POWER TRANSMISSION OVERHEAD LINES
Model, operation and performance

1. Representation of Transmission lines

It is convenient to represent a transmission line by the two-port network shown in Fig. 1.1, where V_S and I_S are the sending-end voltage and current, and V_R and I_R are the receiving-end voltage and current.

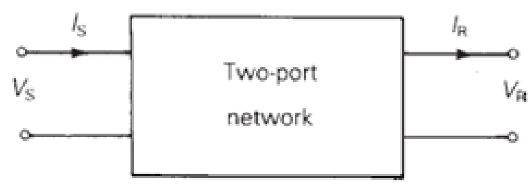

Fig. 3.11: Representation of a four-terminal (two-port) network

The relation between the sending-end and receiving-end quantities can be written as

$$\overline{V_S} = A.\overline{V_R} + B.\overline{I_R} \quad (3.32)$$

$$\overline{I_S} = C.\overline{V_R} + D.\overline{I_R} \quad (3.33)$$

and it can be readily shown that:

$$AD - BC = 1 \quad (3.34)$$

The complex parameters A, B, C and D describe the network in terms of the sending and receiving-end voltages and currents. They depend on the transmission-line constants R, L, C, and G.

1.1. Short Line approximation (up to 80km)

The circuit in Fig. 1.2 represents a short transmission line, usually applied to overhead lines less than 80 km long. Only the series resistance and reactance are included. The shunt admittance is neglected. The circuit applies to either single-phase or completely transposed three-phase lines operating under balanced conditions. For a completely transposed three-phase line, Z is the series impedance, V_S and V_R are line-to-neutral voltages.

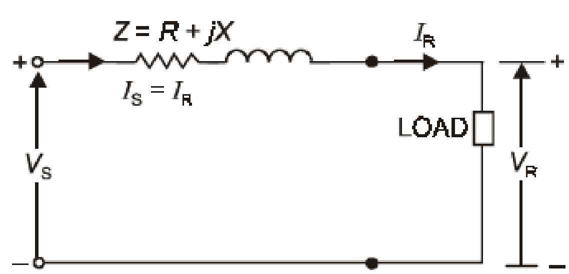

Fig. 3.12: Equivalent circuit of a short line (representation under balanced three phase conditions)

The ABCD parameters for the short line are easily obtained by writing KCL equation as

$$\overline{I_S} = \overline{I_R} \quad (3.35)$$

$$\overline{V_S} = \overline{V_R} + \overline{Z}.\overline{I_R} \tag{3.36}$$

with $\overline{Z} = R + j\omega L$

The ABCD parameters for a short line are:

$$A = D = 1 \qquad B = \overline{Z} \qquad C = 0 \tag{3.37}$$

1.2. Medium-Length Line approximation (up to 240 km)

For medium-length lines, typically ranging from 80 to 250 km at 60 Hz, it is common to lump the total shunt capacitance and locate half at each end of the line. Such a circuit, called a nominal π circuit, is shown in Fig. 1.3. Recall that shunt conductance G is usually neglected for overhead transmission.

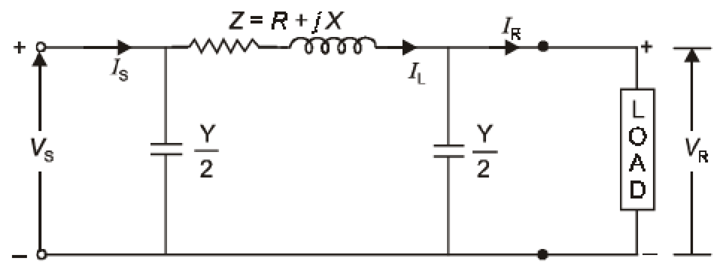

Fig. 3.13 Medium-length line – π equivalent circuit

Writing KCL equations:

$$\overline{V_S} = \left(\overline{I_R} + \frac{\overline{Y}}{2}.\overline{V_R}\right)\overline{Z} + \overline{V_R} = \left(\frac{\overline{Z}\,\overline{Y}}{2} + 1\right)\overline{V_R} + \overline{Z}.\overline{I_R} \tag{3.38}$$

$$\overline{I_S} = \overline{V_S}\frac{\overline{Y}}{2} + \overline{V_R}\frac{\overline{Y}}{2} + \overline{I_R} = \overline{Y}\left(1 + \frac{\overline{Z}\,\overline{Y}}{4}\right)\overline{V_R} + \left(\frac{\overline{Z}\,\overline{Y}}{2} + 1\right)\overline{I_R} \tag{3.39}$$

from which V_S and I_S are obtained in terms of V_R and I_R giving the following constants:

$$A = D = \frac{\overline{Z}\,\overline{Y}}{2} + 1$$
$$B = \overline{Z} \tag{3.40}$$
$$C = \overline{Y}\left(\frac{\overline{Z}\,\overline{Y}}{4} + 1\right)$$

