Chapter 3

Electric Supply Systems

3.1 Introduction

Electric power is produced at the power stations which are located at favorable places, generally quite away from the consumers. It is then transmitted over large distances to load centers with the help of conductors known as transmission lines. Finally, it is distributed to a large number of small and big consumers through a distribution network. In this chapter we will focus on the various aspects of transmission of electric power.

The electric supply system can be broadly classified into:

(i) d.c. or a.c. system,

(ii) overhead or underground system.

Nowadays, 3-phase, 3-wire a.c. system is universally adopted for generation and transmission of electric power as an economical proposition. However, distribution of electric power is done by 3-phase, 4-wire a.c. system. The underground system is more expensive than the overhead system. Therefore, in Egypt, overhead system is mostly adopted for transmission and distribution of electric power.
3.2 Typical A.C. Power Supply Scheme

The large network of conductors between the power station and the consumers can be broadly divided into two parts: transmission system and distribution system. Each part can be further sub-divided into two: primary transmission and secondary transmission and primary distribution and secondary distribution. Fig. 3.1 shows the layout of a typical a.c. power supply scheme by a single line diagram. It may be noted that it is not necessary that all power schemes include all the stages shown in the figure. For example, in a certain power scheme, there may be no secondary transmission and in another case, the scheme may be so small that there is only distribution and no transmission.

(i) *Generating station:*

In Fig 3.1, G.S. represents the generating station where electric power is produced by 3-phase alternators operating in parallel. The usual generation voltage is 11 kV. For economy in the transmission of electric power, the generation voltage (i.e., 11 kV) is stepped up to 132 kV (or more Depending upon the length of transmission line and the amount of power to be transmitted) at the generating station with the help of 3-phase transformers. The transmission of electric power at high voltages has several advantages including the saving of conductor material and high transmission efficiency. It may appear advisable to use the highest possible voltage for
transmission of electric power to save conductor material and have other advantages. But there is a limit to which this voltage can be increased. It is because increase in transmission voltage introduces insulation problems as well as the cost of switchgear and transformer equipment is increased. Therefore, the choice of proper transmission voltage is essentially a question of economics. Generally the primary transmission in Egypt is carried at 66 kV, 132 kV, 220 kV or 500 kV.

(ii) Primary transmission.
The electric power at 132 kV is transmitted by 3-phase, 3-wire overhead system to the outskirts of the city. This forms the primary transmission.

(iii) Secondary transmission.
The primary transmission line terminates at the receiving station (RS) which usually lies at the outskirts of the city. At the receiving station, the voltage is reduced to 33 kV by step-down transformers. From this station, electric power is transmitted at 33 kV by 3-phase, 3-wire over head system to various sub-stations (SS) located at the strategic points in the city. This forms the secondary transmission. It may be worthwhile to mention here that secondary distribution system consists of feeders, distributors and service mains.

Fig. 3.2 shows the elements of low voltage distribution system. Feeders (SC or SA) radiating from the distribution sub-station
(DS) supply power to the distributors (AB, BC, CD and AD). No consumer is given direct connection from the feeders. Instead, the consumers are connected to the distributors through their service mains.

(iv) **Primary distribution:**
The secondary transmission line terminates at the sub-station (SS) where voltage is reduced from 33 kV to 11 kV, 3-phase, 3-wire. The 11 kV lines run along the important road sides of the city. This forms the primary distribution. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub-stations.

(v) **Secondary distribution.**
The electric power from primary distribution line (11 kV) is delivered to distribution sub-stations (DS). These sub-stations are located near the consumers’ localities and step down the voltage to 400 V, 3-phase, 4-wire for secondary distribution. The voltage between any two phases is 400 V and between any phase and neutral is 230 V. The single-phase residential lighting load is connected between any one phase and neutral, whereas 3-phase, 400 V motor load is connected across 3-phase lines directly.
Note:
A practical power system has a large number of auxiliary equipments (e.g., fuses, circuit breakers, voltage control devices etc).
However, such equipments are not shown in Fig. 3.1. It is because the amount of information included in the diagram depends on the purpose for which the diagram is intended.
Here our purpose is to display general layout of the power system. Therefore, the location of circuit breakers, relays etc., is unimportant.
Further, the structure of power system is shown by a single line diagram. The complete 3-phase circuit is seldom necessary to convey even the most detailed information about the system.

