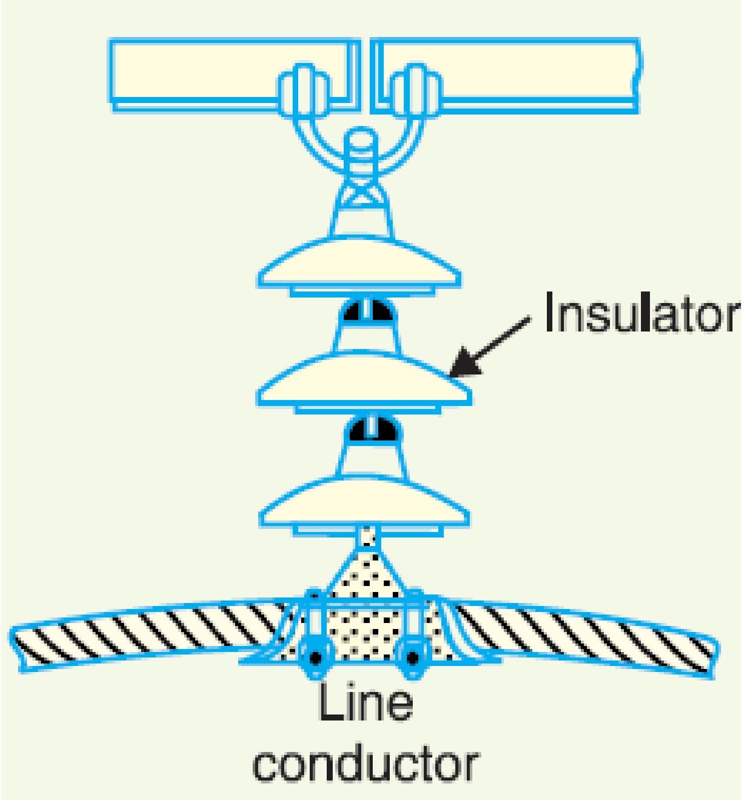
Mechanical Design of Overhead Line ‘Insulators, suspension type’

- 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

Mechanical Design of Overhead Line 'Insulators, suspension type'

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



Mechanical Design of Overhead Line
'Insulators, suspension type'

Typical number of disc insulator units for standard line voltages

Nominal System Phase-to-Phase Voltage kV	Minimum Quantity of Suspension Insulators*
7.5	1
14.4	2
23	2
34.5	3
46	4
69	5
115	8
138	9
161	10
230	12
230	14
345	20

Mechanical Design of Overhead Line
‘Insulators, suspension type’

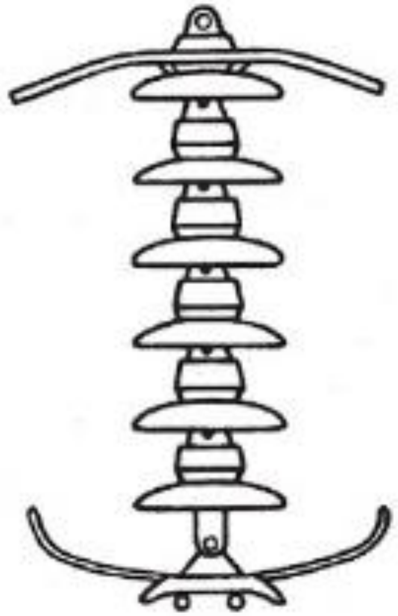
- Advantages
  - Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.
  - If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.
  - The suspension arrangement provides greater flexibility to 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.

Mechanical Design of Overhead Line 'Insulators, suspension type'

- Advantages
  - 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.
  - 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.

Mechanical Design of Overhead Line 'Insulators, suspension type'

