CHAPTER II.

INSULATORS FOR OVERHEAD LINES.

2.1 Material.[8]

The insulators used in connection with overhead systems employing bare conductors are composed almost invariably of glazed porcelain, although some moulded materials are used for low voltage, and glass has been used in the European Continent and in America for medium voltages. The British Standard Specification gives particulars of porcelain only, and requires that " the porcelain shall be ivory white, sound, free from defects, and thoroughly vitrified so that the glaze is not depended upon for insulation". This thorough vitrification of the pocelain is of paramount importance, since the presence of pores or other airspaces will lower the dielectric strength. Any sealed-in impurities will also decrease the dielectric strength, and it therefore follows that porcelain for electrical purposes must be both thoroughly air - free and impervious to the entrance of gases and liquids. Apart from the above requirement, electrical porcelain is

---

[8] H. Cotton, The transmission and Distribution of Electrical Energy. (London: The English Universities Press Ltd, 1958) pp 164 - 165.

practically identical with the pottery which has come down to us through the ages, since the obvious requirement of high dielectric strength is inherent in all porcelain which is homogeneous, and free from impurities. The dielectric strength of mechanically sound porcelain is of the order of 15,000 to 17,000 volts for every one - tenth inch thickness. Actually, it is very difficult to manufacture perfectly homogeneous porcelain of a thickness required for certain types of insulator, and it is then necessary to adopt a two or three pieces construction, the various pieces being fixed and glazed separately and then cemented together.

Very sound insulators are made from glass, its advantages being the very high dielectric strength of 35,000 volts per one- tenth inch thickness, and the possibility of adopting a one piece design, no matter how large the insulator may be . It has also a lower coefficient of themal expansion which minimices the strains due to temperature changes, is transparent to heat rays, thereby heating up but slightly when exposed to sunlight, and is mechanically stronger than porcelain when under compression. In tension it has about the same strength as porcelain. The disadvantages of glass are that moisture more rapidly condenses on the surface, and that in large size the great mass of material, combined with the irregular shape, may result in internal strains after cooling. Under ordinary atmospheric conditions toughened glass is therefore limited to about 30,000 volts, while in dry climates it can be used up to 50,000 volts.

2.2 Types and Feature.

There are three types used in connection with overhead lines:

1) Pin type.
2) Suspension type.
3) Strain type.

2.2.1 Pin Insulators.

The definition is specified in ASA American Standard Insulator Test, C 29.1 - 1961; a pin insulator is an insulator having means for rigid mounting on a separable pin.

The pin type insulator is attached to a steel bolt or pin which is secured to a cross - arm on the transmission pole. According to the British Standards Specification requires that the porcelain shall not engage directly with a hard metal screw. B.S. 137 recognises two methods:

1) The provision of a taper thread cut on the head of pin which screws into a threaded soft metal thimble cemented into the insulator.

2) The provisions of a cast lead thread on the steel spindle which screws directly into a thread formed in the porcelain; on the continent the pin, which has a plain top, is still sometimes wrapped with hemp and the threaded porcelain screwed on.

For operating voltages up to about 25,000 with ordinary designs of insulator a one piece construction can be adopted, up to about 45,000 volts a two piece, up to 66,000 volts a three piece, and beyond this a four piece insulator. Actually, the tendency is to use pin type insulators for voltages up to 50,000 volts only, since they become uneconomical for higher voltages.

2.2.2 Leakage and Arcing Distance of Insulators.

The leakage distance is obtained by measuring the path of the insulator as shown by line A in Fig. 2.1(a). The length of the leakage path alone does not represent the surface resistance of an insulator since the width, which varies, must also be taken into consideration.

