SUBJECT:- POWER SYSTEMS-I

Code:- EEC 401

Departmental Core Subject

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Semester:- B.Tech 4^{th} , EE

Chapter- Insulators

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Reference

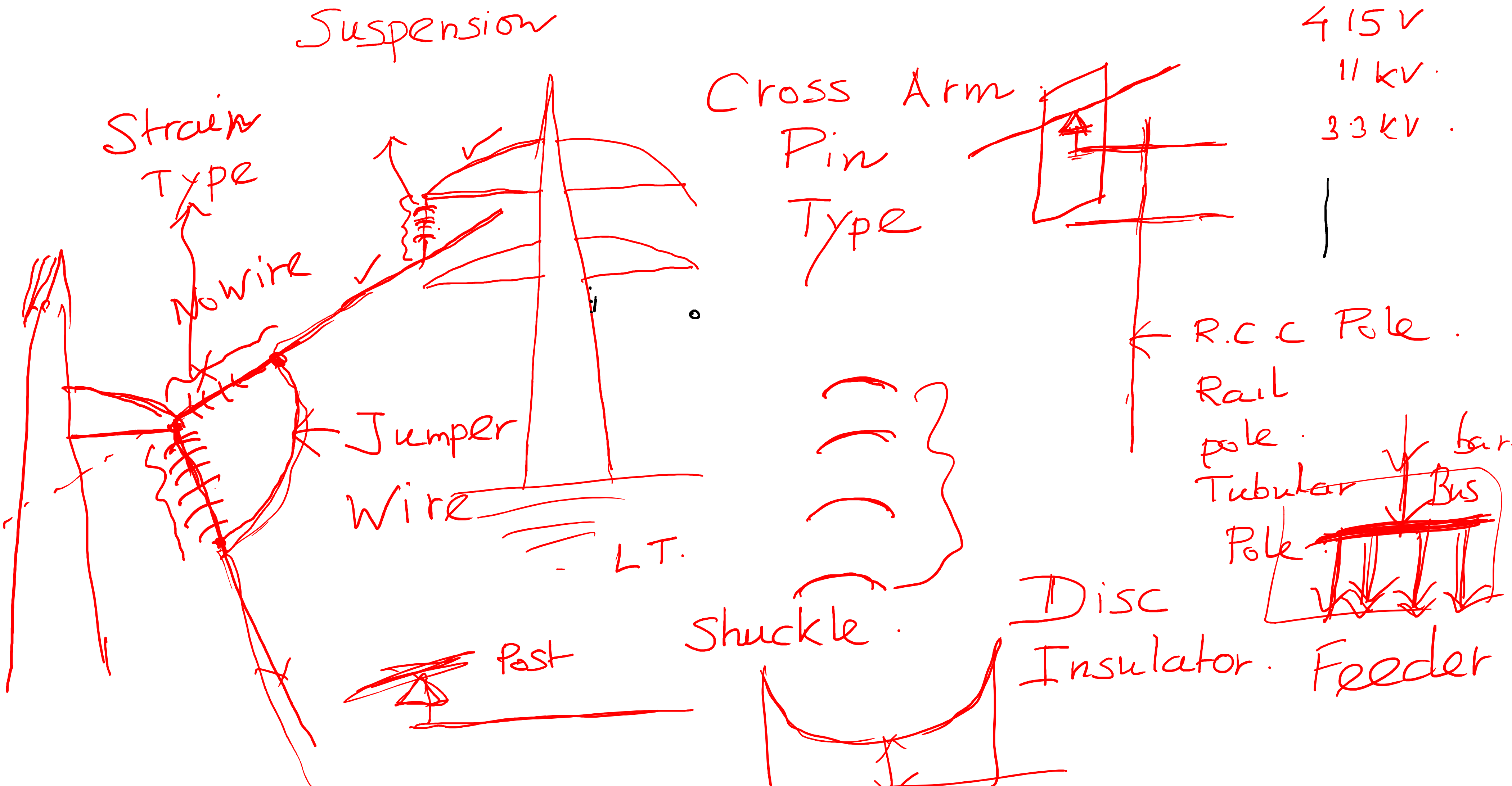
1. IJ Nagrath & DP Kothari, “**Power System Engineering**”, McGraw-Hill Publisher, 3rd Edition 2019.
2. V.K. Meheta & Rohit Meheta, Principles of Power System, 4th Revised Edition, S.Chand & Company Limited.

