

## POWER TRANSMISSION OVERHEAD LINES

### Design considerations & electric parameters

#### 1. General overview

Overhead lines are suspended from insulators which are themselves supported by towers or poles. The insulation of the conductors is air. The span between two towers depends on the allowable sag in the line, and for steel towers with very high-voltage lines the span is normally 370–460 m.

There are two main types of tower:

1. Those for straight runs in which the stress due to the weight of the line alone has to be withstood.
2. Those for changes in route, called deviation towers; these withstand the resultant forces set up when the line changes direction.

When specifying towers and lines, ice and wind loadings are taken into account, as well as extra forces due to a break in the conductors on one side of a tower. For lower voltages and distribution circuits, wood or reinforced concrete poles are used with conductors supported in horizontal formation.

An overhead transmission line consists of conductors, insulators, support structures, and, in most cases, shield wires.

#### 1.1. Support structures

Transmission lines employ a variety of support structures. Typical supporting structures are shown in Fig.3.1 and 3.2.

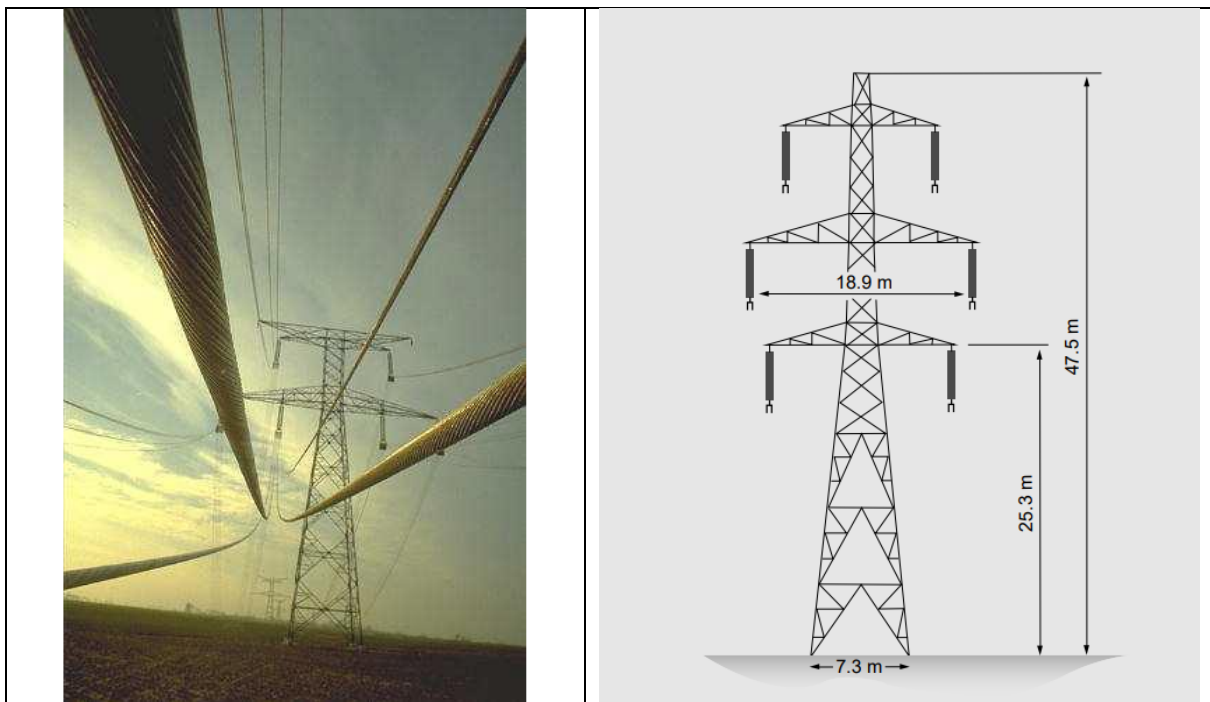
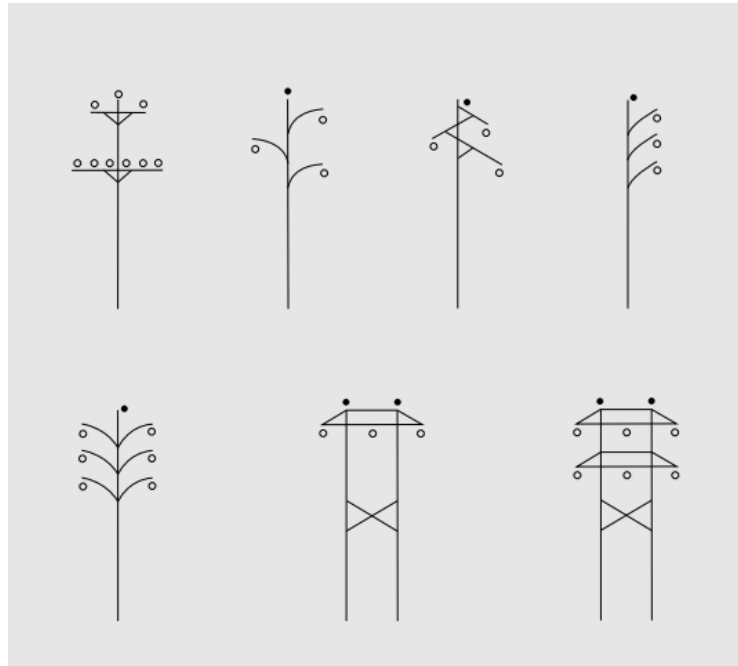


