Performance of Short and Medium Transmission Lines

There are three main types of Overhead Transmission Lines:

1. Short transmission line – The line length is up to 60 km and the line voltage is comparatively low less than 20KV.
2. Medium transmission line – The line length is between 60 km to 160 km and the line voltage is between 20kV to 100kV.
3. Long transmission line – The line length is more than 160 km and the line voltage is high greater than 100KV.

Whatever may be the category of transmission line, the main aim is to transmit power from one end to another.

Like other electrical system, the transmission network also will have some power loss and voltage drop during transmitting power from sending end to receiving end. Hence, performance of transmission line can be determined by its efficiency and voltage regulation.

Voltage regulation:

Voltage regulation of transmission line is measure of change of receiving end voltage from no-load to full load condition.

\[
\% \text{regulation} = \frac{\text{No load receiving end voltage} - \text{Full load receiving end voltage}}{\text{Full load receiving end voltage}} \times 100\
\]

\[
\text{Efficiency of transmission line} = \frac{\text{Power delivered at receiving end}}{\text{Power sent from sending end}} \times 100\
\]

\[
\text{Power sent from sending end} - \text{line losses} = \text{Power delivered at receiving end}
\]

Every transmission line will have three basic electrical parameters. The conductors of the line will have electrical resistance, inductance, and capacitance. As the transmission line is a set of conductors being run from one place to another supported by transmission towers, the parameters are distributed uniformly along the line.

The electrical power is transmitted over a transmission line with a speed of light that is \(3 \times 10^8\) m/sec. Frequency of the power is 50 Hz. The wave length of the voltage and current of the power can be determined by the equation given below,

\[
\text{Therefore, } \lambda = \frac{v}{f}\]

\[
\Rightarrow \lambda = \frac{3 \times 10^8}{50} = 6 \times 10^6 \text{ mtr} = 6,000 \text{ mtr}
\]
\[ f \lambda = \nu \] where, \( f \) is power frequency, \( \lambda \) is wavelength and \( \nu \) is the speed of light.

Hence, the wavelength of the transmitting power is quite long compared to the generally used line length of transmission line.

For this reason, the transmission line, with length less than 160 km, the parameters are assumed to be lumped and not distributed. Such lines are known as electrically short transmission line. This electrically short transmission lines are again categorized as short transmission line (length up to 60 km) and medium transmission line (length between 60 and 160 km). The capacitive parameter of short transmission line is ignored whereas in case of medium length line the, capacitance is assumed to be lumped at the middle of the line or half of the capacitance may be considered to be lumped at each ends of the transmission line. Lines with length more than 160 km, the parameters are considered to be distributed over the line. This is called long transmission line.

**PERFORMANCE OF SINGLE PHASE SHORT TRANSMISSION LINES**

As stated earlier, the effects of line capacitance are neglected for a short transmission line. Therefore, while studying the performance of such a line, only resistance and inductance of the line are taken into account. The equivalent circuit of a single phase short transmission line is shown in Fig.

Here, the total line resistance and inductance are shown as concentrated or lumped instead of being distributed. The circuit is a simple a.c. series circuit.

Let

\[ I = \text{load current} \]
\[ R = \text{loop resistance } i.e., \text{ resistance of both conductors} \]
\[ XL = \text{loop reactance} \]
\[ VR = \text{receiving end voltage} \]
\[ \cos \phi R = \text{receiving end power factor (lagging)} \]
VS = sending end voltage

\( \cos \varphi_S \) = sending end power factor

The phasor diagram of the line for lagging load power factor is shown in Fig. From the right angled triangle \( ODC \), we get,

\[
(OC)^2 = (OD)^2 + (DC)^2
\]

or

\[
V_S^2 = (OE + ED)^2 + (DB + BC)^2
= (V_R \cos \varphi_R + IR)^2 + (V_R \sin \varphi_R + IX_L)^2
\]

\[
\therefore \quad V_S = \sqrt{(V_R \cos \varphi_R + IR)^2 + (V_R \sin \varphi_R + IX_L)^2}
\]