Line Insulators

Syllabus:-types of insulators for low voltage, high voltage and extra high voltage lines and outdoor switchyard, bushing insulators, voltage distribution in a string of suspension insulators, methods of potential equalization; arching horns and grading rings, reasons of overhead line insulator failure, puncture and flashover voltage, design criteria.

After reading this chapter, the students should be able to:

- calculate voltage distribution in string insulators and string efficiency, necessary for safe operation of the systems.
- learn the use of guard ring to improve the voltage distribution along string of suspension type insulators.
- understand the use of arcing horns for protection of insulator strings against flashovers.


Suspension
Strain Type
Nowire
Jumper Wire
L.T.
Cross Arm Pin Type
415 V
11 kV
33 kV
R.C.C Pole
Rail pole
Tubular Pole
Bus
Shuckle
Post
Disc Insulator
Feeder

Introduction:-

$C \propto \epsilon$

- The overhead line conductors must be properly insulated from supports.
- This is achieved by securing line conductors to supports with the help of *insulators*.
- The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth.
- In general, the insulators should have the following desirable properties:
  - **High mechanical strength in order to withstand conductor load, wind load etc.**
  - **High electrical resistance of insulator material in order to avoid leakage currents to earth.**
  - **High relative permittivity of insulator material in order that dielectric strength is high.**
  - **The insulator material should be non-porous, free from impurities and cracks otherwise the permittivity will be lowered.**
  - **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.

Types of Insulators:-

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

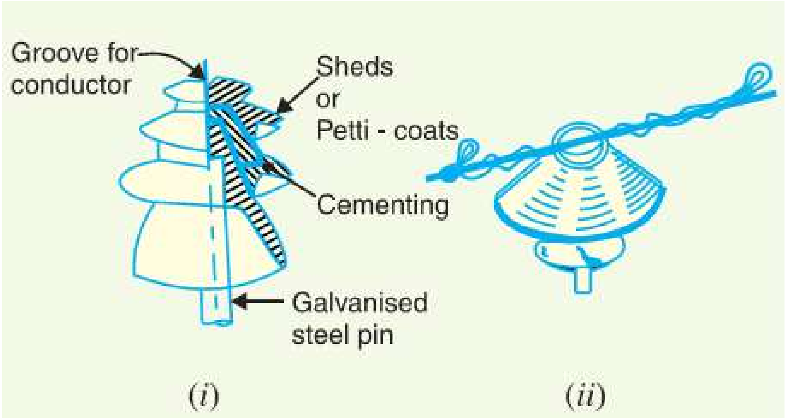


Figure 1

Pin type insulators:- The part section of a pin type insulator is shown in Figure 1. As the name suggests, the pin type insulator is secured to the cross-arm on the pole.

There is a groove on the upper end of the insulator for housing the conductor.

The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor [See Figure 1 (*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.

Types of Insulators:-

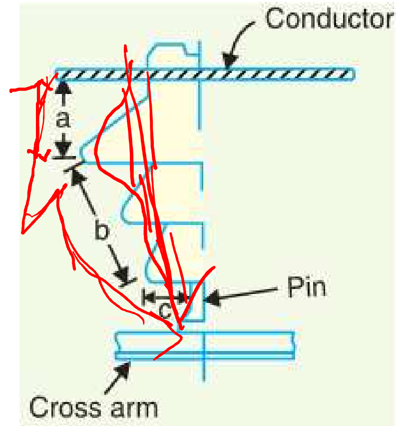


Figure 2

- Figure 2 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.
- 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 flashover voltage is known as safety factor *i.e.,*

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

- 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.