Fig. 3.1 : Electric overhead line

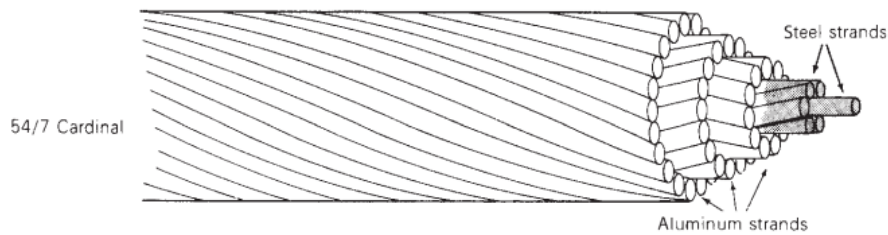


**Fig. 3.2:** Typical pole-type structures

## 1.2. Conductors

Aluminium has replaced copper as the most common conductor metal for overhead transmission. Although a larger aluminium cross-sectional area is required to obtain the same loss as in a copper conductor, aluminium has a lower cost and lighter weight. Also, the supply of aluminium is abundant, whereas that of copper is limited. One of the most common conductor types is aluminium conductor, steel-reinforced (ACSR), which consists of layers of aluminium strands surrounding a central core of steel strands (Fig. 3.3). Stranded conductors are easier to manufacture, since larger conductor sizes can be obtained by simply adding successive layers of strands. Stranded conductors are also easier to handle and more flexible than solid conductors, especially in larger sizes. The use of steel strands gives ACSR conductors a high strength-to-weight ratio. For purposes of heat dissipation, overhead transmission-line conductors are bare (no insulating cover). Other conductor types include the all-aluminium conductor (AAC), all aluminium-alloy conductor (AAAC), aluminium conductor alloy-reinforced (ACAR), and aluminium-clad steel conductor (Alumoweld). Emerging technologies use composite materials, including the aluminium conductor carbon reinforced (ACFR), whose core is a resin-matrix composite containing carbon fiber, and the aluminium conductor composite reinforced (ACCR), whose core is an aluminium-matrix containing aluminium fibers.

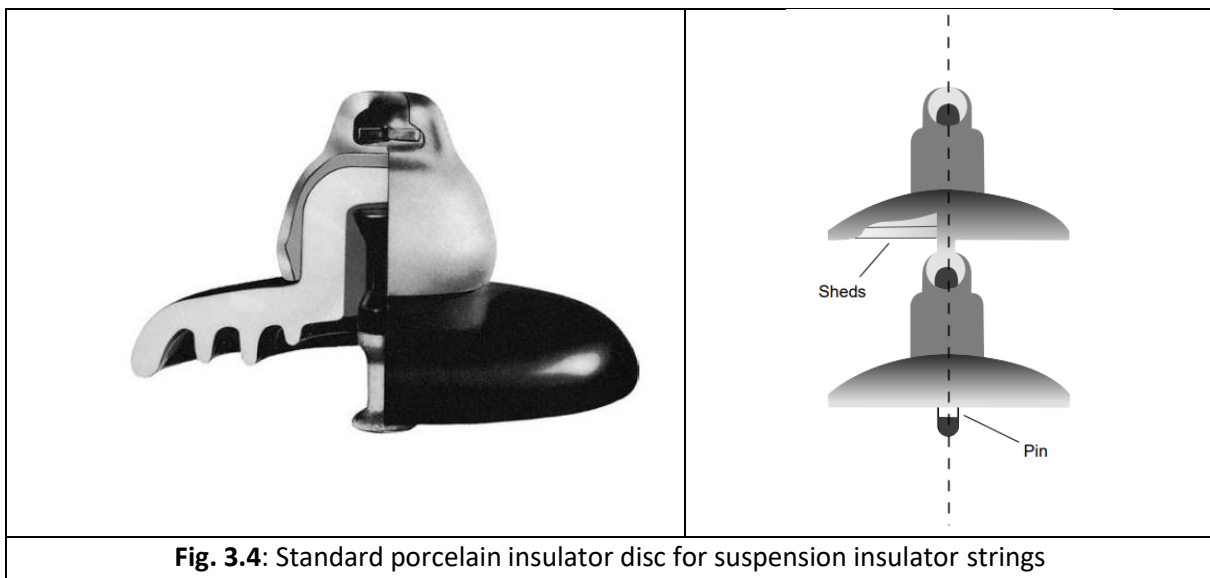
EHV lines often have more than one conductor per phase; these conductors are called a bundle. Bundle conductors have a lower electric field strength at the conductor surfaces, thereby controlling corona. They also have a smaller series reactance.