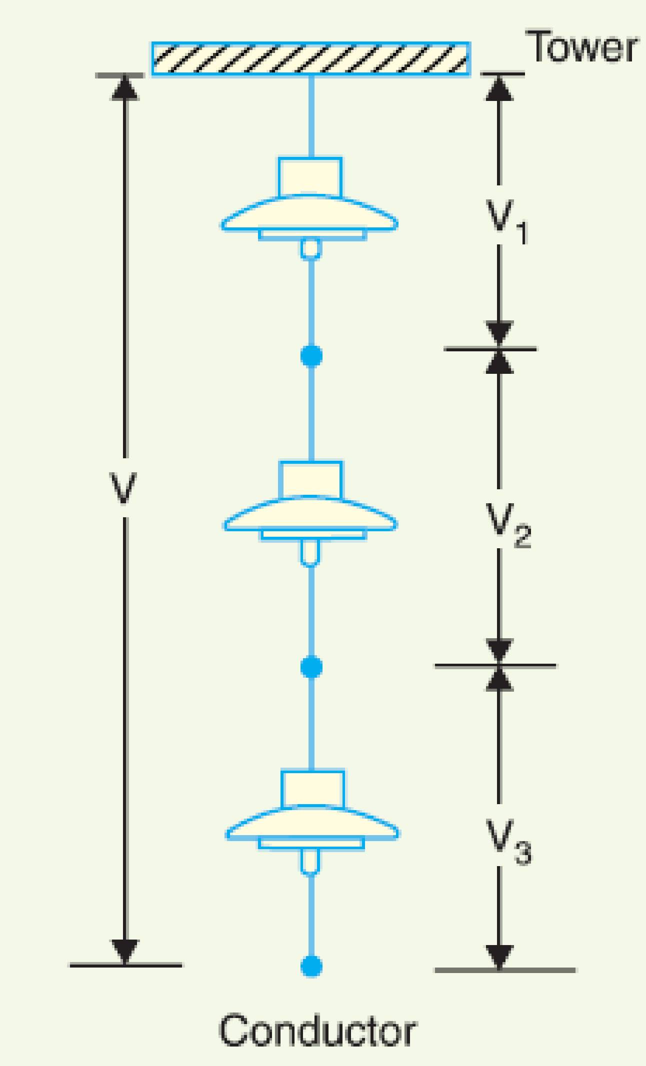
- Arcing horns (Protection of suspension type insulator)
  - They protect the insulator string by providing a shorter path for the arc.
  - They encourage the flashover to occur between themselves rather than across the surface of the insulator they protect
  - Horns are normally paired on either side of the insulator, one connected to the high voltage part and the other to ground.



Mechanical Design of Overhead Line ‘Insulators, suspension type’

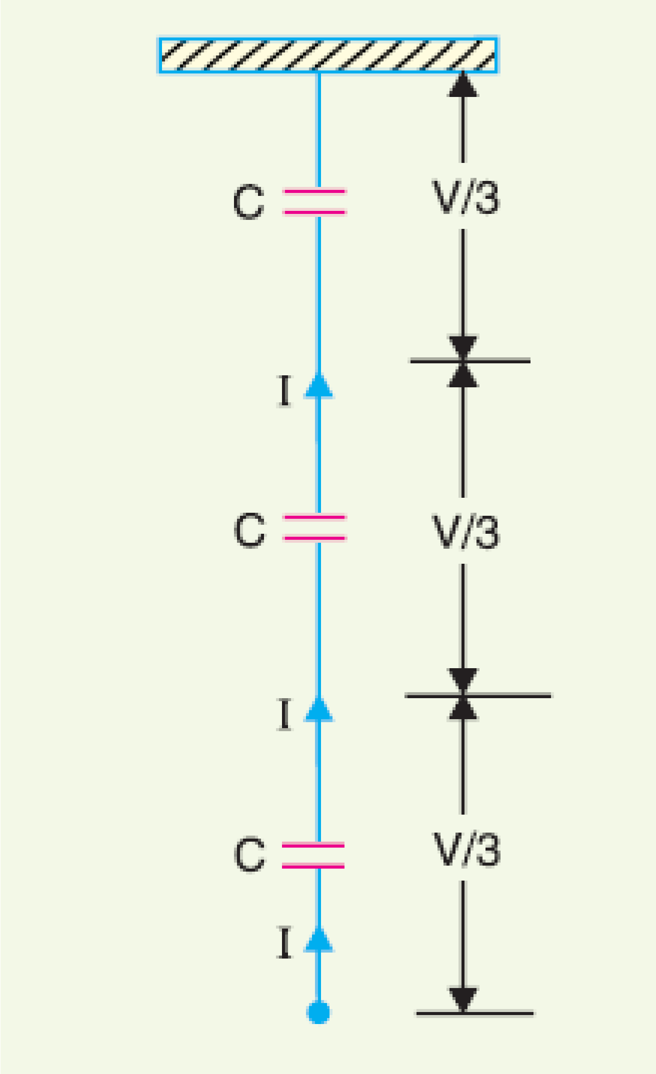
Potential Distribution over Suspension Insulator String

- A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links.
- Consider a 3-disc string of suspension insulators. The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor *C*. This is known as *mutual capacitance* or *self-capacitance*.