3.3 Comparison between D.C. and A.C. Transmission
The electric power can be transmitted either by means of d.c. or a.c. Each system has its own merits and demerits. It is, therefore, desirable to discuss the technical advantages and disadvantages of the two systems for transmitting electric power.

1. D.C. transmission.
For some years past, the transmission of electric power by d.c. has been receiving the active consideration of engineers due to its numerous advantages.
Advantages: The high voltage d.c. transmission has the following advantages over high voltage a.c. transmission

1. It requires only two conductors as compared to three for a.c. transmission.
2. There is no inductance, capacitance, phase displacement and surge problems in d.c. transmission.
3. Due to the absence of inductance, the voltage drop in a d.c. transmission line is less than the a.c. line for the same load and sending end voltage. For this reason, a d.c. transmission line has better voltage regulation.
4. There is no skin effect in a d.c. system. Therefore, entire cross-section of the line conductor is utilized.
5. For the same working voltage, the potential stress on the insulation is less in case of d.c. system than that in a.c. system. Therefore, a d.c. line requires less insulation.
6. A d.c. line has lesser interference with communication circuits.

Disadvantages

1. Electric power cannot be generated at high d.c. voltage due to commutation problems.
2. The d.c. voltage cannot be stepped up for transmission of power at high voltages.
3. The d.c. switches and circuit breakers have their own limitations.

2. A.C. transmission.
Nowadays, electrical energy is almost exclusively generated, transmitted and distributed in the form of a.c.

**Advantages**

1. The power can be generated at high voltages.
2. The maintenance of a.c. sub-stations is easy and cheaper.
3. The a.c. voltage can be stepped up or stepped down by transformers with ease and efficiency. This permits to transmit power at high voltages and distribute it at safe potentials.

**Disadvantages**

1. An a.c. line requires more copper than a d.c. line.
2. The construction of a.c. transmission line is more complicated than a d.c. transmission line.
3. Due to skin effect in the a.c. system, the effective resistance of the line is increased.
4. An a.c. line has capacitance. Therefore, there is a continuous loss of power due to charging current even when the line is open.

**Conclusion:**

From the above comparison, it is clear that: *high voltage d.c. transmission is superior to high voltage a.c. transmission.*

Although at present, transmission of electric power is carried by a.c., there is an increasing interest in d.c and power electronic devices have made it possible to convert a.c. into d.c. transmission. Such devices can operate up to 30 MW at 400 kV
in single units. *The present day trend is towards a.c. for generation and distribution and high voltage d.c. for transmission.*

Fig. 3.3 shows the single line diagram of high voltage d.c. transmission. The electric power is generated as a.c. and is stepped up to high voltage by the sending end transformer TS. The a.c. power at high voltage is fed to an a.c./d.c. converter which convert a.c. into d.c. The transmission of electric power is carried at high d.c. voltage. At the receiving end, d.c. is converted into a.c. with the help of a d.c./a.c. converter. The a.c. supply is stepped down to low voltage by receiving end transformer TR for distribution.

![Diagram of high voltage d.c. transmission](image)

**Fig. 3.3**

### 3.4 Advantages of High Transmission Voltage

The transmission of electric power is carried at high voltages due to the following reasons:

*(i) Reduces volume of conductor material.*

Consider the transmission of electric power by a three-phase line.
Let \( P = \) power transmitted in watts
\( V = \) line voltage in volts
\( \cos \phi = \) power factor of the load
\( l = \) length of the line in metres
\( R = \) resistance per conductor in ohms
\( \rho = \) resistivity of conductor material in ohms metre
\( a = \) area of X-section of conductor in sq. metres.