**Fig. 3.3:** Typical ACSR conductor

### 1.3. Insulators

The live conductors are insulated from the towers by insulators which take two basic forms: the pin-type and the suspension type. Insulators for transmission lines above 69 kV are typically suspension-type insulators, which consist of a string of discs constructed porcelain, toughened glass, or polymer. The standard disc (Fig. 3.4) has a 0.254m diameter, 0.146m spacing between centers of adjacent discs, and a mechanical strength of 7500 kg. The number of insulator discs in a string increases with line voltage (Table 3.1). Other types of discs include larger units with higher mechanical strength and fog insulators for use in contaminated areas.



**Fig. 3.4:** Standard porcelain insulator disc for suspension insulator strings

### 1.4. Shield wires

Shield wires located above the phase conductors protect the phase conductors against lightning. They are usually high- or extra-high-strength steel, Alumoweld, or ACSR with much smaller cross section than the phase conductors. The number and location of the shield wires are selected so that almost all lightning strokes terminate on the shield wires rather than on the phase conductors. Shield wires are grounded to the tower. As such, when lightning strikes a shield wire, it flows harmlessly to ground, provided the tower impedance and tower footing resistance are small.

Table 3.1: Typical transmission-line characteristics

Nominal Voltage (kV)	Phase Conductors				
	Number of Conductors per Bundle	Aluminum Cross-Section Area per Conductor (ACSR) (kcmil)*	Bundle Spacing (cm)	Minimum Clearances	
Phase-to-Phase (m)				Phase-to-Ground (m)	
69	1	—	—	—	—
138	1	300–700	—	4 to 5	—
230	1	400–1000	—	6 to 9	—
345	1	2000–2500	—	6 to 9	7.6 to 11
345	2	800–2200	45.7	6 to 9	7.6 to 11
500	2	2000–2500	45.7	9 to 11	9 to 14
500	3	900–1500	45.7	9 to 11	9 to 14
765	4	900–1300	45.7	13.7	12.2

\* 1 kcmil = 0.5 mm<sup>2</sup>

Nominal Voltage (kV)	Suspension Insulator String		Shield Wires		
	Number of Strings per Phase	Number of Standard Insulator Discs per Suspension String	Type	Number	Diameter (cm)
69	1	4 to 6	Steel	0, 1 or 2	—
138	1	8 to 11	Steel	0, 1 or 2	—
230	1	12 to 21	Steel or ACSR	1 or 2	1.1 to 1.5
345	1	18 to 21	Alumoweld	2	0.87 to 1.5
345	1 and 2	18 to 21	Alumoweld	2	0.87 to 1.5
500	2 and 4	24 to 27	Alumoweld	2	0.98 to 1.5
500	2 and 4	24 to 27	Alumoweld	2	0.98 to 1.5
765	2 and 4	30 to 35	Alumoweld	2	0.98

## 2. Design of overhead transmission lines

The decision to build new transmission is based on power-system planning studies to meet future system requirements of load growth and new generation. The points of interconnection of each new line to the system, as well as the power and voltage ratings of each, are selected based on these studies. Thereafter, transmission-line design is based on optimization of electrical, mechanical, environmental, and economic factors.

### 2.1. Electrical factors

Electrical design dictates the type, size, and number of bundle conductors per phase. Phase conductors are selected to have sufficient thermal capacity to meet continuous, emergency overload, and short-circuit current ratings. For EHV lines, the number of bundle conductors per phase is selected to control the voltage gradient at conductor surfaces, thereby reducing or eliminating corona.

Electrical design also dictates the number of insulator discs, vertical or V-shaped string arrangement, phase-to-phase clearance, and phase-to-tower clearance, all selected to provide adequate line insulation. Line insulation must withstand transient overvoltages due to lightning and switching surges, even when insulators are contaminated by fog, salt, or industrial pollution. Reduced clearances due to conductor swings during winds must also be accounted for.