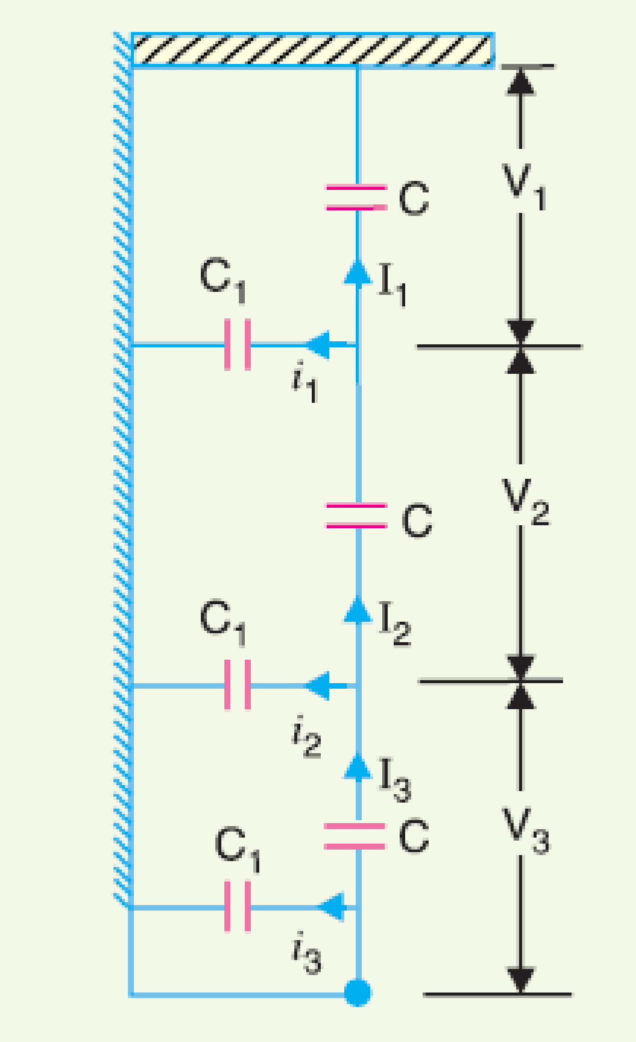
Mechanical Design of Overhead Line ‘Insulators, suspension type’

- If there were mutual capacitance alone, then charging current would have been the same through all the discs
- consequently voltage across each unit would have been the same *i.e.*, *V*/3



Mechanical Design of Overhead Line
'Insulators, suspension type'

- 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. Therefore, voltage across each disc will be different.
- Obviously, the disc nearest to the line conductor will have the maximum voltage. Because charging current through the string has the maximum value at the disc nearest to the conductor.
- V_3 will be much more than V_2 or V_1.



Mechanical Design of Overhead Line ‘Insulators, suspension type’

- The following points may be noted regarding the potential distribution over a string of suspension insulators :
  - 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.
  - 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.
  - The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured. Therefore, means must be provided to equalize the potential across each unit.

Mechanical Design of Overhead Line
‘Insulators, suspension type’

- **String efficiency**
  - ➢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.,

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

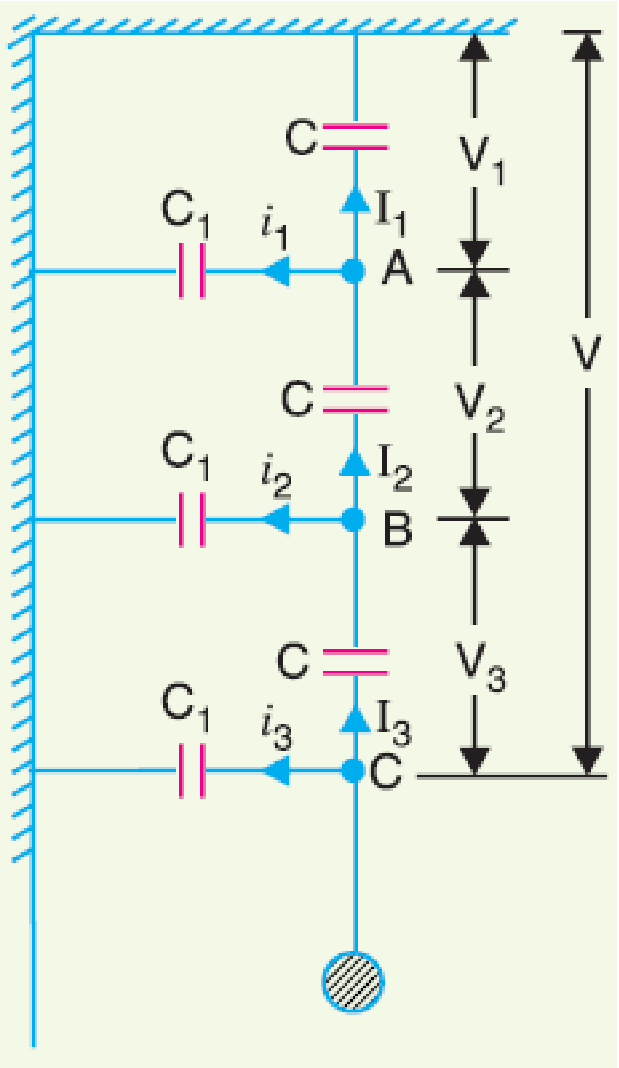
where n is the number of disks in the string