The distance necessary to cause an insulator to arc from wire to pin can be closely approximated by measuring the insulator as shown in Fig.2.1 (b) for dry

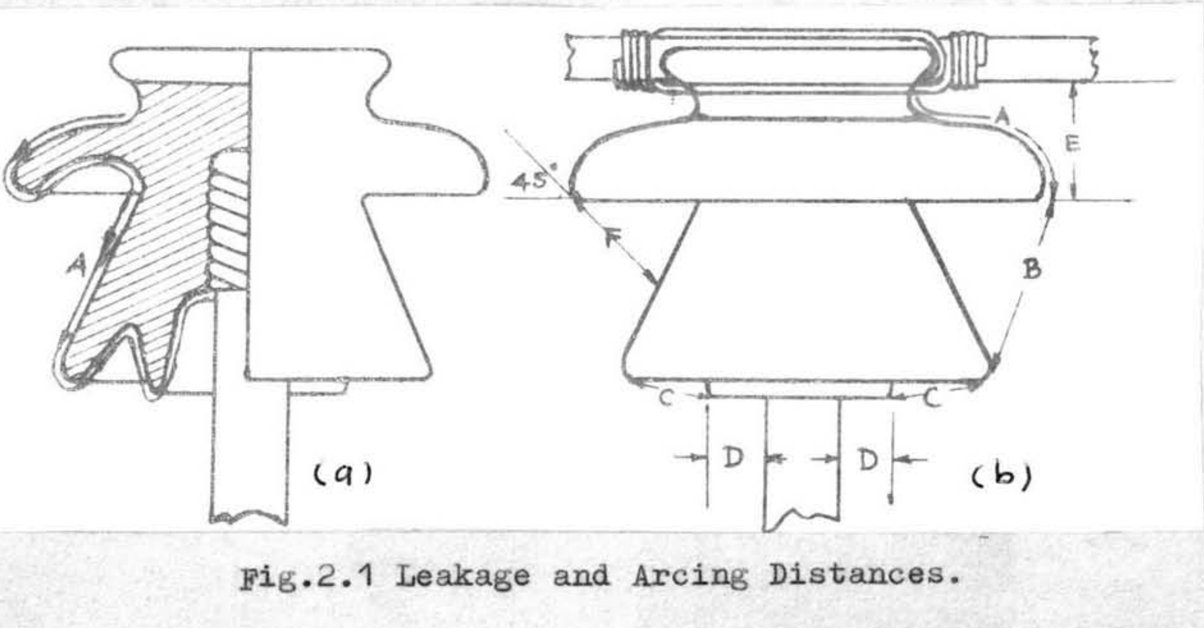

Fig.2.1 Leakage and Arcing Distances.

In Fig.2.1(b) the dry arcing distance= A or E (shortest distance) plus B, C and D; and the wet arcing distance = F+C+D with the precipitation at 45° from the vertical.

Porcelain insulators of ordinary design arc over at some where about 10,000 volts per inch, so that if the sum of distances A + B + C + D , dry, were 10 in., the insulator would arc over at about 100,000 volts.

Recent researchs on dielectrics has shown that thickness of insulation and length of sparking distance are not the only factors which decide the electrical performance of an insulator, but that the distribution of electrostatic tubes of force and equipotential surfaces is also of considerable importance in deciding corona formation and flashover voltage . Researches carried out by Gilchrist and Klinefer have shown that the various sheds should be shaped so as to conform as closely as possible to the equipotential surfaces, that the body should be shaped so as to conform to the electrostatic tubes of force, that the leakage resistance of the various sheds should be approximately equal and that the capacitance of the various sheds should be approximately equal.

Fig. 2.2.

Features of High - Voltage Pin Insulator.

2.2.3 Suspension Insulators.

As ASA C29.1 - 1961 specified definition of suspension insulator is an assembly of one or more suspension insulator units, having means for nonrigidly supporting electrical conductors.

Owing to the cost of a pin type insulator increases very rapidly as the working voltage is increased. For high voltages the pin type is therefore uneconomical, and there is the further disadvantage that replacements are expensive. By these reasons high voltage lines are insulated by means of suspension insulators. Several important advantages follows from this system.

1) Each insulator is designed for a comparatively low working voltage, usually about 11,000 volts, and the insulation for any required line voltage can be obtained by using a " string " of a suitable number of such insulators.

2) In the event of failure of an insulator, one unit, instead of the whole string, has to be replaced.

3) The mechanical stresses are reduced, since the line is suspended flexibly; with pin-type insulators the rigid nature of the attachment results in fatigue and ultimate brittleness of the wire, due to the alternating nature of the stress. Also since the string is free to swing there is an equalisation of the tensions in the conductors of successive spans.