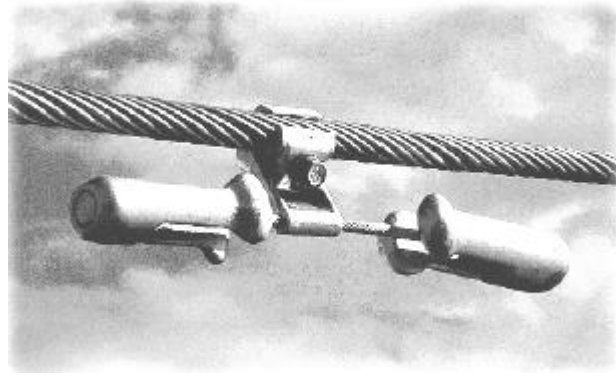
The number, type, and location of shield wires are selected to intercept lightning strokes that would otherwise hit the phase conductors. Also, tower footing resistance can be reduced by using driven ground rods or a buried conductor (called counterpoise) running parallel to the line. Line height is selected to satisfy prescribed conductor-to-ground clearances and to control ground-level electric field and its potential shock hazard.

Conductor spacings, types, and sizes also determine the series impedance and shunt admittance. Series impedance affects line-voltage drops,  $I^2R$  losses, and stability limits. Shunt admittance, primarily capacitive, affects line-charging currents, which inject reactive power into the power system. Shunt reactors (inductors) are often installed on lightly loaded EHV lines to absorb part of this reactive power, thereby reducing overvoltages.

## 2.2. Mechanical factors

Mechanical design focuses on the strength of the conductors, insulator strings, and support structures. Conductors must be strong enough to support a specified thickness of ice and a specified wind in addition to their own weight. Suspension insulator strings must be strong enough to support the phase conductors with ice and wind loadings from tower to tower (span length). Towers that satisfy minimum strength requirements, called suspension towers, are designed to support the phase conductors and shield wires with ice and wind loadings, and, in some cases, the unbalanced pull due to breakage of one or two conductors. Dead-end towers located every mile or so satisfy the maximum strength requirement of breakage of all conductors on one side of the tower. Angles in the line employ angle towers with intermediate strength. Conductor vibrations, which can cause conductor fatigue failure and damage to towers, are also of concern. Vibrations are controlled by adjustment of conductor tensions, use of vibration dampers, and—for bundle conductors—large bundle spacing and frequent use of bundle spacers.

A vibration damper is a device specially designed to absorb the vibrational energy, and thereby prevent the occurrence of any vibration at all. Many designs have been put forward, among which is the stock-bridge damper, an extremely simple, nevertheless effective device for suppressing high frequency vibrations. It consists of two hollow weights of special shape fixed at either end of a length of flexible steel cable which is itself fastened to the conductor at its midpoint by means of an aluminium clamp (Fig. 3.5).



**Fig. 3.5:** A Stock bridge damper

### **2.3. Environmental factors**

Environmental factors include land usage and visual impact. When a line route is selected, the effect on local communities and population centers, land values, access to property, wildlife, and use of public parks and facilities must all be considered. Reduction in visual impact is obtained by aesthetic tower design and by blending the line with the countryside. Also, the biological effects of prolonged exposure to electric and magnetic fields near transmission lines is of concern. Extensive research has been and continues to be done in this area.

### **2.4. Economic factors**

The optimum line design meets all the technical design criteria at lowest overall cost, which includes the total installed cost of the line as well as the cost of line losses over the operating life of the line. Many design factors affect cost. Utilities and consulting organizations use digital computer programs combined with specialized knowledge and physical experience to achieve optimum line design.

## **3. Conductor cross-section calculation**

The selection of the optimum conductor size is considered one of the critical issues in transferring the electricity through an overhead transmission line.

In order to choose the conductor cross-section, we must check three things:

*What is the rated current flowing in the cable?*

*Does it support the short-circuit power?*

*Is the voltage drop well below the limit?*

From a certain voltage level, we must also check that the corona effect does not become too significant. This results in a technically optimal but non-standardized cross-section. We must therefore decide to take a higher standardized cross-section. Calculating the different costs of the line helps us choose the most suitable one.

In reality, we should optimize the overall cost (cable + pylon) by taking into account technical constraints and losses. This is then a more complex calculation to which we add the choice of the voltage level and the average span length (use of computer simulations).

The following explains the electrical criteria for sizing the conductor cross-section of overhead lines. They are very similar to those associated with cables.

### 3.1. Criterion based on the current carrying capacity

The selected size shall withstand the normal transferred current based on the worst weather conditions throughout its life time (highest ambient temperature, lowest wind speed, highest solar radiation, etc.) without reaching its maximum rated temperature. We must verify that the cable supports the rated current over its entire service life.