Types of Insulators:-

TP V T $I^2 R$

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. 3.

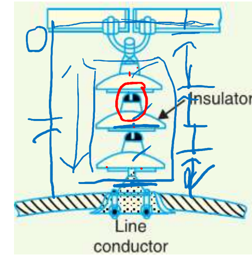


Figure 3

- 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.

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.

Types of Insulators:-

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. 4.

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.

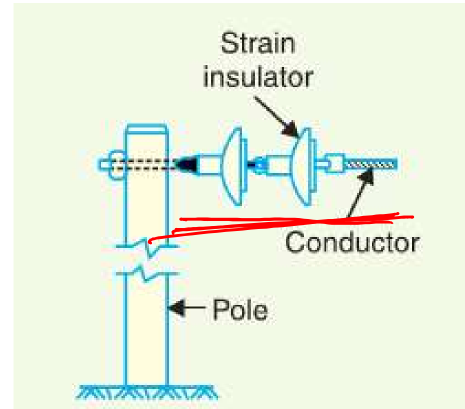


Figure 4

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. 5 shows a shackle insulator fixed to the pole.

The conductor in the groove is fixed with a soft binding wire.

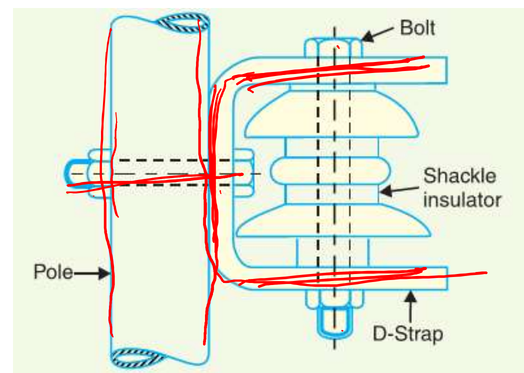


Figure 5

Potential Distribution over Suspension Insulator String:-

Arcing Horn

$V_3 > V_2 > V_1$

$V_3 \neq V_2 \neq V_1$

- A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links.
- Fig. 6 (*i*) shows 3-disc string of suspension insulators. The porcelain portion of each disc is in between two metal links.
- Therefore, each disc forms a capacitor C as shown in Fig. 6 (*ii*).
- This is known as *self-capacitance*.
- If there were self 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. 6(*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. 6 (*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. 6(*iii*), V_3 will be much more than V_2 or V_1.

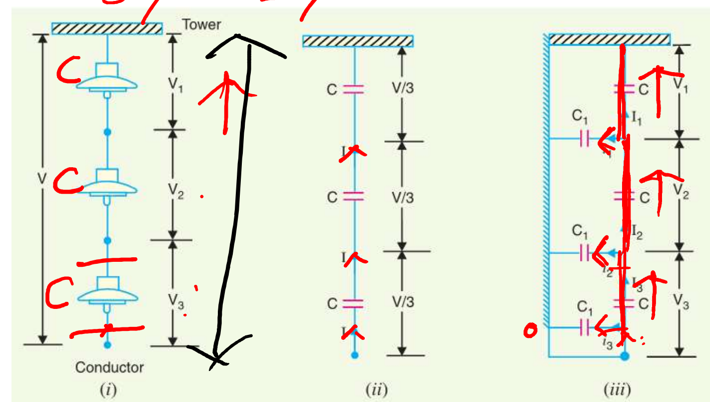
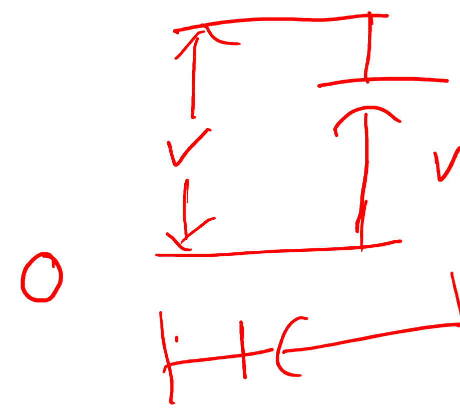
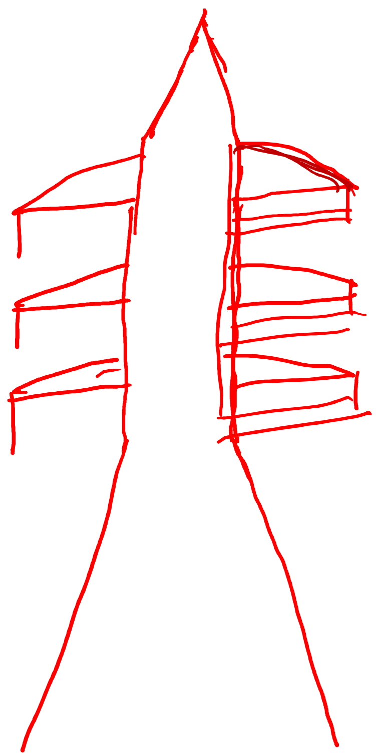
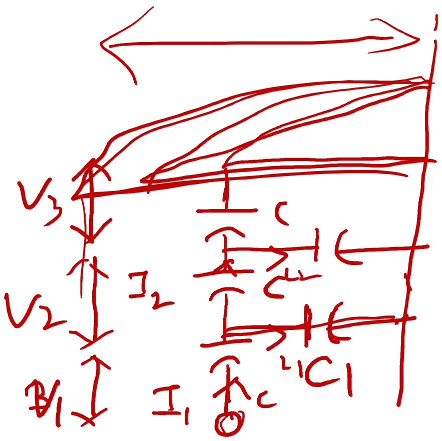