4) In the event of an increase in the operating voltage of the line, this can be met by adding the number of units to each string, instead of replacing all insulators, as would be necessary with the pin type.

There are several types of suspension insulator, that illustrated in Fig. 2.3 being most frequently used in this country and other countries. It will be seen that it consists of a single disc-shaped piece of porcelain grooved on the surface to increase the surface leakage path, and to a metal cap at the top, and to a metal pin underneath. The cap is recessed so as to take the pin of another unit, and in this way a string of any required number of units can be built up. The cap is secured to the insulator by means of cement. The usual diameter of this type of insulator is 10 inches, since it has been found that this size gives a suitable ratio of spark over to puncture voltage. Increasing the diameter increases the spark-over voltage, of course, but it lowers the above ratio and this is undesirable.

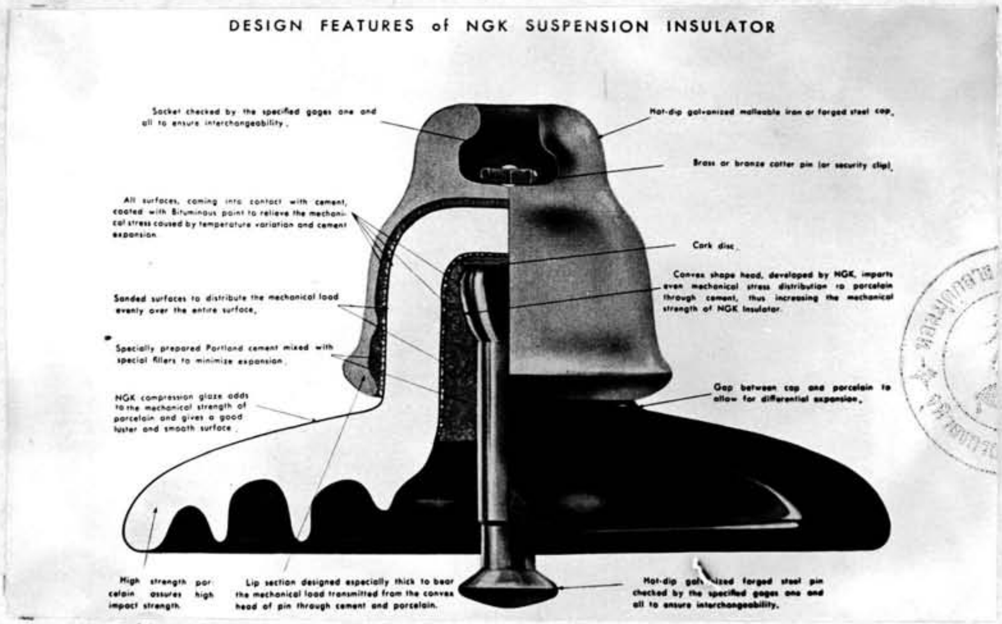

Fig. 2.3

Features of a suspension insulator.

2.2.4 Strain Insulator.

By definition of ASA C 29.1 - 1961, a strain insulator is an insulator generally of elongated shape, with two transverse hole or slots. These insulators are used to take the tension of the conductors at line terminals and at points where the line is deadended , as for example some road-crossing junctions of overhead lines with cables, at angle towers where there is a change in direction of the line and so on. For light low voltage lines, say up to 11,000 volts, the shackle insulator is suitable, but for higher voltages a string of suspension-type insulators is necessary.

The suspension type insulator is used as strain insulators the discs are in a vertical instead of a horizontal plane . This may make some difference to the spark-over voltage, wet, the value for the standard ten inch insulator being 55,000 volts.