Notes:

1. To avoid confusion between total series impedance and series impedance per unit length, we use the z for series impedance per unit length and Z for total impedance; and y for shunt admittance per unit length and Y for total shunt admittance.

$z = R + j\omega L$ and $Z = z \cdot l$

$y = j\omega C$ and $Y = y \cdot l$

l : length of the line

2. A medium-length line could also be approximated by the T circuit lumping half of the series impedance at each end of the line.

Note that for both the short and medium-length lines, the relation $AD - BC = 1$ is verified. Note also that since the line is the same when viewed from either end, $A = D$.

1.3. The Long Line (above 240 km)

Here the treatment assumes distributed parameters. The changes in voltage and current over an elemental length Δx of the line, x metres from the sending end, are determined, and given below (Fig. 1.5):

$$\Delta V = I.\Delta z = Iz.\Delta x \tag{3.41}$$

$$\Delta I = V.\Delta y = Vy.\Delta x \tag{3.42}$$

For an elemental length Δx of the line: $\Delta z = z.\Delta x$ and $\Delta y = y.\Delta x$
where z: impedance/unit length and y: shunt admittance/unit length.

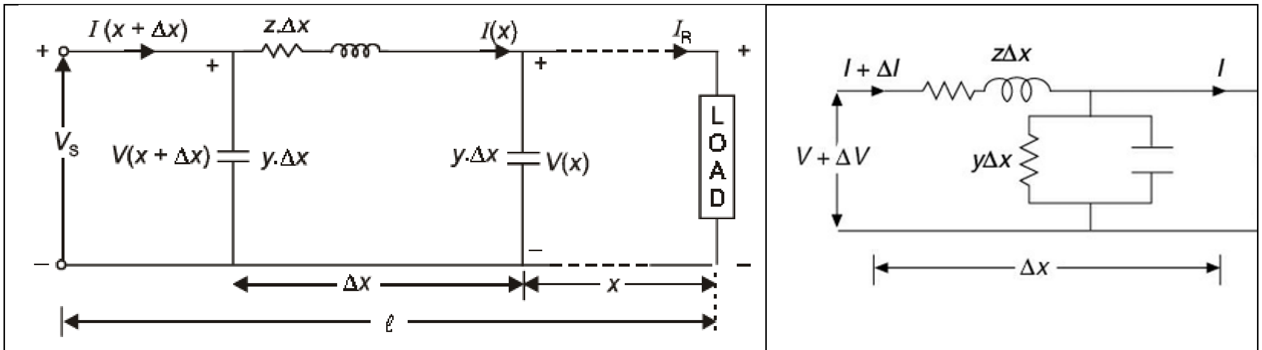

Fig. 3.14: Schematic diagram of a long line with distributed parameters

$$\frac{\Delta V}{\Delta x} = Iz \quad \text{and} \quad \frac{\Delta I}{\Delta x} = Vy \tag{3.43}$$

If $\Delta x \to 0$ then:

$$\frac{\partial V}{\partial x} = Iz \quad \text{and} \quad \frac{\partial I}{\partial x} = Vy \tag{3.44}$$

Hence,

$$\begin{cases} \dfrac{\partial^2 I}{\partial x^2} = y\dfrac{\partial V}{dx} \\ \dfrac{\partial^2 V}{\partial x^2} = z\dfrac{\partial I}{dx} \end{cases} \rightarrow \begin{cases} \dfrac{\partial^2 I}{\partial x^2} = yzI \\ \dfrac{\partial^2 V}{\partial x^2} = yzV \end{cases} \tag{3.45}$$

