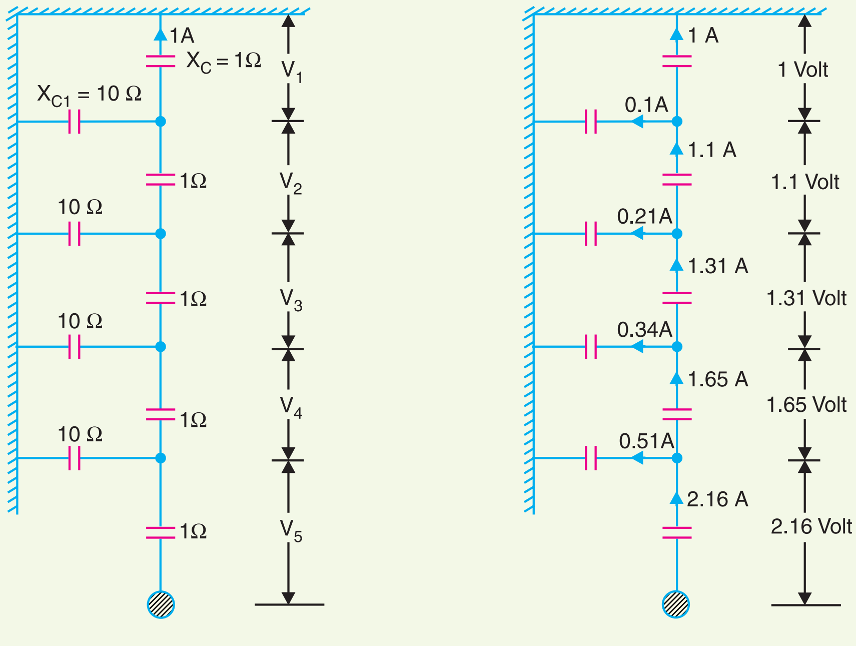

Fig. 8.17

The value obtained for $V = 1 + 1{\cdot}1 + 1{\cdot}31 + 1{\cdot}65 + 2{\cdot}16 = 7{\cdot}22$ volts and starting from top, the percentage of V (*i.e.*, 7·22 volts) across various units are :

*13·8 %, 15·2 %, 18·2 %, 22·8 % and 30%

Voltage across string $= 100/\sqrt{3} = 57{\cdot}7$ kV

(*i*) Voltage across top insulator, $V_1 = 0{\cdot}138 \times 57{\cdot}7 =$ **7·96 kV**

Voltage across 2nd from top, $V_2 = 0{\cdot}152 \times 57{\cdot}7 =$ **8·77 kV**

---

* % age of V (*i.e.*, 7·22 volts) across top unit $= \dfrac{1}{7 \cdot 22} \times 100 = 13{\cdot}8\%$

% age of V across 2nd from top $= \dfrac{1 \cdot 1}{7 \cdot 22} \times 100 = 15{\cdot}2\%$

Voltage across 3rd from top, $V_3 = 0{\cdot}182 \times 57{\cdot}7 =$ **10·5 kV**

Voltage across 4th from top, $V_4 = 0{\cdot}228 \times 57{\cdot}7 =$ **13·16 kV**

Voltage across 5th from top, $V_5 = 0{\cdot}3 \times 57{\cdot}7 =$ **17·3 kV**

(*ii*) String efficiency $= \dfrac{57{\cdot}7}{5 \times 17{\cdot}3} \times 100 =$ **66·7%**

Example 8.8. *Each conductor of a 3-phase high-voltage transmission line is suspended by a string of 4 suspension type disc insulators. If the potential difference across the second unit from top is 13·2 kV and across the third from top is 18 kV, determine the voltage between conductors.*

Solution. Suppose $X_C = 1\ \Omega$. If K is the ratio of shunt-capacitance to self-capacitance, then $X_{C1} = 1/K$ ohms as shown in Fig. 8.18 (*i*). Suppose voltage across string is such that current in top insulator disc is 1 A. Then voltage across each insulator can be easily determined [see Fig. 8.18 (*ii*)]. Thus the voltage across first shunt capacitance from top is 1 volt and its reactance is 1/K ohms. Therefore, current through it is K ampere. Hence current through second insulator from top is $(1 + K)$ amperes and voltage across it is $(1 + K) \times 1 = (1 + K)$ volts.