2.3 Potential Distribution over a String of Suspension Insulators.

If all the units of suspension insulators in a string are identical and could be situated so far from neighboring metal work that the capacitances between this metal work and the metal of the insulators would be neglibly small in comparision with the capacitance of each unit, then the potential difference applied to the whole string would be divided equally between the various units. The capacitance of each unit is sometimes called the " mutual capacity." In practice this condition is not fulfilled because of the nearness of the tower, the cross-arm, and the line, and we shall see that these aditional capacitances have an important effect in proportioning the potential difference between the units. Denoting the spark-over voltage by S.O.V. we have for a string of n insulators

$$\text{String efficiency} = \frac{\text{S.O.V. for n insulators}}{\text{nx S.O.V. for one insulator.}}$$

This efficiency is generally higher for wet than for dry flash - over, except for a small number of units in the string; it also depends on the ratio.

$$\frac{\text{Capacity per insulator}}{\text{Capacity to earth}}$$

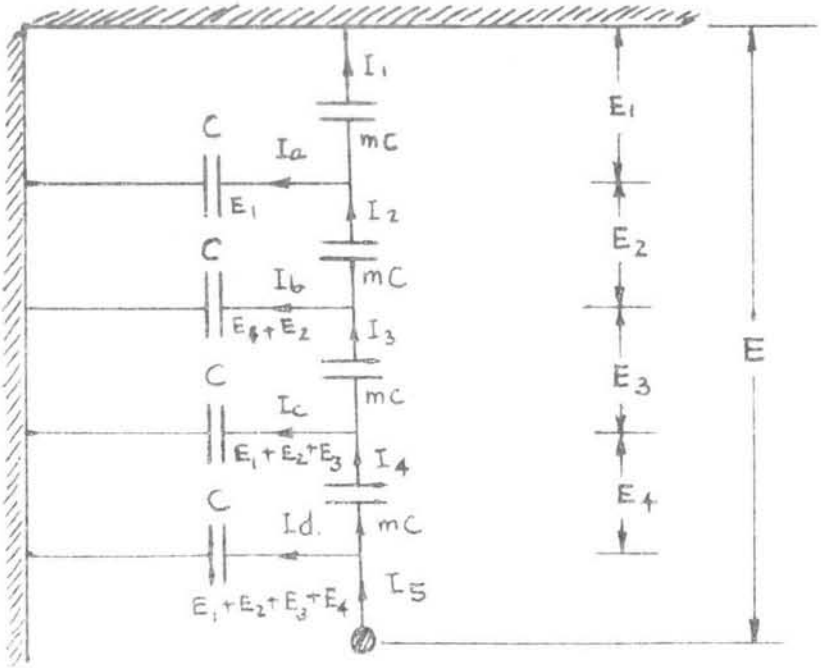

Fig. 2·4. Capacitance of a String of Suspension Insulators.

Fig. 2.4 shows a string of suspension insulators with the circuit diagram of capacitances. It will be seen that the mutual capacitances of the various units are in series between line and ground, while the capacities to ground act in the manner of a series of shunts to ground. The performance is thus dependent on the ratio

$$m \equiv \frac{\text{mutual capacitance}}{\text{capacitance to ground}}$$

$$\begin{aligned}
\text{Let } C &= \text{capacitance to ground} \\
\therefore mC &= \text{mutual capacitance} \\
I_1 &= wCmE_1 \\
I_a &= wCE_1 \\
I_2 &= I_1 + I_a \\
&= wCE_1(1 + m) \\
\therefore E_2 &= \frac{I_2}{wCm} \\
&= E_1 \cdot \frac{m+1}{m} \\
&= E_1\left(1 + \frac{1}{m}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.1)
\end{aligned}$$

The voltage producing the current I_b

$$\begin{aligned}
E_1 + E_2 &= E_1\left(1 + \frac{m+1}{m}\right) \\
&= E_1 \cdot \frac{2m+1}{m} \\
\therefore I_b &= wCE_1 \cdot \frac{2m+1}{m} \\
\text{also } I_3 &= I_b + I_2
\end{aligned}$$

$$I_3 = wCE_1\left(\frac{2m + 1}{m} + 1 + m\right)$$

$$= wCE_1\left(\frac{m^2 + 3m + 1}{m}\right)$$

$$\text{But } I_3 = wmCE_3$$

$$\therefore \quad E_3 = E_1 \cdot \frac{m^2 + 3m + 1}{m^2}$$

$$= E_1\left(1 + \frac{3}{m} + \frac{1}{m^2}\right) \quad \ldots\ldots\ldots\ldots\ldots (2.2)$$