Figure 6



$V = \frac{I}{\omega C}$





$$V = \frac{1}{\omega C}$$

$i_1 \to 0$

$i_2 \to 0$

$$V_1 \gtrsim V_2 \gtrsim V_3$$

$$I_2 = I_1 - \boxed{i_1} \uparrow$$

$$I_2 \ll I_1$$

$$I = V \cdot \omega C_1$$

$$C_1 \downarrow \propto \frac{1}{d \uparrow}$$

$\frac{1}{\omega C} = \infty \qquad f = 0 \qquad > \underline{4\ mA}$

Potential Distribution over Suspension Insulator String:-

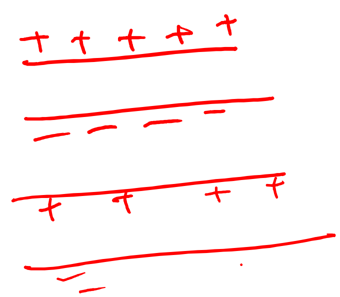
- The following points may be noted regarding the potential distribution over a string of suspension insulators:

(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.

(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.



String Efficiency:-

- The voltage applied across the string of suspension insulators is not uniformly distributed across various units or 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.,*

$$String\ efficiency\ =\ Voltage\ across\ the\ string / (n\ \times\ Voltage\ across\ disc\ nearest\ to\ conductor)$$

where n = number of discs in the string.

- String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution.
- Thus 100% string efficiency is an ideal case for which the voltage across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts are made to improve it as close to this value as possible.
- Fig. 7 shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C_1 is some fraction K of self capacitance *i.e.,* $C_1 = KC$.
- Starting from the cross-arm or tower, the voltage across each unit is V_1, V_2 and V_3 respectively as shown.
- Applying Kirchhoff's 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 $V_2\omega C = V_1\omega C + V_1\omega KC$