Referring to Fig. 8.18 (*ii*), we have,

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

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

Also $$V_3/V_1 = (1 + 3K + K^2)/1$$

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

Dividing (*ii*) by (*i*), we get,

$$\frac{V_3}{V_2} = \frac{1 + 3K + K^2}{1 + K}$$

It is given that $V_3 = 18$ kV and $V_2 = 13{\cdot}2$ kV

$\therefore$ $$\frac{18}{13{\cdot}2} = \frac{1 + 3K + K^2}{1 + K}$$

or $$13{\cdot}2\,K^2 + 21{\cdot}6\,K - 4{\cdot}8 = 0$$

Solving this equation, we get, $K = 0{\cdot}2$.

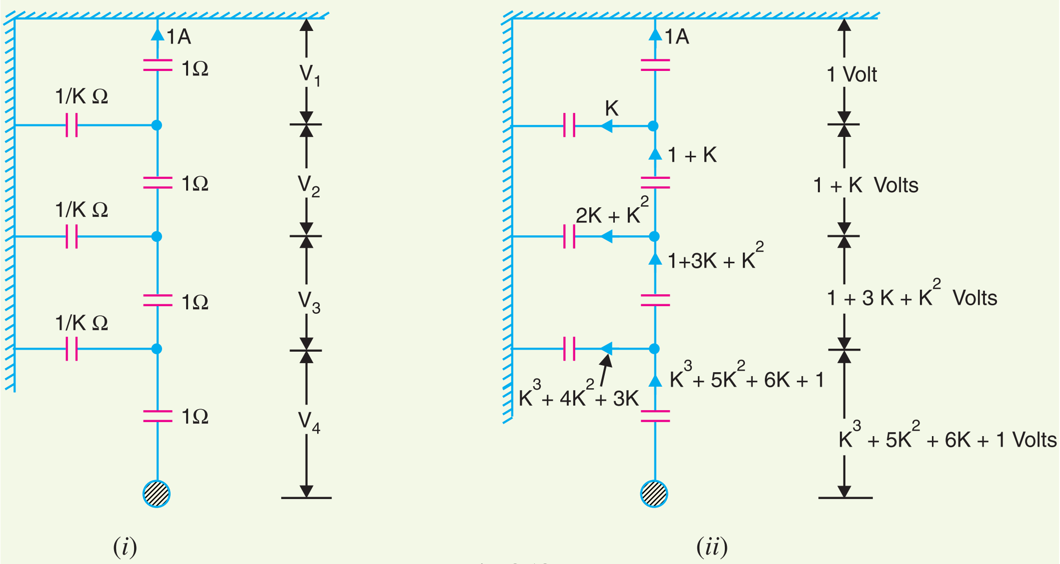

Fig. 8.18

$\therefore \quad V_1 = V_2/(1 + K) = 13{\cdot}2/1{\cdot}2 = 11$ kV

$V_4 = V_1\,(1 + K^3 + 5K^2 + 6K) = 11\,(1 + 0{\cdot}008 + 0{\cdot}2 + 1{\cdot}2) = 26{\cdot}49$kV

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

$= V_1 + V_2 + V_3 + V_4$

$= 11 + 13{\cdot}2 + 18 + 26{\cdot}49 = 68{\cdot}69$ kV

Voltage between conductors (*i.e.*, line voltage)

$= 68{\cdot}69 \times \sqrt{3}$ = **119 kV**

Example 8.9. *A string of four insulators has a self-capacitance equal to 5 times pin to earth capacitance. Find (i) the voltage distribution across various units as a percentage of total voltage across the string and (ii) string efficiency.*

Solution. The ratio of self-capacitance (C) to pin-earth capacitance (C_1) is $C/C_1 = 5$. Suppose $X_C = 1\,\Omega$. Then $X_{C1} = 5\,\Omega$. Suppose the voltage V across string is such that current in the top insulator is 1A as shown in Fig. 8.19 (*i*). The potential across various insulators will be as shown in Fig. 8.19 (*ii*).