Given the starting power  $P_{start}$  and a growth rate  $a$ , we first determine the power flowing in the cable after  $T$  years of use by the relationship:

$$P_T = P_{start} \cdot (1 + a)^T \quad [MW] \quad (3.1)$$

We then find the current flowing in each phase of the line:

$$I_{r,T} = \frac{P_T}{\sqrt{3} \cdot U \cdot \cos\varphi} \quad [A] \quad (3.2)$$

### 3.2. Criterion based on the short circuit current

The selected size shall withstand the maximum short circuit current with its duration in the network without losing its strength. We directly deduce this current from the formula giving the short-circuit power:

$$I_{cc} = \frac{S_{cc}}{\sqrt{3} \cdot U} \quad [A] \quad (3.3)$$

The short-circuit power  $S_{cc}$  is function of the network surrounding the line studied, but from a dimensioning point of view, we often retain the following values according to the main characteristic voltages (Table 3.2) :

Table 3.2: short circuit Power and current

Voltage line to line $U$ [kV]	short-circuit power $S_{cc}$ [MVA]	short-circuit current $I_{cc}$ [kA]
150	8000	30.8
70	2500	20.6
15	350	13.5
6	120	11.6

In order to find the minimum section allowing this current to be supported during time  $t_{cc}$ , we have the following formula, where  $a$  is a factor depending on the type of material constituting the cable:

$$s = \frac{I_{cc} \cdot \sqrt{t_{cc}}}{a} \quad (\forall t < 5sec) \quad [mm^2] \quad (3.4)$$

This new current value then leads to the choice of a new standardized section (the one which is just greater than it).

**Notes:**

- copper is always superior to aluminium for the same section, given its better capacity to evacuate heat;
- the values of the parameter  $a$  are as follows:  $a = 105.3$  for copper,  $a = 55.07$  for aluminum and  $a = 61.98$  for AMS.

**3.3. Criterion based on the voltage drop**

A quick calculation gives us the voltage drop formula:

$$\frac{\Delta U}{U} \cong \sqrt{3} \cdot \frac{I_N}{U_N} \cdot (R_{70^\circ\text{C}} \cdot l \cdot \cos\varphi + X \cdot l \cdot \sin\varphi) \quad (3.5)$$

where  $\Delta U = |U_2| - |U_1| \neq |U_2 - U_1|$

We can then determine the maximum resistance of the conductor at 20°C.

In the case of lines, we neglect capacitive effects because the values are approximately 50 times lower for lines than for cables. For the longitudinal impedance, we will generally take 0.4 Ω/km as a starting value.

**3.4. Criterion based on the cost**

The conductor size shall be selected to achieve the lowest running and fixed costs as in some circumstances the size may be increased to achieve lower power loss and in return lower running costs. A form of the cost function for conductor adopted is as follows:

$$T_1(s) = A + B \cdot s + \frac{C}{s} \quad (3.6)$$

where  $A$  is relative to fixed costs (installation, parts and accessories, etc.),  $B \cdot s$  represents the part of the cable cost that is proportional to the section  $s$  and  $C/s$  reflects the actualization costs and losses. Losses are inversely proportional to the section because a larger section results in lower Joule losses. This function is far from perfect but, as a first approach to the problem, it is sufficient.

The economic optimum section is the one that gives the derivative of  $T_1(s)$  equals 0. Given the form of  $T_1(s)$ , we can determine it directly:

$$s = \sqrt{\frac{C}{B}} \quad [\text{mm}^2] \quad (3.7)$$

The economic criterion is a rather vague criterion. The aim is to justify our choice. The ideal is to compare, depending on the section, the short-term and long-term costs as well as the investments and losses. We can then get an idea of what we gain or what we lose depending on the section.

**4. Transmission line parameters**

An electric transmission line can be represented by a series combination of resistance, inductance and shunt combination of conductance and capacitance. These parameters are symbolized as  $R$ ,  $L$ ,  $G$  and  $C$  respectively.

#### 4.1 Resistance

This is the essential element that determines the value of the transmission losses. The total resistance of the line characterizes and simulates the Joule power losses  $P_J$  in each phase conductor. The effective resistance of a conductor is given by

$$R = \frac{P_J}{I^2} \quad (3.8)$$

$P_J$ : Conductor real power loss (W)

$I$ : Current flowing through the conductor (A)

The dc resistance of a conductor at a specified temperature  $T$  is given by

$$R_{DC} = \rho \frac{l}{S} \quad (3.9)$$

with  $\rho$ : conductor resistivity at temperature  $T$

$l$ : conductor length

$S$ : conductor cross-sectional area

The effective resistance is equal to the dc resistance of the conductor only if the current is uniformly distributed throughout the section of the conductor. The conductor resistance is affected by three factors: frequency, spiraling, and temperature.

##### 1. Spiraling

For stranded conductors, alternate layers of strands are spiraled in opposite directions to hold the strands together. Spiraling makes the strands 1 or 2% longer than the actual conductor length. As a result, the dc resistance of a stranded conductor is 1 or 2% larger than that calculated for a specified conductor length.