Mechanical Design of Overhead Line
'Insulators, suspension type'

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

Mechanical Design of Overhead Line ‘Insulators, suspension type’

- **Mathematical expressions**
  - ➢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



Mechanical Design of Overhead Line ‘Insulators, suspension type’

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

$$I_2 = I_1 + i_1$$

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

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

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

Mechanical Design of Overhead Line
‘Insulators, suspension type’

- Applying Kirchhoff’s current law to node *B*, we get,

$$I_3 = I_2 + i_2$$

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

$$V_3\omega C = V_2\omega C + (V_1 + V_2)\omega KC$$

$$V_3 = KV_1 + V_2(1 + K) = V_3 KV_1 + V_1(1 + K)^2$$

$$V_3 = V_1\left[K + (1 + K)^2\right] = V_1\left[K^2 + 3K + 1\right]$$

Mechanical Design of Overhead Line
'Insulators, suspension type'

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

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

$$\text{or } V_1 = \frac{V}{(1+K)(3+K)}$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

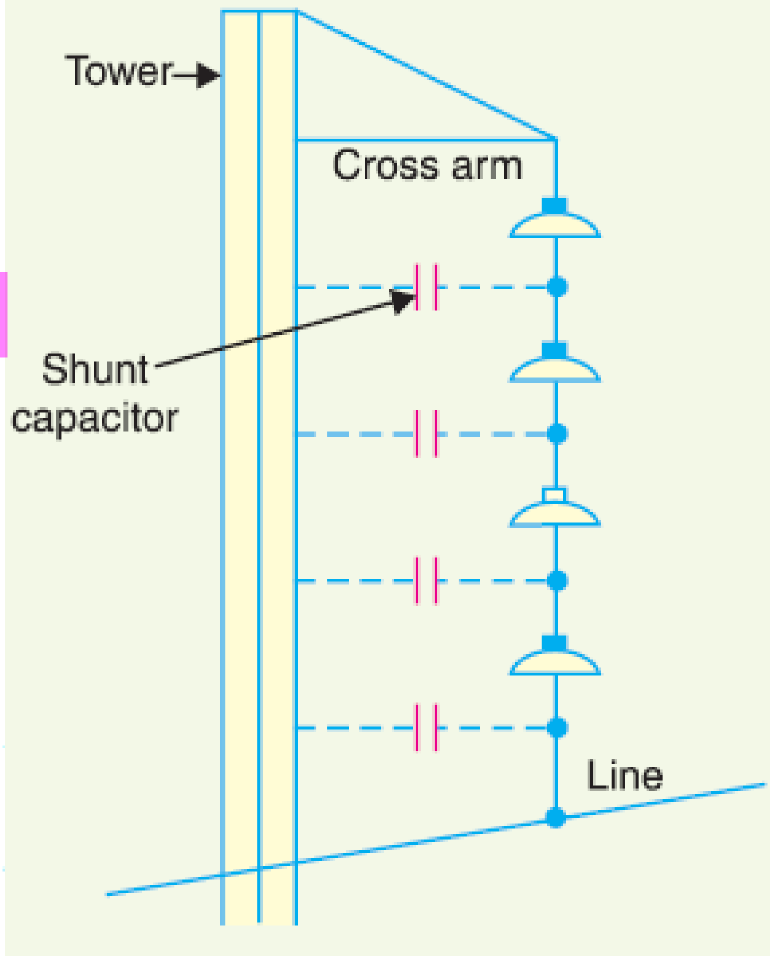
- %age string efficiency

$$\eta = \frac{V}{3V_3} = \frac{V_1\left(3+4K+K^2\right)}{3V_1\left(1+3K+K^2\right)} = \frac{3+4K+K^2}{3+9K+3K^2}$$

- The following points may be noted from the above mathematical analysis :
  - If $K = 0{\cdot}2$ (Say), 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.
  - 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.
  - 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.

Mechanical Design of Overhead Line ‘Insulators, suspension type’

- **Methods of Improving String Efficiency**
  - *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.