(i) %age Voltage regulation = \( \frac{V_S - V_R}{V_R} \times 100 \)

(ii) Sending end p.f., \( \cos \varphi_S = \frac{OD}{OC} = \frac{V_R \cos \varphi_R + IR}{V_S} \)

(iii) Power delivered = \( V_R I_R \cos \varphi_R \)

Line losses = \( I^2 R \)

Power sent out = \( V_R I_R \cos \varphi_R + I^2 R \)

%age Transmission efficiency = \( \frac{\text{Power delivered}}{\text{Power sent out}} \times 100 \)

= \( \frac{V_R I_R \cos \varphi_R}{V_R I_R \cos \varphi_R + I^2 R} \times 100 \)
THREE-PHASE SHORT TRANSMISSION LINES

For reasons associated with economy, transmission of electric power is done by 3-phase system. This system may be regarded as consisting of three single phase units, each wire transmitting one-third of the total power. As a matter of convenience, we generally analyse 3-phase system by considering one phase only. Therefore, expression for regulation, efficiency etc. derived for a single phase line can also be applied to a 3-phase system. Since only one phase is considered, phase values of 3-phase system should be taken. Thus, Vs and VR are the phase voltages, whereas R and XL are the resistance S and inductive reactance per phase respectively.

Fig (i) shows a Y-connected generator supplying a balanced Y-connected load through a transmission line. Each conductor has a resistance of $R \, \Omega$ and inductive reactance of $X \, \Omega$. Fig. ( ii) shows one phase separately. The calculations can now be made in the same way as for a single phase line.

The regulation and efficiency of a transmission line depend to a considerable extent upon the power factor of the load.

1. Effect on regulation.

The expression for voltage regulation of a short transmission line is given by:

\[
\text{%age Voltage regulation} = \frac{IR \cos \phi_R + IX_L \sin \phi_R}{V_R} \times 100 \quad \text{(for lagging p.f.)}
\]

\[
\text{%age Voltage regulation} = \frac{IR \cos \phi_R - IX_L \sin \phi_R}{V_R} \times 100 \quad \text{(for leading p.f.)}
\]
The following conclusions can be drawn from the above expressions:

(i) When the load p.f. is lagging or unity or such leading that \( I R \cos \phi R > I XL \sin \phi R \), then voltage regulation is positive \( i.e. \), receiving end voltage \( VR \) will be less than the sending end voltage \( VS \).

(ii) For a given \( VR \) and \( I \), the voltage regulation of the line increases with the decrease in p.f. for lagging loads.

(iii) When the load p.f. is leading to this extent that \( I XL \sin \phi R > I \cos \phi R \), then voltage regulation is negative \( i.e. \) the receiving end voltage \( VR \) is more than the sending end voltage \( VS \).

(iv) For a given \( VR \) and \( I \), the voltage regulation of the line decreases with the decrease in p.f. for leading loads.

ii) Effect on transmission efficiency.

The power delivered to the load depends upon the power factor.

\[
P = V_R \cdot I \cos \phi_R \quad \text{(For 1-phase line)}
\]

\[
I = \frac{P}{V_R \cos \phi_R}
\]

\[
P = 3 \cdot V_R I \cos \phi_R \quad \text{(For 3-phase line)}
\]

\[
I = \frac{P}{3V_R \cos \phi_R}
\]

It is clear that in each case, for a given amount of power to be transmitted (\( P \)) and receiving end voltage Power Factor Meter (\( V_R \)), the load current \( I \) is inversely proportional to the load p.f. \( \cos \phi_R \). Consequently, with the decrease in load p.f., the load current and hence the line losses are increased. This leads to the conclusion that transmission efficiency of a line decreases with the decrease in load Power Factor Regulator p.f. and vice-versa.
MEDIUM TRANSMISSION LINES

In short transmission line calculations, the effects of the line capacitance are neglected because such lines have smaller lengths and transmit power at relatively low voltages (< 20 kV). However, as the length and voltage of the line increase, the capacitance gradually becomes of greater importance.