The voltage producing the current I_c

$$E_1 + E_2 + E_3 = E_1\left(1 + \frac{m + 1}{m} + \frac{m^2 + 3m + 1}{m^2}\right)$$

$$\therefore I_c = wCE_1\left(1 + \frac{m + 1}{m} + \frac{m^2 + 3m + 1}{m^2}\right)$$

$$= wCE_1\left(\frac{3m^2 + 4m + 1}{m^2}\right)$$

$$\therefore \quad I_4 = I_3 + I_c$$

$$= wCE_1\left(\frac{m^2 + 3m + 1}{m} + \frac{3m^2 + 4m + 1}{m^2}\right)$$

$$\text{But} \qquad I_4 = wCmE_4$$

$$\therefore \quad E_4 = E_1\left(\frac{m^2 + 3m + 1}{m} + \frac{3m^2 + 4m + 1}{m^2}\right)$$

$$= E_1\left(\frac{m^2 + 3m + 1}{m^2} + \frac{3m^2 + 4m + 1}{m^3}\right)$$

$$= E_1\left(1 + \frac{6}{m} + \frac{5}{m^2} + \frac{1}{m^3}\right) \quad \ldots\ldots\ldots\ldots (2.3)$$

For the fifth insulator from the top, similar resoning gives

$$E_5 = E_1 \left(1 + \frac{10}{m} + \frac{15}{m^2} + \frac{7}{m^3} + \frac{1}{m^4} \right)$$

and so on for the complete string. Finally we have

$$E = E_1 + E_2 + E_3 + E_4 + \ldots\ldots\ldots\ldots$$

and thus by substituting the above values of E_2, E_3, etc., in terms of E_1 we have an equation for E_1 in term of E.The voltages E_2, E_3, etc., can then be calculated.

As a numerial example take the following problem. Find the potential difference across each unit of an overhead line suspension insulator consisting of four similar units. The pressure between the line conductor and earth is 60 kilovolts and the ratio of the capacity of each unit insulator to the capacity relative to earth, of each unit intermediate section of the connecting metalwork, is five to one. It is assumed that no leakage takes place.

$$m = 5$$

$$\therefore E_2 = E_1 \left(1 + \frac{1}{5} \right) = 1.2\, E_1$$

$$E_3 = E_1 \left(1 + \frac{3}{5} + \frac{1}{25} \right) = 1.64\, E_1$$

$$E_4 = E_1 \left(1 + \frac{6}{5} + \frac{5}{25} + \frac{1}{125} \right) = 2.408 E_1$$

$$\therefore E = E1 + E2 + E3 + E4$$

$$\therefore 60 = E_1 (1 + 1.2 + 1.64 + 2.408) = 6.248\, E_1$$

$$\therefore E_1 = \frac{60}{6.248} = 9.6 \text{ kV.}$$

$E_2 = 1.2E_1 = 11.5$ kV.

$E_3 = 1.64\ E_1. = 15.8$ kV.

$E_4 = 2.408E_1 = 23.1$ kV.

Total $= 60.0$ kV.

This example shows very clearly that the units far removed from the line conductor are stressed very much below their normal value, and that only the unit adjacent to the line is highly stressed. The string efficiency is also given by

$$\frac{\text{Voltage across string}}{\text{n x voltage across unit adjacent to line}}$$

where n is the number of units in the string. Thus, when $n = 4$, as in the numerical example, and $m = 5$

$$\text{String efficiency} = \frac{E}{4 \text{ x } E_4}$$

$$= \frac{60}{4 \text{ x } 23.5}$$

$$= .638 \text{ or } 63.8\ \%$$

It will be seen that the performance of the string is dependent on the value of m, and that as m is increased the division of voltage becomes more equalised. Thus

when $m = 1, E_2 = 2E_1;\ E_3 = 5E_1;\ E_4 = 13E_1$; and so on

when $m = 5, E_2 = 1.2E_1,\ E_3 = 1.64E_1;\ E_4 = 2.48E_1$; and so on

when $m = 10,\ E_2 = 1.1\ E_1;\ E_3 = 1.31E_1;\ E_4 = 1.65E_1$; and so on

when $m = \infty,\ E_2 = E_1;\ E_3 = E_1;\ E_4 = E_1$; and so on

Thus, when m is small the top units are performing very little work and adding further units has very little effect on the voltage across the unit adjacent to the line conductor. For high line voltages, say, over 100,000 volts, it is thus imperative that m shall be large, otherwise an impossibly large number of units per string will be required.