Mechanical Design of Overhead Line ‘Insulators, suspension type’

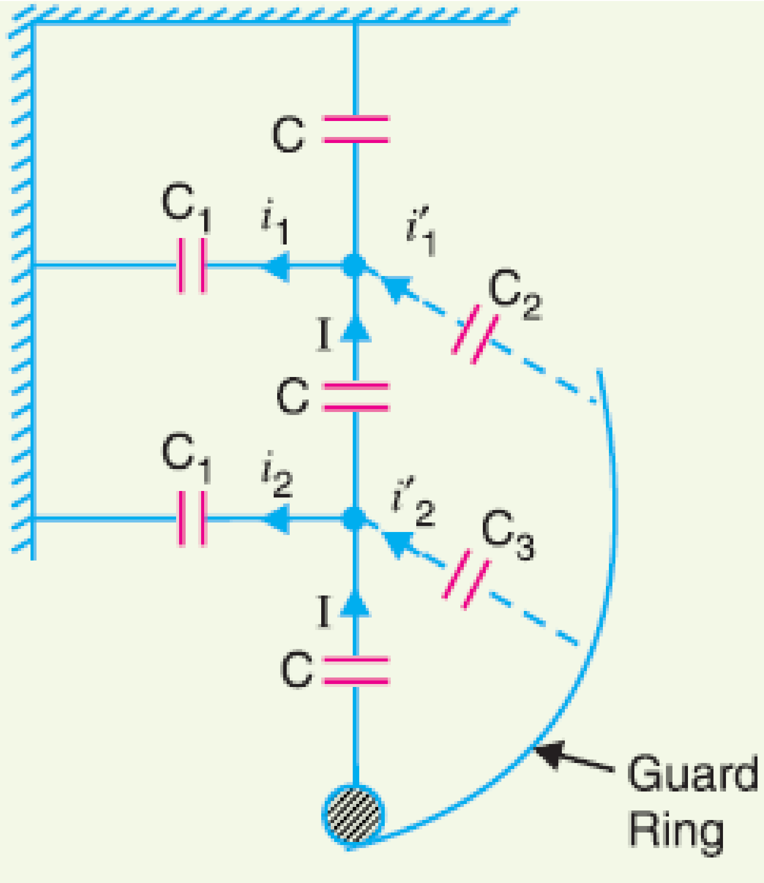
- *By grading the insulators.*
  - In this method, insulators of different dimensions are so chosen that each has a different capacitance.
  - The insulators are capacitance graded *i.e.* they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively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

Mechanical Design of Overhead Line ‘Insulators, suspension type’

- *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.

Mechanical Design of Overhead Line
'Insulators, suspension type'

- 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



Mechanical Design of Overhead Line ‘Insulators, suspension type’

Example

- 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
  (ii) The string efficiency.

Mechanical Design of Overhead Line
‘Insulators, suspension type’

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 $$V_2 = 1{\cdot}11\, V_1$$

At Junction B

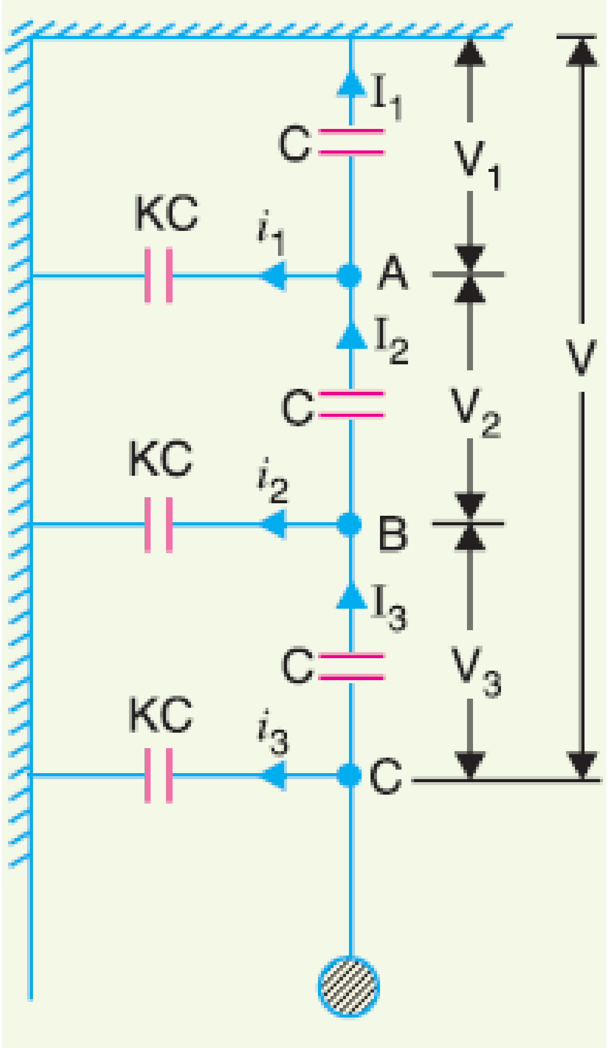
$$I_3 = I_2 + i_2$$

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

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

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

$\therefore$ $$V_3 = 1{\cdot}342\, V_1$$



Mechanical Design of Overhead Line 'Insulators, suspension type'

(*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, $V_1 = 19{\cdot}05/3{\cdot}452 = \mathbf{5{\cdot}52\ kV}$

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

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

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

Mechanical Design of Overhead Line
‘Insulators, suspension type’

Example

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.