$$\boxed{\therefore V_2 = V_1(1+K)}$$

$\boxed{C_1 = KC}$

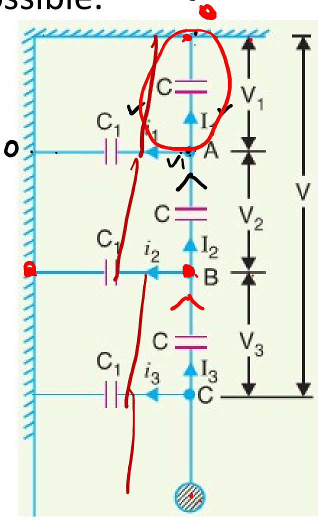


Figure 7

String Efficiency:-

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

$k = \frac{C_1}{C}$

Voltage Across the String phase voltag

$k = \frac{C_1}{C}$

$$I_3 = I_2 + i_2$$
$$or\ V_3\omega C = V_2\omega C + (V_1 + V_2)\omega C_1$$
$$or\ V_3\omega C = V_2\omega C + (V_1 + V_2)\omega KC$$
$$or\ V_3 = V_2 + (V_1 + V_2)K = KV_1 + V_2(1 + K)$$
$$= KV_1 + V_1(1 + K)2\ [As\ V_2 = V_1(1 + K)]$$
$$= V_1[K + (1 + K)2]$$
$$\therefore V_3 = V_1[1 + 3K + K^2]$$

$V_2 = V_1(1+k)$

$V = V_{ph}$

V_3

$Voltage\ between\ conductor\ and\ earth (i.e., tower)\ is\ V = V_1 + V_2 + V_3$
$$= V_1 + V_1(1 + K) + V_1(1 + 3K + K^2) = V_1(3 + 4K + K^2)$$
$$\therefore V = V_1(1 + K)(3 + K)$$

V_3

$From\ expressions, we\ get,$

$$Voltage\ across\ top\ unit, V_1 = \frac{V_1}{1} = \frac{V_2}{(1+K)} = \frac{V_3}{(1+3K+K^2)} = \frac{V}{(1+K)(3+K)}$$

$(3+4k+k^2)$

$Voltage\ across\ second\ unit\ from\ top, V_2 = V_1(1 + K)$
$Voltage\ across\ third\ unit\ from\ top, V_3 = V_1(1 + 3K + K^2)$

$$\%age\ String\ efficiency = \frac{Voltage\ across\ String}{n \times Voltage\ across\ disc\ nearest\ to\ the\ conductor} \times 100 = \frac{V}{n \times V_3} \times 100$$

$$\frac{V_3\left[\frac{3+4k+k^2}{1+3k+k^2}\right]}{3 \times V_3} \qquad \frac{V_1(3+4k+k^2)}{3 \times V_3} \qquad = \frac{3+4k+k^2}{3(1+3k+k^2)} \times 100\ \%$$

String Efficiency:-

LV → LT   EHV → EHT

HV → HT

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

(i) If K = 0·2 (Say), then 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 is 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.

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

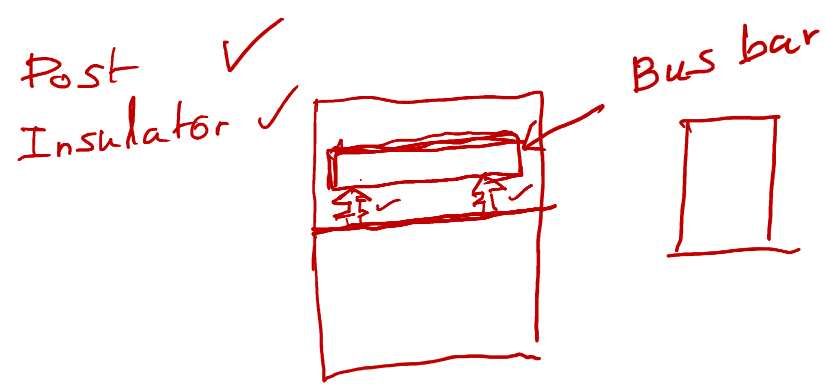
(i) The maximum voltage appears across the disc nearest to the conductror (*i.e.,* line conductor).

(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

Problem:- *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.*



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:
  - ***By using longer cross-arms*:-** The value of string efficiency depends upon the value of K *i.e.*, ratio of shunt capacitance to self 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.

Methods of Improving String Efficiency:- $\frac{1}{\omega C}$ ①

$I \propto V\omega C$

$V = \frac{1}{\omega C} I$

- ***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.
- ***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.
- 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.