In the above discussion the effects of leakage and corona have been neglected; they are to equalise somewhat the voltage distribution. The capacitances between the various connectors and the line conductor have also been neglected. These also tend to equalise the distribution and, with certain ratios between the various capacitances, may give the minimum voltage, not on the top unit, but on one lower down. In every case the maximum voltage is on the bottom unit.

2.4 Methods of Equalising the Potential.

2.4.1 Elimination of m

Since an increase in m improves the performance of the string the obvious method is to make m as large as possible, and therefore to make the capacitances to ground relative to the mutual capacitance as small as possible. Something can be done by using a long cross-arm, but obviously this method is limited by the strenght and cost of the towers; m = 10 is about the limit that can be achieved by this method

2.4.2 Grading of the Units.

From the previous calculations it will be apparent that if the mutual capacitance of the lowest unit can be increased, the top unit having the lowest capacitance; then, since the voltage for a given current is inversely proportional to the capacitance, it follows that the effect will be to reduce the voltage across the lower units and to increase that across the higher units. By correct grading of the c capacitances complete equality of voltages can be obtained. In the following discussion the capacitances between metal work and line conductor are again neglected. Referring to Fig. 2.5 and putting

C = each capacitance to earth

mC = mutual capacitance of top unit

x = mutual capacitance of second unit

y = mutual capacitance of third unit, and so on

$$I_1 = wCmE'$$

$$I_a = wCE'$$

$$I_2 = I_1 + I_a$$

$$= wCE'(1 + m)$$

But $E' = \dfrac{I_2}{wx}$

$$E' = \frac{wCE'(1 + m)}{wx}$$

$$x = C(1 + m) = mC + C \quad \text{.................} (2.4)$$

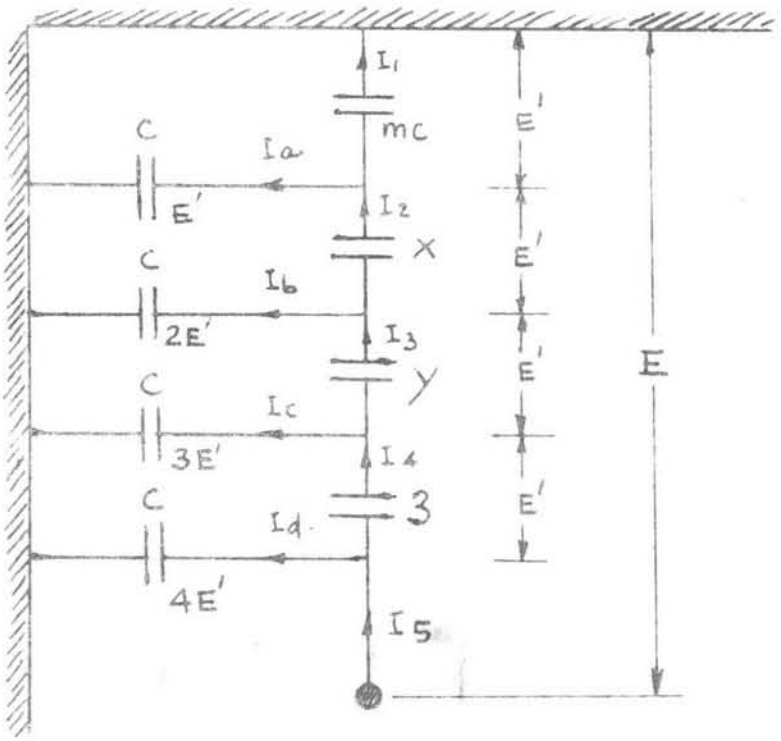

Fig 2·5 Capacitance Grading

Voltage producing $I_b = 2E'$

$$\therefore \quad I_b = 2wCE'$$

$$\text{also } I_3 = I_b + I_2$$

$$= 2wCE' + wCE'(1 + m)$$

$$= wCE'(3 + m)$$

$$\text{But } I_3 = E'wy$$

$$\therefore \quad y = C(3 + m)$$

$$= C(1 + 2 + m)$$

$$= mC + (1 + 2)C$$