\[
\text{Load current, } I = \frac{P}{\sqrt{3} V \cos \phi}
\]

\[
\text{Resistance/conductor, } R = \frac{\rho l}{a}
\]

\[
\text{Total power loss, } W = 3 I^2 R = 3 \left( \frac{P}{\sqrt{3} V \cos \phi} \right)^2 \times \frac{\rho l}{a}
\]

\[
= \frac{P^2 \rho l}{V^2 \cos^2 \phi a}
\]

\[
\therefore \text{Area of X-section, } a = \frac{P^2 \rho l}{W V^2 \cos^2 \phi}
\]

Total volume of conductor material required

\[
= 3 a l = 3 \left( \frac{P^2 \rho l}{W V^2 \cos^2 \phi} \right) l
\]

Total volume of conductor material required = \[
\frac{3P^2 \rho l^2}{W V^2 \cos^2 \phi}
\]

It is clear from the last equation that for given values of \( P, l, \rho \) and \( W \), the volume of conductor material required is inversely proportional to the square of transmission voltage and power.
factor. **In other words, the greater the transmission voltage, the lesser is the conductor material required.**

(ii) **Increases transmission efficiency**

\[
\text{Power Losses} = 3I^2R = 3 \frac{P^2}{3V^2\cos^2\phi} \times \frac{\rho l}{a} = \frac{P^2\rho l}{V^2a\cos^2\phi}
\]

Increasing the transmission voltage will reduce the power losses and hence increasing transmission efficiency

(iii) **Decreases percentage line drop**

\[
\text{Voltage line drop} = I R = \frac{P\rho l}{V \times \sqrt{3} \ a \ \cos \ \phi}
\]

From the last equation we can observe that increasing the transmission voltage will reduce the power voltage line drop.

3.4.1 **Limitations of high transmission voltage.**

From the above discussion, it might appear advisable to use the highest possible voltage for transmission of power in order to save conductor material.

However, it must be realized that high transmission voltage results in:

(i) the increased cost of insulating the conductors

(ii) the increased cost of transformers, switchgear and other terminal apparatus.

Therefore, there is a **limit to the higher transmission voltage which can be economically employed in a particular case.**
This limit is reached when the saving in cost of conductor material due to higher voltage is offset by the increased cost of insulation, transformer, switchgear etc. Hence, the choice of proper transmission voltage is essentially a question of economics. Further discussion on this topic will be discussed later in this chapter.

3.5 Various Systems of Power Transmission

It has already been pointed out that for transmission of electric power, 3-phase, 3-wire a.c. system is universally adopted. However, other systems can also be used for transmission under special circumstances. The main systems used in transmission are:

1. D.C. two-wire system.
2. Single-phase A.C. system
3. Three-phase A.C. system
   (i) Three-phase three-wire.
   (ii) Three-phase four-wire.

It is difficult to say which is the best system unless and until some method of comparison is adopted. Now, the cost of conductor material is one of the most important charges in a system. Obviously, the best system for transmission of power is that for which the volume of conductor material required is minimum. Therefore, the volume of conductor material required forms the basis of comparison between different systems.
Example 3.1: What is the percentage saving in feeder copper if the line voltage in a 2-wire d.c. system is raised from 200 volts to 400 volts for the same power transmitted over the same distance and having the same power loss?

Solution:

Let $P$ be the power delivered and $W$ be power loss in both cases. Let $v_1$ and $a_1$ be the volume and area of X-section for 200 V system and $v_2$ and $a_2$ for that of 400 V system.