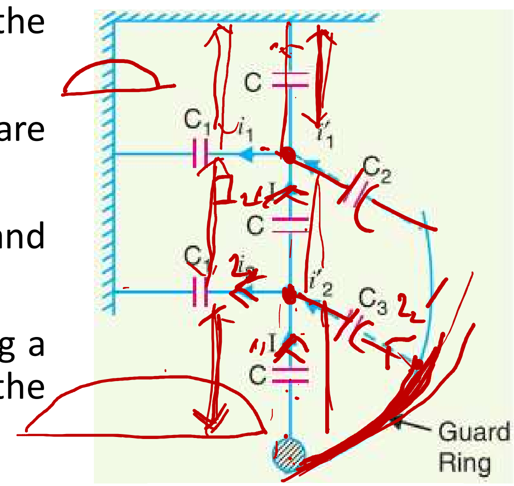


Figure 8

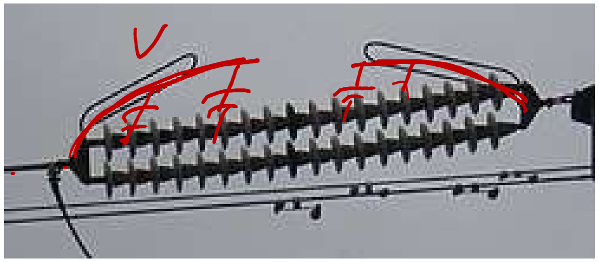
$I_3 + \cancel{i_2} = \cancel{i_2} + I_2$

$I_3 = I_2$

Arcing Horn:-

$\frac{dV}{dx} \to E.F \to DS > DE.S_{Air}$

- Arcing horns form a spark gap across the insulator with a lower breakdown voltage than the air path along the insulator surface.
- So an overvoltage will cause the air to break down and the arc to form between the arcing horns, diverting it away from the surface of the insulator.
- An arc between the horns is more tolerable for the equipment, providing more time for the fault to be detected and the arc to be safely cleared by remote circuit breakers.
- The geometry of some designs encourages the arc to migrate away from the insulator, driven by rising currents as it heats the surrounding air.
- As it does so, the path length increases, cooling the arc, reducing the electric field and causing the arc to extinguish itself when it can no longer span the gap.
- Other designs can utilise the magnetic field produced by the high current to drive the arc away from the insulator.
- This type of arrangement can be known as a magnetic blowout.



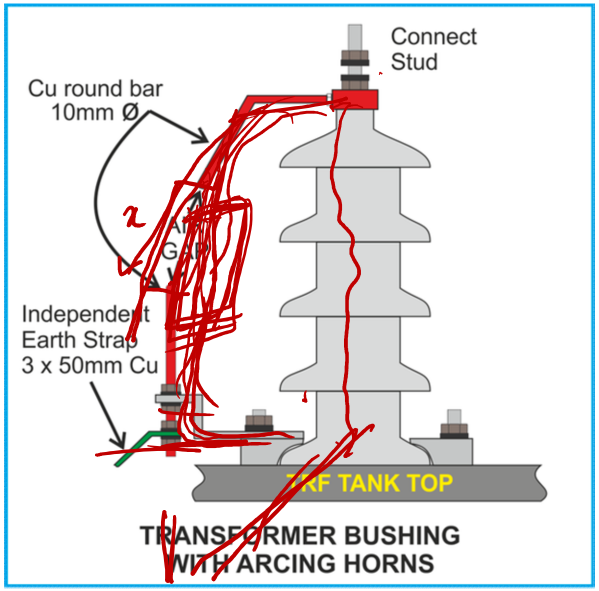
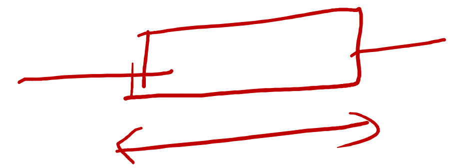