Mechanical Design of Overhead Line
‘Insulators, suspension type’

maximum voltage will appear across the lowest unit in the string.

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

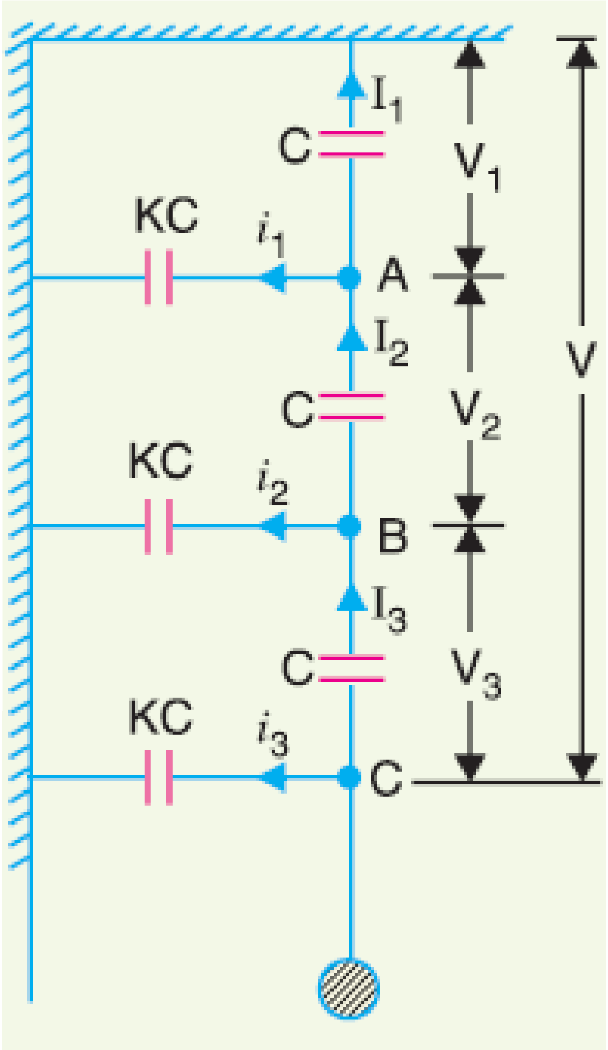
Applying Kirchhoff’s current law to junction A, we get,

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

or $\quad V_1 = V_2/(1 + K) = V_2/(1 + 0{\cdot}125) = 0{\cdot}89\ V_2$

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

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



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Mechanical Design of Overhead Line
'Insulators, suspension type'

$$\therefore \quad V_3 = 1.236\, V_2$$

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

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

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

$$\text{String efficiency} = \frac{37{\cdot}92}{3 \times 15} \times 100 = \mathbf{84{\cdot}26\ \%}$$

Mechanical Design of Overhead Line ‘Insulators, suspension type’

Example

Suspension type insulator of 5 disks is connected to a 3-phase line of voltage 33 kV. If $K = 0.1$:

(i) What is the voltage distribution over the unit of string and what will be the string efficiency

(ii) When the string is supplied by a guard ring and this leads to add two air capacitance of values 0.2 C and 0.1 C, respectively, to the nearest to the conductor. Find the new voltage distribution and the new efficiency

Mechanical Design of Overhead Line
‘Insulators, suspension type’

(i)

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

$$I_2 = I_1 + i_1$$
$$V_2\omega C = V_1\omega C + V_1\omega C_1$$
$$V_2\omega C = V_1\omega C + V_1\omega KC$$
$$V_2 = V_1(1 + K)$$

Mechanical Design of Overhead Line ‘Insulators, suspension type’

- Applying Kirchhoff’s current law to node *B*, we get,

$$I_3 = I_2 + i_2$$

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

$$V_3\omega C = V_2\omega C + (V_1 + V_2)\omega KC$$

$$V_3 = KV_1 + V_2(1+K) = V_3KV_1 + V_1(1+K)^2$$

$$V_3 = V_1\left[K + (1+K)^2\right] = V_1\left[K^2 + 3K + 1\right]$$

Mechanical Design of Overhead Line
'Insulators, suspension type'

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

$$I_4 = I_3 + i_3$$

$$V_4\omega C = V_3\omega C + (V_1 + V_2 + V_3)\omega C_1$$

$$V_4\omega C = V_3\omega C + (V_1 + V_2 + V_3)\omega KC$$

$$V_4 = V_3 + (V_1 + V_2 + V_3)K$$

$$V_4 = (1 + 3K + K^2)V_1 + ((1) + (1 + K) + (1 + 3K + K^2))KV_1$$

$$V_4 = (1 + 6K + 5K^2 + K^3)V_1$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