Now, $P = V_1 I_1 = 200 I_1$ \hspace{1cm} \ldots(i)

And $P = V_2 I_2 = 400 I_2$ \hspace{1cm} \ldots(ii)

As same power is delivered in both cases,

\[
200 I_1 = 400 I_2 \text{ or } I_2 = \left(\frac{200}{400}\right) I_1 = 0.5 I_1
\]

Power loss in 200 V system, $W_1 = 2I_1^2 R_1$

Power loss in 400 V system, $W_2 = 2I_2^2 R_2 = 2(0.5 I_1)^2 R_2 = 0.5 I_1^2 R_2$

As power loss in the two cases is the same,

\[
W_1 = W_2
\]

or $2 I_1^2 R_1 = 0.5 I_1^2 R_2 \Rightarrow \frac{R_2}{R_1} = \frac{2}{0.5} = 4$

or $\frac{a_1}{a_2} = 4 \Rightarrow \frac{v_1}{v_2} = 4 \Rightarrow \frac{v_2}{v_1} = \frac{1}{4} = 0.25$

\[
\text{\% age saving in feeder copper} = \frac{V_1 - V_2}{V_1} \times 100 = \left(\frac{V_1}{V_1} - \frac{V_2}{V_1}\right) \times 100 \]

\[
= (1 - 0.25) \times 100 = 75\%
\]
Example 3.2: A d.c. 2-wire system is to be converted into a.c. 3-phase, 3-wire system by the addition of a third conductor of the same cross-section as the two existing conductors. Calculate the percentage additional load which can now be supplied if the voltage between wires and the percentage loss in the line remain unchanged. Assume a balanced load of unity power factor.

Solution:

Solution:
Suppose $V$ is the voltage between conductors for the two cases. Let $R$ be the resistance per conductor in each case.
Two-wire d.c. system. Referring to Fig. (i),

\[
\text{Power supplied, } P_1 = V I_1 \\
\text{Power loss, } W_1 = 2 I_1^2 R
\]

\[
\text{Percentage power loss} = \frac{2 I_1^2 R}{V I_1} \times 100 \quad \text{...(i)}
\]

3-phase, 3-wire a.c. system. Referring to Fig. (ii),

\[
\text{Power supplied, } P_2 = \sqrt{3} V I_2 \\
\text{Power loss, } W_2 = 3 I_2^2 R
\]

\[
\text{Percentage power loss} = \frac{3 I_2^2 R}{\sqrt{3} V I_2} \times 100 \quad \text{...(ii)}
\]

As the percentage power loss in the two cases is the same,

\[
\therefore \quad \text{exp. (i)} = \text{exp. (ii)}
\]

\[
2 I_1 = \sqrt{3} I_2
\]

\[
I_2 = \frac{2}{\sqrt{3}} I_1
\]

Now,

\[
\frac{P_2}{P_1} = \frac{\sqrt{3} V I_2}{V I_1} = \frac{\sqrt{3} V \times \frac{2}{\sqrt{3}} I_1}{V I_1} = 2
\]

\[
\therefore \quad P_2 = 2 P_1
\]

\textit{i.e.} additional power which can be supplied at unity p.f.

\textbf{by 3-phase, 3-wire a.c. system} = \textbf{100\%}

3.6 Elements of a Transmission Line

For reasons associated with economy, transmission of electric power is done at high voltage by 3-phase, 3-wire overhead system. The principal elements of a high-voltage transmission line are:
(i) **Conductors:** usually three for a single-circuit line and six for a double-circuit line. The usual material is aluminium reinforced with steel.

(ii) **Step-up and step-down transformers:** at the sending and receiving ends respectively. The use of transformers permits power to be transmitted at high efficiency.

(iii) **Line insulators:** which mechanically support the line conductors and isolate them electrically from the ground.

(iv) **Support:** which provide support to the conductors.

(v) **Protective devices:** such as ground wires, lightning arrestors, circuit breakers, relays etc. They ensure the satisfactory service of the transmission line.

(vi) **Voltage regulating devices:** which maintain the voltage at the receiving end within permissible limits.

### 3.7 Economics of Power Transmission

While designing any scheme of power transmission, the engineer must have before him the commercial aspect of the work entrusted to him. He must design the various parts of transmission scheme in a way that maximum economy is achieved. The economic design and layout of a complete power transmission scheme is outside the scope of this chapter. However, the following two fundamental economic principles which closely influence the electrical design of a transmission line will be discussed:
(i) Economic choice of conductor size, and
(ii) Economic choice of transmission voltage

3.7.1 Economic choice of conductor size
The cost of conductor material is generally a very considerable part of the total cost of a transmission line. Therefore, the determination of proper size of conductor for the line is of vital importance. The most economical area of conductor is that for which the total annual cost of transmission line is minimum. This is known as Kelvin’s Law after Lord Kelvin who first stated it in 1881. The total annual cost of transmission line can be divided broadly into two parts: annual charge on capital outlay and annual cost of energy wasted in the conductor.