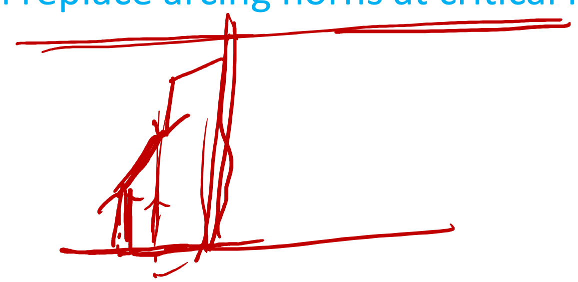
Figure 8

Arcing Horn:-

$\downarrow R \propto \frac{1}{V \uparrow}$

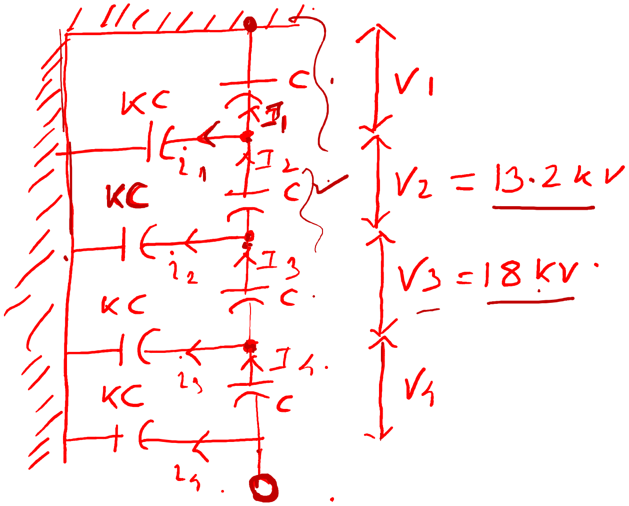


- As operating voltages increase, greater consideration must be given to such design principles. At medium voltages, one of the two horns may be omitted as the horn-to- horn gap can otherwise be small enough to be bridged by an alighting bird.
- Alternatively, duplex gaps consisting of two sections on opposite sides of the insulator can be fitted.
- Low voltage distribution systems, in which the risk of arcing is much lower, may not use arcing horns at all.
- The presence of the arcing horns necessarily disturbs the normal electric field distribution across the insulator due to their small but significant capacitance.
- More importantly, a flashover across arcing horns produces an earth fault resulting in a circuit outage until the fault is cleared by circuit breaker operation.
- For this reason, non-linear resistors known as varistors can replace arcing horns at critical locations.



Problem:-*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.*

$$\frac{V_1+V_2+V_3+V_4}{4\times V_4}\times 100\%$$



$I_2 = I_1 + i_1$

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

13.2 $\quad V_2 = V_1(1+k)$ — (1) $\quad V_1 = 21$

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

$V_3 = V_2(1+k) + V_1 k$

$V_3 = V_1[1+3k+k^2]$ — (2)

(1)/(2)

$$\frac{13.2}{18} = \frac{1+k}{1+k^2+3k}$$

$(k^2+3k+1) = \frac{18}{13.2}(1+k)$

$k^2 + 1.6363k - 0.363 = 0$

$k = 0.1979$

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

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

$V_4 = 26.3552\,kV$

$V = V_1+V_2+V_3+V_4$

$= 68.5744\,kV \quad 69\,kV$

$V_{Line} = \sqrt{3}V$

$= 118.7743\,kV$

$V_1 = 11.0792\,kV$

1st disc $= \frac{V_1}{V_L}\times 100\%$
$= 9.2774\%$

2nd disc $= \frac{V_2}{V_L}\times 100\%$
$= 11.1135\%$

3rd disc $= \frac{V_3}{V_L}\times 100\%$
$= 15.1547\%$

4th disc $= \frac{V_4}{V_L}\times 100\%$
$= 22.189\%$

1st $= \frac{V_1}{V}\times 100\%$
$= 16.1769\%$

2nd $= \frac{V_2}{V}\times 100\%$
$= 19.249\%$

3rd $= \frac{V_3}{V}\times 100\%$
$= 26.2488\%$

4th $= 38.433\%$