##### 2. Frequency (skin effect)

When an alternating current flows through a conductor, the distribution is not uniform over the conductor cross-sectional area and the degree of non-uniformity increases with increase in frequency. The current density is greatest at the surface of the conductor. This causes the ac resistance to be somewhat higher than the dc resistance. This effect is known as skin effect. The ac resistance is usually referred as the effective resistance of the conductor. At power frequencies (50 Hz), the ac resistance is at most a few percent higher than the dc resistance, generally in the order of 1 to 2%.

$$R_{AC} \approx 1.015R_{DC} \quad (3.9)$$

Conductor manufacturers normally provide dc, 50-Hz, and 60-Hz conductor resistance based on test data.

##### 3. Temperature

The conductor resistance increases with the increase of temperature. Since the value of  $\rho$  is given at a specific temperature and the line operates at higher temperature, the actual resistance is higher.

The resistance of conductor increases linearly over normal operating temperatures:

$$R_T = R_0(1 + \alpha \cdot T) \quad (3.10)$$

with  $R_T$  : resistance at  $T^\circ\text{C}$   
 $R_0$  : resistance at  $0^\circ\text{C}$   
 $\alpha$  : temperature coefficient of resistance at  $0^\circ\text{C}$

The previous equation can be written, for two values of resistance  $R_1$  and  $R_2$  corresponding to temperatures  $T_1$  and  $T_2$ , respectively.

$$\frac{R_2}{R_1} = \frac{T + T_2}{T + T_1} \quad (3.11)$$

$T = \frac{1}{\alpha}$  is the constant that characterizes the absolute temperature of the material used in the conductor. For aluminium:  $T = 228$  and for copper:  $T = 234^\circ\text{C}$

### 3.2 Conductance

Conductance accounts for real power loss between conductors or between conductors and ground. For overhead lines, this power loss is due to leakage currents at insulators and to corona. Insulator leakage current depends on the amount of dirt, salt, and other contaminants that have accumulated on insulators, as well as on meteorological factors, particularly the presence of moisture. Corona occurs when a high value of electric field strength at a conductor surface causes the air to become electrically ionized and to conduct. The real power loss due to corona, called corona loss, depends on meteorological conditions, particularly rain, and on conductor surface irregularities. Losses due to insulator leakage and corona are usually small compared to conductor  $I^2R$  loss. Conductance is usually neglected in power system studies because it is a very small component of the shunt admittance.

### 3.3 Inductance

It is a series parameter distributed uniformly along the line referred to the unit of length. A current carrying conductor produces a magnetic field which is in the form of closed circular loops around the conductor. The inductance characterizes the storage of energy in magnetic form by the interaction of current and magnetic field. The derivation of calculation formulas for different configurations is provided in annex 1.

#### 1. Inductance of a single phase line

The inductance of a single-phase two-wire line is

$$L = L_{int} + L_{ext} = \frac{\mu}{8\pi} + \frac{\mu}{2\pi} \text{Ln} \frac{D}{r} = \frac{\mu}{4\pi} \left[ \frac{1}{2} + 2\text{Ln} \left( \frac{D-r}{r} \right) \right] \quad (\text{H/m}) \quad (3.12)$$

where  $D$  is the distance between the centres, and  $r$  is the radius, of the conductors.  $\mu$  is the permeability.

Since  $D \gg r$

$$L = \frac{\mu}{4\pi} \left[ \frac{1}{2} + 2\text{Ln} \left( \frac{D}{r} \right) \right] \quad (3.13)$$

Using the identity  $\frac{1}{2} = 2\text{Ln}(e^{1/4})$  in eq., a more convenient expression is obtained

$$L = \frac{\mu}{4\pi} \left[ 2\ln(e^{1/4}) + 2\ln\left(\frac{D}{r}\right) \right] = \frac{\mu}{2\pi} \ln\left(\frac{D}{re^{-1/4}}\right) \quad (3.14)$$

Defining  $r' = re^{-\frac{1}{4}} = 0,7788r$

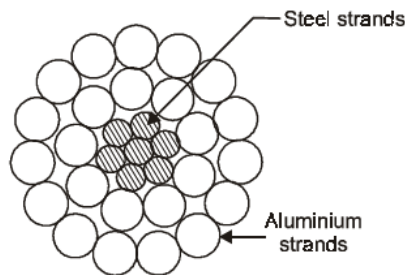
and substituting  $\mu = \mu_0 = 4\pi \cdot 10^{-7} \text{ H/m}$  (air)

$$L = \frac{\mu}{2\pi} \ln\left(\frac{D}{r'}\right) = 2 \cdot 10^{-7} \ln\left(\frac{D}{r'}\right) \quad (\text{H/m}) \quad (3.15)$$

The total inductance of a solid conductor of radius  $r$  can be assimilated to the external inductance of a hollow imaginary conductor of internal radius  $r'$ . The radius  $r'$  is that of a fictitious conductor assumed to have no internal flux linkages but with the same inductance as the actual conductor with radius  $r$ . The multiplying factor 0.7788 to adjust the radius in order to account for internal flux linkages applies only to solid round conductors.