(i) Annual charge on capital outlay.
This is on account of interest and depreciation on the capital cost of complete installation of transmission line. In case of overhead system, it will be the annual interest and depreciation on the capital cost of conductors, supports and insulators and the cost of their erection. Now, for an overhead line, insulator cost is constant, the conductor cost is proportional to the area of X-section and the cost of supports and their erection is partly constant and partly proportional to area of X-section of the conductor. Therefore, annual charge on an overhead transmission line can be expressed as:
Annual charge = \( P_1 + P_2 a \) \( .... \) (i)

where \( P_1 \) and \( P_2 \) are constants and \( a \) is the area of X-section of the conductor.

(ii) Annual cost of energy wasted.

This is on account of energy lost mainly in the conductor due to \( I^2R \) losses. Assuming a constant current in the conductor throughout the year, the energy lost in the conductor is proportional to resistance. As resistance is inversely proportional to the area of X-section of the conductor, therefore, the energy lost in the conductor is inversely proportional to area of X-section. Thus, the annual cost of energy wasted in an overhead transmission line can be expressed as:

Annual cost of energy wasted = \( P_3 / a \) \( ... \) (ii)

where \( P_3 \) is a constant.

Total annual cost, \( C \) = exp. (i) + exp. (ii)

\[
= (P_1 + P_2 a) + P_3 / a
\]

\[
\therefore \ C \ = \ P_1 + P_2 a + P_3 / a \ \ \ ... \ (iii)
\]

In exp. (iii), only area of X-section \( a \) is variable. Therefore, the total annual cost of transmission line will be minimum if differentiation of \( C \) with respect to \( a \) is zero i.e.
\[
\frac{d}{da} (C) = 0
\]
\[
or \quad \frac{d}{da} (P_1 + P_2a + P_3/a) = 0
\]
\[
or \quad P_2 - \frac{P_3}{a^2} = 0
\]
\[
or \quad P_2 = \frac{P_3}{a^2}
\]
\[
or \quad P_2a = \frac{P_3}{a}
\]
i.e.

**Variable part of annual charge = Annual cost of energy wasted**

Therefore Kelvin’s Law can also be stated in another way i.e. the most economical area of conductor is that for which the variable part of annual charge is equal to the cost of energy losses per year.

➢ **Graphical illustration of Kelvin’s law:**

Kelvin’s law can also be illustrated graphically by plotting annual cost against X-sectional area ‘\(a\)’ of the conductor as shown in Fig. 3.4. In the diagram, the straight line (1) shows the relation between the annual charge (i.e., \(P_1 + P_2a\)) and the area of X-section \(a\) of the conductor. Similarly, the rectangular hyperbola (2) gives the relation between annual cost of energy wasted and X-sectional area \(a\). By adding the ordinates of curves (1) and (2), the curve (3) is obtained. This latter curve shows the relation between total annual cost \((P_1 + P_2a + P_3/a)\) of transmission line and area of X-section \(a\). The lowest point
on the curve (i.e., point P) represents the most economical area of X-section.

Fig. 3.4

➢ **Limitations of Kelvin’s law:**

Although theoretically Kelvin’s law holds good, there is often considerable difficulty in applying it to a proposed scheme of power transmission. In practice, the limitations of this law are:

(i) It is not easy to estimate the energy loss in the line without actual load curves, which are not available at the time of estimation.

(ii) The assumption that annual cost on account of interest and depreciation on the capital outlay is in the form $P_1 + P_2 a$ is strictly speaking not true. For instance, in cables neither
the cost of cable dielectric and sheath nor the cost of laying vary in this manner.

(iii) This law does not take into account several physical factors like safe current density, mechanical strength, corona loss etc.