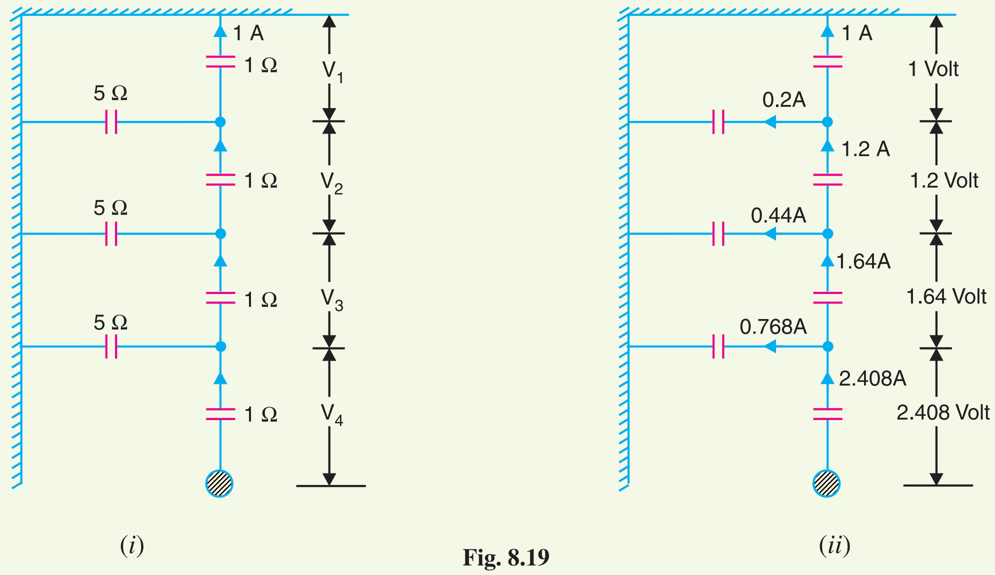

Fig. 8.19

The voltage obtained across the string is given by ;

$V = 1 + 1{\cdot}2 + 1{\cdot}64 + 2{\cdot}408 = 6{\cdot}248$ volts

(*i*) The voltage across each unit expressed as a percentage of V (*i.e.*, 6·248 volts) is given by :

Top Unit $= (1/6{\cdot}248) \times 100$ = **16%**

Second from top $= (1{\cdot}2/6{\cdot}248) \times 100$ = **19·2%**

Third from top $= (1{\cdot}64/6{\cdot}248) \times 100$ = **26·3%**

Fourth from top $= (2{\cdot}408/6{\cdot}248) \times 100$ = **38·5%**

(*ii*) String efficiency $= \dfrac{6{\cdot}248}{4 \times 2{\cdot}408} \times 100$ = **64·86%**

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 work of each insulator to earth is 0·15 C while for line it is 0·1 C. Calculate (i) the voltage across each insulator as a percentage of the line voltage to earth and (ii) string efficiency.*

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.