Since medium transmission lines have sufficient length (50-150 km) and usually operate at voltages greater than 20 kV, the effects of capacitance cannot be neglected. Therefore, in order to obtain reasonable accuracy in medium transmission line calculations, the line capacitance must be taken into consideration.

The capacitance is uniformly distributed over the entire length of the line. However, in order to make the calculations simple, the line capacitance is assumed to be lumped or concentrated in the form of capacitors shunted across the line at one or more points. Such a treatment of localising the line capacitance gives reasonably accurate results. The most commonly used methods (known as localised capacitance methods) for the solution of medium transmissions lines are:

(i) End condenser method

(ii) Nominal T method

(iii) Nominal π method.

Although the above methods are used for obtaining the performance calculations of medium lines, they can also be used for short lines if their line capacitance is given in a particular problem.

i) End Condenser Method

In this method, the capacitance of the line is lumped or concentrated at the receiving or load end as shown in Fig. This method of localising the line capacitance at the load end overestimates the effects of capacitance. In Fig, one phase of the 3-phase transmission line is shown as it is more convenient to work in phase instead of line-to-line values.
Let

\[ \begin{align*}
I_R &= \text{load current per phase} \\
R &= \text{resistance per phase} \\
XL &= \text{inductive reactance per phase} \\
C &= \text{capacitance per phase} \\
\cos \phi R &= \text{receiving end power factor (lagging)} \\
V_S &= \text{sending end voltage per phase}
\end{align*} \]

The phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage \( V_R \) as the reference phasor,

we have, \( \overrightarrow{V_R} = V_R + j0 \)

Load current, \( \overrightarrow{I_R} = I_R (\cos \phi_R - j \sin \phi_R) \)

Capacitive current, \( \overrightarrow{I_C} = j \overrightarrow{V_R} \omega C = j 2 \pi f C \overrightarrow{V_R} \)

The sending end current \( \overrightarrow{I_S} \) is the phasor sum of load current \( \overrightarrow{I_R} \) and capacitive current \( \overrightarrow{I_C} \), i.e.,

\[ \overrightarrow{I_S} = \overrightarrow{I_R} + \overrightarrow{I_C} \]

\[ = I_R (\cos \phi_R - j \sin \phi_R) + j 2 \pi f C V_R \]

\[ = I_R \cos \phi_R + j (-I_R \sin \phi_R + 2 \pi f C V_R) \]

\[ = \overrightarrow{I_S} (R + j X_L) \]

\[ \overrightarrow{V_S} = \overrightarrow{V_R} + \overrightarrow{I_S} Z = \overrightarrow{V_R} + \overrightarrow{I_S} (R + j X_L) \]

Thus, the magnitude of sending end voltage \( V_S \) can be calculated.

\[ \frac{\% \text{ Voltage regulation}}{} \times 100 = \frac{V_S - V_R}{V_R} \times 100 \]

\[ \frac{\% \text{ Voltage transmission efficiency}}{} \times 100 = \frac{\text{Power delivered/phase}}{\text{Power delivered/phase} + \text{losses/phase}} \times 100 \]

\[ = \frac{V_R I_R \cos \phi_R}{V_R I_R \cos \phi_R + I_S^2 R} \times 100 \]

Limitations

Although end condenser method for the solution of medium lines is simple to work out calculations, yet it has the following drawbacks:

(i) There is a considerable error (about 10%) in calculations because the distributed capacitance has been assumed to be lumped or concentrated.
(ii) This method overestimates the effects of line capacitance.

**ii) Nominal T Method**

In this method, the whole line capacitance is assumed to be concentrated at the middle point of the line and half the line resistance and reactance are lumped on its either side as shown in Fig. Therefore, in this arrangement, full charging current flows over half the line. In Fig. one phase of 3-phase transmission line is shown as it is advantageous to work in phase instead of line-to-line values.