(iv) The conductor size determined by this law may not always be practicable one because it may be too small for the safe carrying of necessary current.

(v) Interest and depreciation on the capital outlay cannot be determined accurately.

Example 3.3: A 2-conductor cable 1 km long is required to supply a constant current of 200 A throughout the year. The cost of cable including installation is LE (20 a + 20) per metre where ‘a’ is the area of X-section of the conductor in cm$^2$. The cost of energy is LE 0.05 per kWh and interest and depreciation charges amount to 10%. Calculate the most economical conductor size. Assume resistivity of conductor material to be 1·73 $\mu$ Ω cm.

Solution:
The capital cost (variable) of the cable is given to be 20 a LE/m. Therefore, for 1 km length of the cable, the capital cost (variable) is LE 20 a × 1000 = LE 20,000 a.

**Variable annual charge = Annual interest and depreciation on capital cost (variable) of cable**

\[ \text{Variable annual charge} = \text{Annual interest and depreciation on capital cost (variable) of cable} \]

\[ = \text{LE } 0.1 \times 20,000 \text{ a } = \text{LE } 2000 \text{ a } \quad \text{(ii)} \]

According to Kelvin’s law, for most economical X-section of the conductor, **Variable annual charge = Annual cost of energy lost**

or \[ 2000 a = 6062 / a \]

\[ \therefore a = \frac{6062}{2000} = 1.74 \text{ cm}^2 \]

**Example 3.4:** A 2-wire feeder carries a constant current of 250 A throughout the year. The portion of capital cost which is proportional to area of X-section is LE 5 per kg of copper conductor. The interest and depreciation total 10% per annum.
and the cost of energy is 5 P per kWh. Find the most economical area of X-section of the conductor. Given that the density of copper is 8.93 gm/cm³ and its specific resistance is $1.73 \times 10^{-8} \, \Omega \, m$.

**Solution:** Consider 1 metre length of the feeder. Let $a$ be the most economical area of X-section of each conductor in m².

Resistance of each conductor, $R = \frac{\rho l}{a} = \frac{1.73 \times 10^{-8} \times l}{a} = 1.73 \times 10^{-8} \, \Omega$

Energy lost per annum $= \frac{2 f^2 R l}{1000} \, kWh = \frac{2 \times (250)^2 \times 1.73 \times 10^{-8} \times 8760}{1000 \times a}$

$= \frac{18,94,350}{a} \times 10^{-8} \, kWh$

Annual cost of energy lost $= \text{LE} \, \frac{5}{100} \times \frac{18,94,350 \times 10^{-8}}{a} = \text{LE} \, \frac{94,717.5 \times 10^{-8}}{a}$

Mass of 1 metre feeder $= 2 \times (\text{Volume} \times \text{density}) = 2 \times a \times 1 \times 8.93 \times 10^3 \, kg$

$= 17.86 \times 10^3 a \, kg$

Capital cost (variable) $= \text{LE} \, 5 \times 17.86 \times 10^3 \times a = \text{LE} \, 89.3 \times 10^3 a$

Variable Annual charge $= 10\% \, \text{of capital cost (variable)}$

$= 0.1 \times 89.3 \times 10^3 a = \text{LE} \, 8930 a$

For most economical area of X-section,

Variable annual charge = Annual cost of energy lost

or

$\text{LE} \, 8930 a = \frac{94,717.5 \times 10^{-8}}{a}$

$\therefore a = \sqrt{\frac{94,717.5 \times 10^{-8}}{8930}} = 3.25 \times 10^{-4} \, m^2 = 3.25 \, \text{cm}^2$

**3.7.2 Economic choice of transmission voltage**

It has been shown earlier in the chapter that if transmission voltage is increased, the volume of conductor material required is reduced. This decreases the expenditure on the conductor
material. It may appear advisable to use the highest possible transmission voltage in order to reduce the expenditure on conductors to a minimum. However, it may be remembered that as the transmission voltage is increased, the cost of insulating the conductors, cost of transformers, switchgear and other terminal apparatus also increases. Therefore, for every transmission line, there is optimum transmission voltage, beyond which there is nothing to be gained in the matter of economy. The transmission voltage for which the cost of conductors, cost of insulators, transformers, switchgear and other terminal apparatus is minimum, is called economical transmission voltage.