- Applying Kirchhoff’s current law to node *D*, we get,

$$I_5 = I_4 + i_4$$

$$V_5 \omega C = V_4 \omega C + (V_1 + V_2 + V_3 + V_4)\omega C_1$$

$$V_5 \omega C = V_4 \omega C + (V_1 + V_2 + V_3 + V_4)\omega KC$$

$$V_5 = V_4 + (V_1 + V_2 + V_3 + V_4)K$$

$$V_4 = (1 + 6K + 5K^2 + K^3)V_1 + ((1) + (1 + K) + (1 + 3K + K^2) + (1 + 6K + 5K^2 + K^3))KV_1$$

$$V_4 = (1 + 10K + 15K^2 + 7K^3 + K^4)V_1$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

- String voltage,

$$V = V_1 + V_2 + V_3 + V_4 + V_5$$

$$V = (1)V_1 +$$

$$+ (1 + K)V_1 +$$

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

$$+ (1 + 6K + 5K^2 + K^3)V_1 +$$

$$+ (1 + 10K + 15K^2 + 7K^3 + K^4)V_1 +$$

$$V = (5 + 20K + 21K^2 + 8K^3 + K^4)V_1$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

$$V_1 = \frac{V}{5 + 20K + 21K^2 + 8K^3 + K^4} =$$

$$= \frac{33/\sqrt{3}}{5 + 20\times 0.1 + 21\times 0.1^2 + 8\times 0.1^3 + 0.1^4} = 2.63\,\text{kV}$$

Mechanical Design of Overhead Line
'Insulators, suspension type'

- Voltage distribution and efficiency

$$V_1 = (1)V_1 = 2.63\,\text{kV}$$

$$V_2 = (1+K)V_1 = 2.89\,\text{kV}$$

$$V_3 = (1+3K+K^2)V_1 = 3.44\,\text{kV}$$

$$V_4 = (1+6K+5K^2+K^3)V_1 = 4.34\,\text{kV}$$

$$V_5 = (1+10K+15K^2+7K^3+K^4)V_1 = 5.67\,\text{kV}$$

$$\eta = \frac{V}{5V_5} = \frac{33/\sqrt{3}}{5\times 5.67} = 67.22\%$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

(ii)

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

$$I_2 = I_1 + i_1$$

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

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

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

$$V_2 = 1.1V_1$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

- Applying Kirchhoff’s current law to node *B*, we get,

$$I_3 = I_2 + i_2$$

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

$$V_3\omega C = V_2\omega C + (V_1 + V_2)\omega KC$$

$$V_3 = KV_1 + V_2(1+K) = V_3KV_1 + V_1(1+K)^2$$

$$V_3 = V_1\left[K + (1+K)^2\right] = V_1\left[K^2 + 3K + 1\right]$$

$$V_3 = 1.31V_1$$

Mechanical Design of Overhead Line ‘Insulators, suspension type’

- Applying Kirchhoff’s current law to node *C*, we get,

$$V_4 = V_3 + (V_1 + V_2 + V_3)K + (V_1 + V_2 + V_3 - V)0.1$$

$$V_4 = 1.31V_1 + (V_1 + 1.1V_1 + 1.31V_1)0.1 + (V_1 + 1.1V_1 + 1.31V_1 - V)0.1$$

$$V_4 = 1.31V_1 + 0.1V_1 + 0.11V_1 + 0.131V_1 + 0.1V_1 + 0.11V_1 + 0.131V_1 - 0.1V$$

$$V_4 = 1.992V_1 - 0.1V$$

Mechanical Design of Overhead Line ‘Insulators, suspension type’

- Applying Kirchhoff’s current law to node *D*, we get,

$$V_5 = V_4 + \left(V_1 + V_2 + V_3 + V_4\right)K + \left(V_1 + V_2 + V_3 + V_4 - V\right)0.2$$

$$V_5 = \left(2.333V_1 - 0.2V\right) + \left(V_1 + 1.1V_1 + 1.31V_1 + 2.333V_1 - 0.2V\right)0.1 +$$

$$+\left(V_1 + 1.1V_1 + 1.31V_1 + 2.333V_1 - 0.2V - V\right)0.2$$

$$= 3.6126V_1 - 0.33V$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

- String voltage

$$V = V_1 + V_2 + V_3 + V_4 + V_5$$

$$V = (1)V_1 +$$

$$+(1.1)V_1 +$$

$$+(1.31)V_1 +$$

$$+1.992V_1 - 0.1V +$$

$$+3.6126V_1 - 0.33V$$

$$V = 9.0146V_1 - 0.43V$$

$$V = 6.304V_1$$

Mechanical Design of Overhead Line
'Insulators, suspension type'

$$V_1 = \frac{V}{6.304} = \frac{33/\sqrt{3}}{6.304} = 3.02 \text{ kV}$$

Mechanical Design of Overhead Line
‘Insulators, suspension type’