and so on, giving the capacity for the n^{th} unit

$$C_n = mC + (1 + 2 + 3 + \ldots\ldots + \overline{n - 1})C$$

For example, taking $m = 5$ as before, the capacities of the various units, in terms of C, are as follows:

$$C_1 = 5C$$

$$C_2 = 5C + C = 6C$$

$$C_3 = 5C + (1 + 2)C = 8C$$

$$C_4 = 5C + (1 + 2 + 3)C = 11C \quad \text{and so on}$$

It will be obvious that to carry out the capacitance grading to this extent will be quite impossible in practice, since it will require that all the insulators in the string will be different from one another. Good results have been obtained by using standard insulators for most of the string and larger units for that adjacent to the line, and possibly the next insulator above. In practice, the method of capacitance grading is only suitable for very high-voltage lines, say, 200 KV or over.

2.4.3 Static Shielding.

The voltage distribution is controlled in this method by the employment of a grading or guard ring, which usually takes the form of a large metal ring surrounding the bottom of this unit, and therefore to the line. This ring, or shield, has the effect of increasing the capacitances between metal work and line, which capacitances we have neglected in the previous discussions.

Using the same notation as before, assuming similar units, and denoting the capacities to the shield by x, y, z

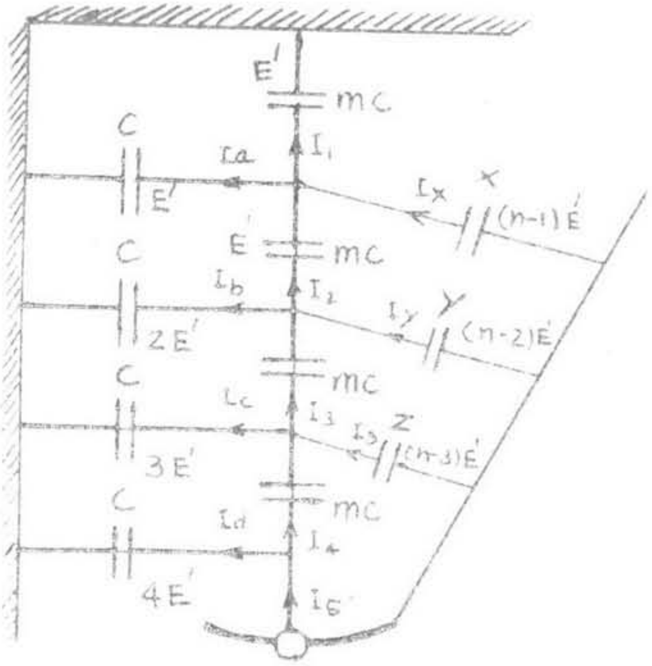

Fig. 2.6 Static Shielding.

In Fig. 2.6

$$I_2 = I_1 + I_a - I_x$$

$$I_3 = I_2 + I_b - I_y \quad \text{etc.}$$

But if the voltage is E' across every unit and all n units are identical, the currents I_1, I_2, I_3 etc, must be equal , from which we have:

$$I_x = I_a; \qquad I_y = I_b , \quad I_z = I_c$$

$$\therefore E'Cw = (n-1)E'xw$$

$$2E'Cw = (n-2)E'yw$$

$$3E'Cw = (n-3)E'zw$$

$$\therefore x = \frac{C}{n-1}$$

$$y = \frac{2C}{n-2}$$

$$z = \frac{3C}{n-3}$$

Hence in general, the capacitance from the shield to the p^{th} link from the top (the link being the connector between two consecutive units, and not the metal work joining the whole string to the cross-arm), is given by:

$$C_p = \frac{pC}{n-p}$$

With this method also it is impossible to obtain in practice an equal distribution of voltage, but considerable improvements are possible nevertheless.