The method of finding the economical transmission voltage is as follows. Power to be transmitted, generation voltage and length of transmission line are assumed to be known. We choose some standard transmission voltage and work out the following costs:

(i) **Transformers:** at the generating and receiving ends of transmission line. For a given power, this cost increases slowly with the increase in transmission voltage.

(ii) **Switchgear:** This cost also increases with the increase in transmission voltage.

(iii) **Lightning arrestor:** This cost increases rapidly with the increase in transmission voltage.
(iv) **Insulation and supports:** This cost increases sharply with the increase in transmission voltage.

(v) **Conductor:** This cost decreases with the increase in transmission voltage.

The sum of all above costs gives the total cost of transmission for the voltage considered. Similar calculations are made for other transmission voltages. Then, *a curve is drawn for total cost of transmission against voltage* as shown in Fig. 3.5. The lowest point (P) on the curve gives the economical transmission voltage. Thus, in the present case, OA is the optimum transmission voltage. This method of finding the economical transmission voltage is rarely used in practice as different costs cannot be determined with a fair degree of accuracy.

The present day trend is to follow certain *empirical formulae* for finding the economical transmission voltage. Thus, according to American practice, the economic voltage between lines in a 3-phase a.c. system is

\[ V = 5.5 \sqrt{0.62 \cdot l} + \frac{3P}{150} \]

Where:

- \( V \) = line voltage in kV
- \( P \) = maximum kW per phase to be delivered to single circuit
- \( l \) = distance of transmission line in km
It may be noted here that in the above formula, power to be transmitted and distance of transmission line have been taken into account. It is because both these factors influence the economic voltage of a transmission line. This can be easily explained. If the distance of transmission line is increased, the cost of terminal apparatus is decreased, resulting in higher economic transmission voltage. Also if power to be transmitted is large, large generating and transforming units can be employed. This reduces the cost per kW of the terminal station equipment.

![Diagram](image)

**Fig. 3.5**

### 3.8 Requirements of Satisfactory Electric Supply
The electric power system in India is 3-phase a.c. operating at a frequency of 50 Hz. The power station delivers power to consumers through its transmission and distribution systems. The power delivered must be characterized by constant or nearly constant voltage, dependability of service, balanced voltage, and efficiency so as to give minimum annual cost, sinusoidal waveform and freedom from inductive interference with telephone lines.

(i) Voltage regulation.
A voltage variation has a large effect upon the operation of both power machinery and lights. A motor is designed to have its best characteristics at the rated voltage and consequently a voltage that is too high or too low will result in a decrease in efficiency. If the fluctuations in the voltage are sudden, these may cause the tripping of circuit breakers and consequent interruptions to service. Usually the voltage at the generator terminals, where this is done, in some cases the voltage variations at the load may be made sufficiently small by keeping the resistance and reactance of the lines and feeders low.

(ii) Dependability.
One important requirement of electric supply is to furnish uninterrupted service. The losses which an industrial consumer sustains due to the failure of electric power supply are usually vastly greater than the actual value of the power that he would
use during this period. It is on account of the expense of idle workmen and machines and other overhead charges. Interruptions to service cause irritation and are sometimes positively dangerous to life and property. For example, failure of power in hospitals, in crowded theatres and stores may lead to very grave consequences. Therefore, it is the duty of electric supply company to keep the power system going and to furnish uninterrupted service.

(iii) Balanced voltage.
It is very important that the poly-phase voltage should be balanced. If an unbalanced poly-phase voltage is supplied to a consumer operating synchronous or induction motors, it will result in a decrease in the efficiency of his machinery and also a decrease in its maximum power output. Motors called upon to deliver full load when their terminal voltages are unbalanced are liable to considerable damage due to overheating. One method of maintaining balance of voltage is by having balanced loads connected to the circuit.