Solution to these equations with initial condition: $x = 0$, $V = V_R$ and $I = I_R$ for a distance x from the receiving end takes the form:

$$V(x) = \frac{V_R + Z_c I_R}{2} e^{\gamma x} + \frac{V_R - Z_c I_R}{2} e^{-\gamma x} \tag{3.46}$$

$$I(x) = \frac{\frac{V_R}{Z_c} + I_R}{2} e^{\gamma x} - \frac{\frac{V_R}{Z_c} - I_R}{2} e^{-\gamma x} \tag{3.47}$$

where:

$Z_c = \sqrt{\frac{z}{y}}$: characteristic impedance of the line

$\gamma = \sqrt{yz} = \alpha + j\beta$: propagation constant

α : attenuation constant and β: phase constant

The propagation constant γ represents the changes occurring in the transmitted wave as it progresses along the line; α measures the attenuation, and β the angular phase-shift.

Using hyperbolic functions:

$$\cosh\theta = \frac{e^{\theta} + e^{-\theta}}{2} \quad \text{and} \quad \sinh\theta = \frac{e^{\theta} - e^{-\theta}}{2}$$

we obtain:

$$V(x) = V_R \cosh(\gamma x) + I_R Z_c \sinh(\gamma x) \tag{3.48}$$

$$I(x) = \frac{V_R}{Z_c}\sinh(\gamma x) + I_R \cosh(\gamma x) \tag{3.49}$$

Usually conditions at the sending are required when $x = l$ in equations (3.6): $V(l) = V_S$ and $I(l) = I_S$

$$\overline{V_S} = \overline{V_R} \cosh(\gamma l) + \overline{I_R} Z_c \sinh(\gamma l) \tag{3.50}$$

$$\overline{I_S} = \frac{\overline{V_R}}{Z_c}\sinh(\gamma l) + \overline{I_R} \cosh(\gamma l) \tag{3.51}$$

Or alternatively:

$$\overline{V_R} = \overline{V_S} \cosh(\gamma l) - \overline{I_S} Z_c \sinh(\gamma l) \tag{3.52}$$

$$\overline{I_R} = -\frac{\overline{V_S}}{Z_c}\sinh(\gamma l) + \overline{I_S} \cosh(\gamma l) \tag{3.53}$$

The parameters of the equivalent four-terminal network are thus,

$$\begin{aligned} A = D &= \cosh(\gamma l) \\ B &= Z_c \sinh(\gamma l) \\ C &= \frac{\sinh(\gamma l)}{Z_c} \end{aligned} \tag{3.54}$$

An equivalent circuit for the long line can be expressed in the form of the π model. The circuit shown in Fig. 1.6 is identical in structure to the nominal pi circuit of Fig. 1.3, except that Z' and Y' are used instead of Z and Y. Our objective is to determine Z' and Y' such that the equivalent π circuit has the same $ABCD$ parameters as those of the distributed line. The $ABCD$ parameters of the equivalent pi circuit are:

$$\begin{aligned} A = D &= \frac{\overline{Z'}\,\overline{Y'}}{2} + 1 \\ B &= \overline{Z'} \\ C &= \overline{Y'}\left(\frac{\overline{Z'}\,\overline{Y'}}{4} + 1\right) \end{aligned} \tag{3.55}$$

which yields the four-terminal network equations:

$$\overline{V_S} = \left(\frac{\overline{Z'}\,\overline{Y'}}{2} + 1\right)\overline{V_R} + \overline{Z'}.\overline{I_R} \tag{3.56}$$

$$\overline{I_S} = \overline{Y'}\left(1 + \frac{\overline{Z'}\,\overline{Y'}}{4}\right)\overline{V_R} + \left(\frac{\overline{Z'}\,\overline{Y'}}{2} + 1\right)\overline{I_R} \tag{3.57}$$

By identification:

$$Z' = Z_c \sinh(\gamma l) = Z\frac{\sinh(\gamma l)}{\gamma l} \tag{3.58}$$

$$\frac{Y'}{2} = \frac{\cosh(\gamma l) - 1}{Z_c \sinh(\gamma l)} = \frac{Y}{2}\,\frac{tgh(\gamma l/2)}{\gamma l/2} \tag{3.59}$$

where Z: total series impedance of line and Y: total shunt admittance of line ($Z = zl$ and $Y = yl$).