- Voltage distribution and efficiency

$$V_1 = (1)V_1 = 3.01\ \text{kV}$$

$$V_2 = (1.1)V_1 = 3.31\ \text{kV}$$

$$V_3 = (1.31)V_1 = 3.94\ \text{kV}$$

$$V_4 = 1.992V_1 - 0.1V = 4.09\ \text{kV}$$

$$V_5 = 3.6126V_1 - 0.33V = 4.61\ \text{kV}$$

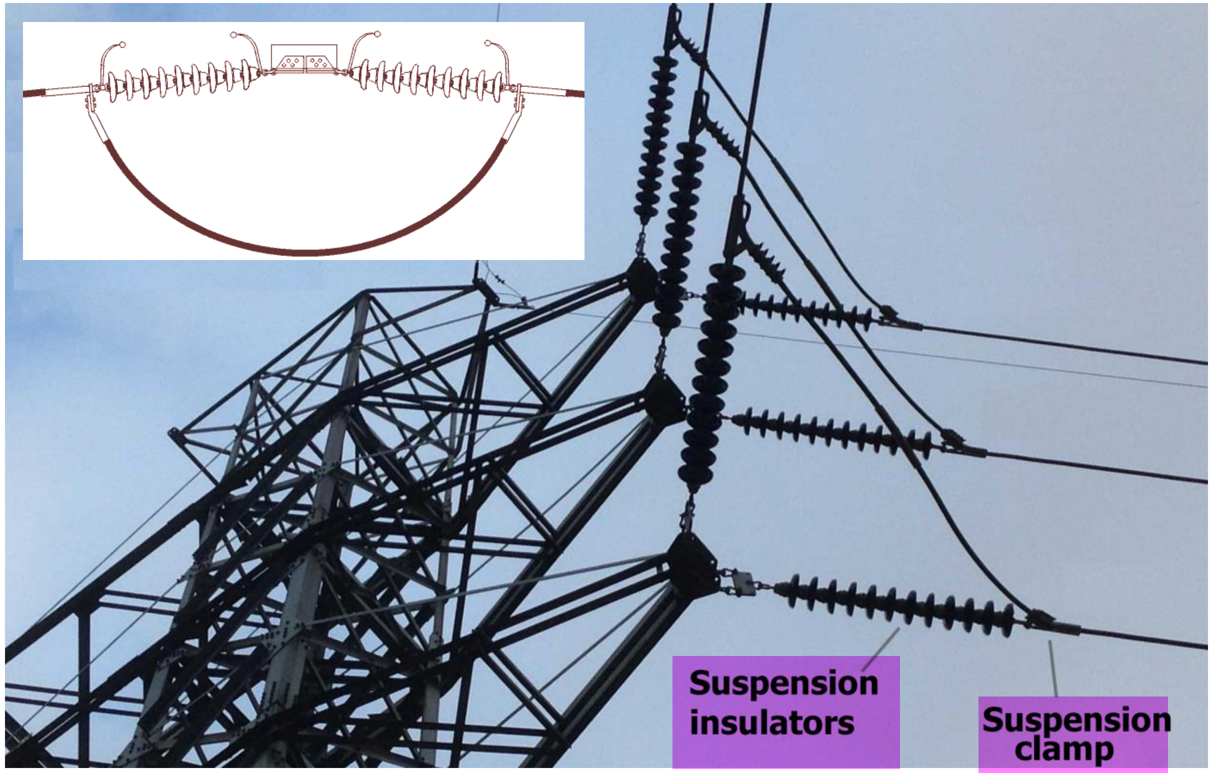
$$\eta = \frac{V}{5V_5} = \frac{33/\sqrt{3}}{5 \times 4.61} = 82.74\%$$

Mechanical Design of Overhead Line
‘Insulators, Post-type’

- Post-type insulators are used for medium- and low-voltage transmission lines, where insulators replace the cross-arm.
- However, the majority of post insulators are used in substations where insulators support conductors, bus bars, and equipment
- This type of insulator can be mounted on supporting structure horizontally as well as vertically.

Mechanical Design of Overhead Line ‘Insulators, Strain’

- They may be either post or suspension type
- These insulators are used on dead-end towers at bends or corners of transmission lines, or when making very long spans



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Mechanical Design of Overhead Line
'Insulators, Shackle'

- The insulator can be directly fixed to the pole with a bolt or to the cross arm
- They are mounted in a clamp
- The conductor in the groove is fixed with a soft binding wire
- They are used for low voltage distribution lines