(iv) Efficiency.
The efficiency of a transmission system is not of much importance in itself. The important economic feature of the design being the layout of the system as a whole so as to perform the requisite function of generating and delivering power with a minimum overall annual cost. The annual cost can be minimized to a considerable extent by taking care of
power factor of the system. It is because losses in the lines and machinery are largely determined by power factor. Therefore, it is important that consumers having loads of low power factor should be penalized by being charged at a higher rate per kWh than those who take power at high power factors. Loads of low power factor also require greater generator capacity than those of high power factor (for the same amount of power) and produce larger voltage drops in the lines and transformers.

(v) **Frequency.**
The frequency of the supply system must be maintained constant. It is because a change in frequency would change the motor speed, thus interfering with the manufacturing operations.

(vi) **Sinusoidal waveform.**
The alternating voltage supplied to the consumers should have a sine waveform. It is because any harmonics which might be present would have detrimental effect upon the efficiency and maximum power output of the connected machinery. Harmonics may be avoided by using generators of good design and by avoidance of high flux densities in transformers.

(vii) **Freedom from inductive interference.**
Power lines running parallel to telephone lines produce electrostatic and electromagnetic field disturbances. These fields tend to cause objectionable noises and hums in the apparatus connected to communication circuits. Inductive
interference with telephone lines may be avoided by limiting as much as possible the amount of zero-sequence and harmonic current and by the proper transposition of both power lines and telephone lines.
Exercise 3

1. What is the percentage saving in copper feeder if the line voltage in a 2-wire d.c. system is raised from 220V to 500 V for the same power transmitted over the same distance and having the same power loss?  
   Ans. 80·64%

2. A single phase a.c. system supplies a load of 200 kW and if this system is converted to 3-phase, 3-wire a.c. system by running a third similar conductor, calculate the 3-phase load that can now be supplied if the voltage between the conductors is the same. Assume the power factor and transmission efficiency to be the same in the two cases  
   Ans. 400 kW

3. A 50 km long transmission line supplies a load of 5 MVA at 0·8 p.f. lagging at 33 kV. The efficiency of transmission is 90%. Calculate the volume of aluminium conductor required for the line when (i) single phase, 2-wire system is used (ii) 3-phase, 3-wire system is used. The specific resistance of aluminium is $2·85 \times 10^{-8} \, \Omega m$.  
   Ans. $16.35 \, m^3$, $12.27 \, m^3$

4. A sub-station supplies power at 11 kV, 0·8 p.f. lagging to a consumer through a single phase transmission line having total resistance (both go and return) of 0.15 Ω. The voltage drop in the line is 15%. If the same power is to be supplied to the same consumer by two wire d.c. system by a new line
having a total resistance of 0.05 Ω and if the allowable voltage drop is 25%, calculate the d.c. supply voltage.

**Ans. 4400 V**

5. The cost of a 3-phase overhead transmission line is LE (25000 a + 2500) per km where ‘a’ is the area of X-section of each conductor in cm². The line is supplying a load of 5 MW at 33 kV and 0.8 p.f. lagging assumed to be constant throughout the year. Energy costs 4 P per kWh and interest and depreciation total 10% per annum. Find the most economical size of the conductor. Given that specific resistance of conductor material is 10⁻⁶ Ω cm.

**Ans. 0.71 cm²**

6. Determine the most economical cross-section for a 3-phase transmission line, 1 km long to supply at a constant voltage of 110 kV for the following daily load cycle:

- **6 hours** 20 MW at p.f. 0.8 lagging
- **12 hours** 5 MW at p.f. 0.8 lagging
- **6 hours** 6 MW at p.f. 0.8 lagging

The line is used for 365 days yearly. The cost per km of line including erection is LE (9000+ 6000 a) where ‘a’ is the area of X-section of conductor in cm². The annual rate of interest and depreciation is 10% and the energy costs 6 P per kWh. The resistance per km of each conductor is 176·0/a.

**Ans. 1.56 cm²**