Transmission line conductors used in practice are always stranded to provide the necessary flexibility for stringing. Stranded conductors are also known as composite conductors as they compose of two or more elements or strands electrically in parallel. In overhead transmission lines, ACSR conductor is most commonly used (Fig. 3.6). In order to obtain the overall radius of a stranded conductor, we use an equivalent radius which is the geometric mean distance of all strands, called geometric mean radius (*GMR*). For a real stranded conductor, the manufacturer provides the *GMR* of the conductor used so that:

$$L = 2 \cdot 10^{-7} \ln\left(\frac{D}{GMR}\right) \quad (\text{H/m}) \quad (3.16)$$



**Fig. 3.6:** Cross-sectional view of ACSR conductor

## 2. Inductance of a three phase line

When performing calculations on three-phase systems it is usual to consider one phase only, with the appropriate angular adjustments made for the other two phases. Therefore, phase voltages are used and the inductances (and capacitances) are the equivalent phase or line-to-neutral values.

For a three phase line with equilateral spacing (Fig. 3.7), The line-neutral inductance for  $D \gg r$

$$L = \frac{\mu}{4\pi} \left[ \frac{1}{2} + 2\ln\left(\frac{D}{r}\right) \right] = \frac{\mu}{2\pi} \ln\frac{D}{r'} = 2 \cdot 10^{-7} \ln\frac{D}{r'} \quad (\text{H/m}) \quad (3.17)$$

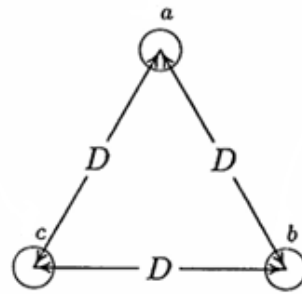


Fig. 3.7: 3-phase line with symmetrical spacing

In practice, the conductors are rarely spaced in equilateral formation. A transposition operation is then carried out in order to balance the three phases (Figure 3.8). By transposition of conductors is meant the exchanging of position of the power conductors at regular intervals along the line, so that each conductor occupies the original position of every other conductor over an equal distance.

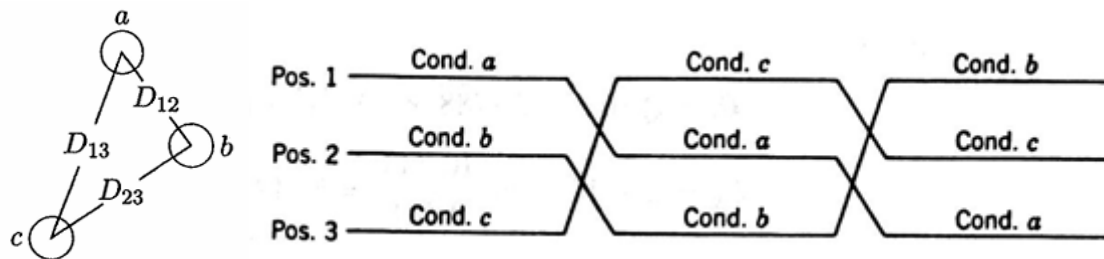


Fig. 3.8: 3-phase line with asymmetrical spacing and with transposition

Although the conductors are not spaced in the equilateral formation, it can be shown that the average value of inductance for any formation of conductors can be obtained by the representation of the system by one of equivalent equilateral spacing. The equivalent spacing  $D_{eq}$  between conductors is given by

$$D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}} \tag{3.18}$$

and

$$L = 2.10^{-7} Ln \frac{D_{eq}}{r'} \tag{3.19}$$

$D_{eq}$  is also called geometric mean distance *GMD*.

### 3. Bundled conductors

For voltages in excess of 230 kV, it is in fact not possible to use a round single conductor. Instead of going in for a hollow conductor it is preferable to use more than one conductor per phase which is known as bundling of conductors. A bundle conductor is a conductor made up of two or more sub-conductors and is used as one phase conductor (Fig. 3.9). The use of bundle conductors, that is, more than one conductor per insulator, reduces the reactance; it also reduces conductor to ground surface voltage gradients and hence corona loss and radio interference.

Geometric mean radius of bundled conductors can be obtained in the same manner as that of stranded conductors.