![Phasor Diagram](image)

Let

\[ I_R = \text{load current per phase} ; \quad R = \text{resistance per phase} \]

\[ XL = \text{inductive reactance per phase} ; \quad C = \text{capacitance per phase} \]

\[ \cos \phi_R = \text{receiving end power factor (lagging)} ; \quad V_S = \text{sending end voltage/phase} \]

\[ V_1 = \text{voltage across capacitor C} \]

The phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage \( V_R \) as the reference phasor, we have,
iii) Nominal π Method

In this method, capacitance of each conductor (i.e., line to neutral) is divided into two halves; one half being lumped at the sending end and the other half at the receiving end as shown in Fig. It is obvious that capacitance at the sending end has no effect on the line drop. However, its charging current must be added to line current in order to obtain the total sending end current.

Voltage across $C$, \[ \bar{V}_1 = \bar{V}_R + \bar{I}_R \bar{Z} / 2 \]

= $V_R + I_R (\cos \phi_R - j \sin \phi_R) \left( \frac{R}{2} + j \frac{X_L}{2} \right)$

Capacitive current, \[ \bar{I}_C = j \omega C \bar{V}_1 = j 2\pi f C \bar{V}_1 \]

Sending end current, \[ \bar{I}_S = \bar{I}_R + \bar{I}_C \]

Sending end voltage, \[ \bar{V}_s = \bar{V}_1 + \bar{I}_S \frac{R}{2} = \bar{V}_1 + \bar{I}_S \left( \frac{R}{2} + j \frac{X_L}{2} \right) \]

Receiving end voltage, \[ \bar{V}_R = V_R + j 0 \]

Load current, \[ \bar{I}_R = I_R (\cos \phi_R - j \sin \phi_R) \]
Let

\[ IR = \text{load current per phase} \quad R = \text{resistance per phase} \]
\[ XL = \text{inductive reactance per phase} \quad C = \text{capacitance per phase} \]
\[ \cos \phi_R = \text{receiving end power factor (lagging)} \quad V_S = \text{sending end voltage per phase} \]

The phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage as the reference phasor, we have,

\[ \overline{V_R} = V_R + j0 \]
\[ \overline{I_R} = I_R \left( \cos \phi_R - j \sin \phi_R \right) \]

Load current,

Charging current at load end is

\[ \overline{I_{C1}} = j \omega \left( \frac{C}{2} \right) \overline{V_R} = j \pi f C \overline{V_R} \]
ASSIGNMENT QUESTIONS

1. A single phase overhead transmission line delivers 1100 KW at 33 KV at 0.8 p.f. lagging. The total resistance and inductive reactance of the line are 10 Ω and 15 Ω respectively. Determine: i) sending end voltage ii) sending end power factor and iii) transmission efficiency.

2. An overhead 3- phase transmission line delivers 5000 KW at 22 kV at 0.8 p.f. lagging. The resistance and reactance of each conductor are 4 Ω and 6 Ω respectively. Determine: i) sending end voltage ii) percentage regulation and iii) transmission efficiency.

3. A medium single phase transmission line 100 km long has resistance/km is 0.25 Ω, reactance/km is 0.8 Ω, susceptance/km 14 × 10^{-6} siemen and receiving end line voltage 66000 V. Assuming that the total capacitance of the line is localized at the receiving end alone, determine i) the sending end current, ii) sending end voltage, iii) regulation, iv) supply power factor. The line is delivering 15000 kW at 0.8 power factor lagging.

4. A 3-phase, 50 Hz overhead transmission line 100 km long has resistance/km/phase is 0.1 Ω, inductive reactance/km/phase is 0.2 Ω, capacitive susceptance/km/phase 0.04 × 10^{-4} siemen. determine i) the sending end current, ii) sending end voltage, iii) sending end power factor and iv) transmission efficiency when supplying a balance load of 10000 kW at 66 kV, p.f. 0.8 lagging using nominal T method.

5. A 100 km long, 3-phase, 50 Hz overhead transmission line has resistance/km/phase is 0.1 Ω, reactance/km/phase is 0.5 Ω, susceptance/km/phase 10 × 10^{-6} S. If the line supplies load p.f. of 20 MW at 0.9 p.f. lagging at 66 kV at the receiving end, determine by nominal π method i) sending end power factor ii) regulation and iii) transmission efficiency.