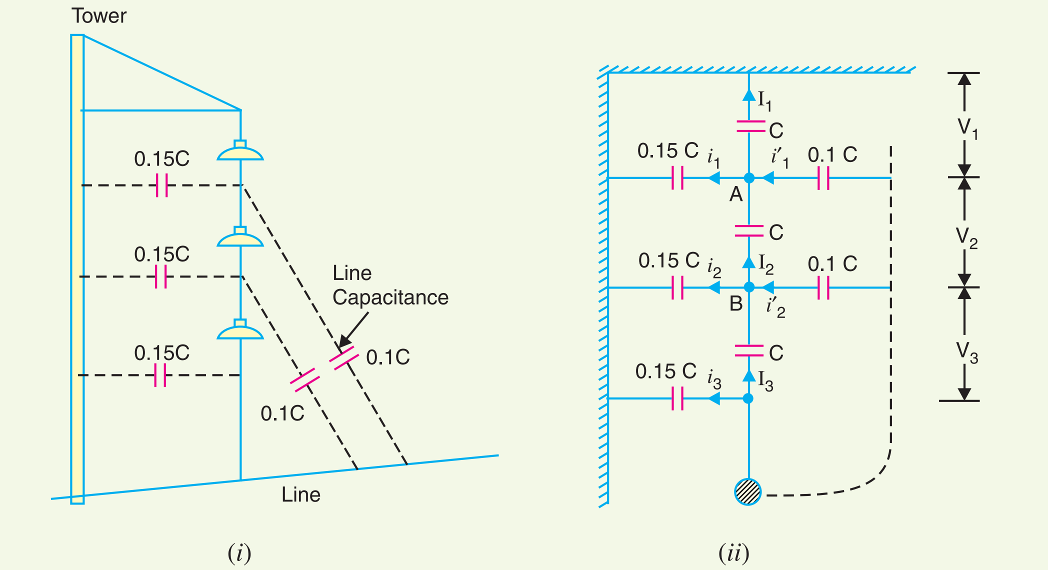

Fig. 8.20

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 $V_3 = 11{\cdot}5\,V_1 - 11\,V_2$ ...(*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 $1{\cdot}1\,V_3 = 1{\cdot}15\,V_2 + 0{\cdot}15\,V_1$ ...(*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 $V_2 = \dfrac{12\cdot 5}{13\cdot 25}V_1$ ...(*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

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

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

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

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

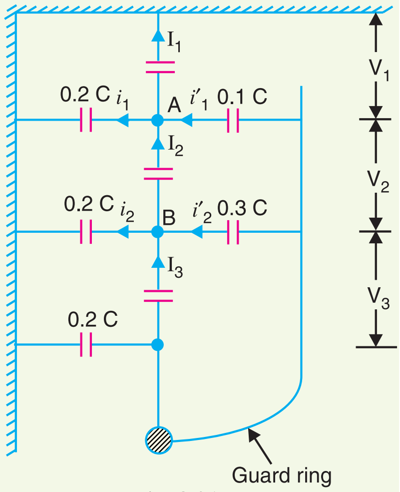

Fig. 8.21

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,

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

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,

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

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

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

String efficiency $= \dfrac{3 \cdot 07\, V_1}{3 \times 1 \cdot 077\, V_1} \times 100 =$ **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,

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

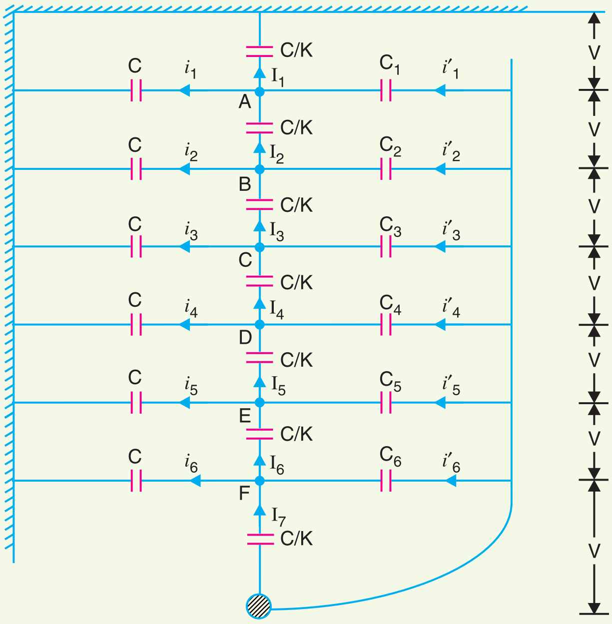

Fig. 8.22

At Junction A

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

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

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

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

At Junction B

$$i_2' = i_2$$

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

$\therefore \quad C_2 = \dfrac{2C}{5} = \mathbf{0{\cdot}4\,C}$

At Junction C

$$i_3' = i_3$$

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

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

At Junction D

$$i_4' = i_4$$

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

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

At Junction E

$$i_5' = i_5$$

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

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

At Junction F

$$i_6' = i_6$$

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

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

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% (*i*) 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 (*i*) 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]**

8.10 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