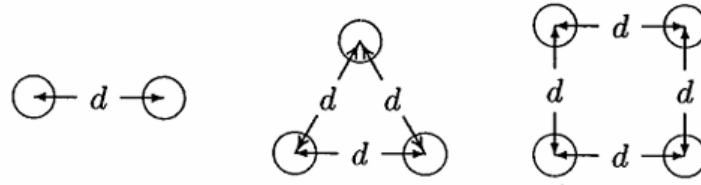


Figure 3.9: Configuration of bundled conductors

For a two conductor arrangement:  $GMR_L = (GMR \cdot d)^{1/2} = \sqrt{GMR \cdot d}$  (3.20)

For a three conductor arrangement:  $GMR_L = (GMR \cdot d \cdot d)^{1/3} = \sqrt[3]{GMR \cdot d^2}$  (3.21)

For a four conductor arrangement:  $GMR_L = (GMR \cdot d \cdot d \cdot d \sqrt{2})^{1/4} = 1.09 \sqrt[4]{GMR \cdot d^3}$  (3.22)

where  $GMR \equiv r'$  is provided by the manufacturer for an elementary conductor.

#### 4. Generalization

For all cases, single-phase or three-phase line, with single or composite conductors, in bundles or not:

$$L = 2 \cdot 10^{-7} \ln \frac{GMD}{GMR_L} \quad (H/m) \quad (3.23)$$

$GMD$ : Geometric mean distance between phases (mutual distance)

$GMR_L$ : Geometric mean radius (self-distance)

#### 3.4 Capacitance

Transmission line conductors exhibit capacitances with respect to each other due to the potential difference between them. This capacitance together with conductance forms the shunt admittance of a transmission line. When an ac voltage is applied to the transmission line, the line capacitance draws a leading current. The line capacitance is proportional to the length of the line and may be neglected for a line less than 100 km of length.

##### 1. Capacitance of a single phase line

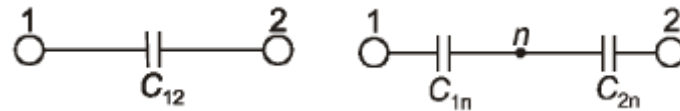
For a single phase line consisting of two long solid conductors 1 and 2 having radius  $r$  and spaced by distanced  $D$  (again  $D \gg r$ ), the capacitance is given by:

$$C_{12} = \frac{\pi \epsilon}{\ln \left( \frac{D}{r} \right)} \quad (F/m) \quad (3.24)$$

The height of the conductors from the ground is much larger than  $D$ . Therefore, the effect of distortion is negligible and the charge is assumed to be uniformly distributed.

Equation (3.23) gives the line-to-line capacitance between the conductors. For the purpose of transmission line modelling it is convenient to define capacitance between each conductor and a neutral as shown in Fig. 3.10.

$$C = C_{1n} = C_{2n} = 2C_{12} = \frac{2\pi \epsilon}{\ln \left( \frac{D}{r} \right)} \quad (F/m) \quad (3.25)$$



**Fig. 3.10:** Relationship between line-line and line-neutral capacitances

## 2. Capacitance of a three phase line

With three-phase conductors spaced equilaterally, the capacitance of each line to the hypothetical neutral is double that for the two-wire circuit, that is.

$$C = \frac{2\pi\epsilon}{\text{Ln}\left(\frac{D}{r}\right)} \quad (F/m) \quad (3.26)$$

For an untransposed line the capacitances between conductor to neutral of the three conductors are unequal. In transposed lines the average capacitance of each conductor to neutral is the same as the capacitance to neutral of any other phase. The capacitance per phase to neutral of the transposed line is then given by:

$$C = \frac{2\pi\epsilon}{\text{Ln}\left(\frac{D_{eq}}{r}\right)} \quad (F/m) \quad (3.27)$$

For a symmetrical spacing of the conductors,  $D_{eq} = D$ .

## 3. Bundled conductors

As mentioned before, the bundle usually comprises two, three or four conductors. Geometric mean radius of the bundle conductor calculated earlier for the inductance calculation with the exception that the radius  $r$  of each conductor is used; If the  $d$  is the bundle spacing, then

$$\text{For a two conductor arrangement: } GMR_c = (r \cdot d)^{1/2} = \sqrt{r \cdot d} \quad (3.28)$$

$$\text{For a three conductor arrangement: } GMR_c = (r \cdot d \cdot d)^{1/3} = \sqrt[3]{r \cdot d^2} \quad (3.29)$$

$$\text{For a four conductor arrangement: } GMR_c = (r \cdot d \cdot d \cdot d\sqrt{2})^{1/4} = 1.09\sqrt[4]{r \cdot d^3} \quad (3.30)$$

Considering the line to be transposed, the capacitance per phase is given as

$$C = \frac{2\pi\epsilon}{\text{Ln}\left(\frac{GMD}{GMR_c}\right)} \quad (F/m) \quad (3.31)$$