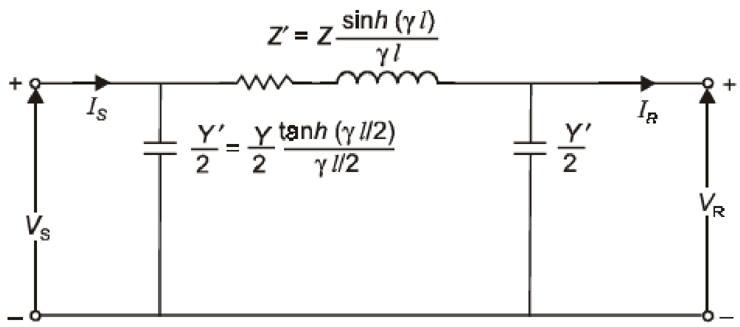

Fig. 3.15: Equivalent circuit to represent the terminal conditions of a long line

The $ABCD$ parameters given by (3.54) are exact parameters valid for any line length. For accurate calculations, these equations must be used for overhead 50-Hz lines longer than 250km.The $ABCD$ parameters derived in sections 1.1 and 1.2 are approximate parameters that are more conveniently used for hand calculations involving short and medium-length lines.

2. Voltage regulation

Voltage regulation of the transmission line may be defined as the percentage change in voltage at the receiving end of the line when the load varies from no-load to a full load at a specified power factor, while the sending-end voltage is held constant. Expressed in percent of full-load voltage,

$$RV(\%) = \frac{V_{R0} - V_R}{V_R} \times 100 \tag{3.60}$$

avec: V_{R0} magnitude of no-load receiving end voltage

V_R magnitude of full-load receiving end voltage

At no load, $I_R = 0, V_R = V_{R0}$

Hence,

$$\overline{V_S} = A.\overline{V_{R0}} \quad \rightarrow \quad V_{R0} = \frac{V_S}{|A|} \tag{3.61}$$

then:

$$RV(\%) = \frac{V_S - |A|V_R}{|A|V_R} \times 100 \tag{3.62}$$

In practice, transmission-line voltages decrease when heavily loaded and increase when lightly loaded. When voltages on EHV lines are maintained within ±5% of rated voltage, corresponding to about 10% voltage regulation, unusual operating problems are not encountered. Ten percent voltage regulation for lower voltage lines including transformer-voltage drops is also considered good operating practice.

For a short line, $A = 1$, hence,

$$RV(\%) = \frac{V_S - V_R}{V_R} \times 100 \tag{3.63}$$

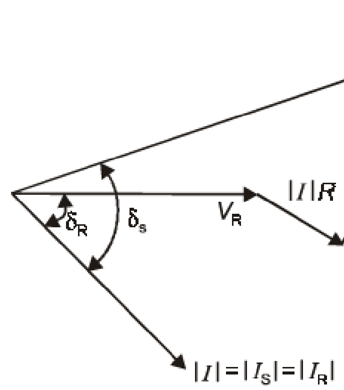

Fig. 3.16: Phasor diagram

The phasor diagram is shown in Fig. 3.16 for lagging load current. We ca write

$$V_S \cos(\varphi_S - \varphi_R) = RI\,cos\,\varphi_R + XI\,sin\,\varphi_R + V_R$$

$(\varphi_S - \varphi_R)$ is very small, so $\cos(\varphi_S - \varphi_R) \approx 1$

$$V_S = V_R + I(Rcos\,\varphi_R + X\,sin\,\varphi_R)$$

Then

$$RV(\%) = \frac{I(Rcos\,\varphi_R + X\,sin\,\varphi_R)}{V_R} \times 100 \tag{3.64}$$

In the above derivation, φ_R has been considered positive for a lagging load. φ_R will be negative, for leading load.

From the above equations, it is clear that the voltage regulation is a measure of line voltage drop and depends on the load power factor.

Line voltage drop in terms of active and reactive powers can be written:

$$\Delta V = V_S - V_R = \frac{V_R}{V_R} I\left(Rcos\,\varphi_R + X\,sin\,\varphi_R\right) = \frac{V_R IRcos\,\varphi_R + V_R I\,X\,sin\,\varphi_R}{V_R}$$

Or

$$\Delta V = \frac{R\,P_R + X\,Q_R}{V_R} \tag{3.65}$$

Ferranti effect

In long transmission lines and cables, receiving-end voltage is greater than sending-end voltage during light-load or no-load operation. This occurs due to high-charging current. This effect is known as Ferranti effect. When an open-circuited line (no-load) is charged, it draws significant amount of current due to capacitive effect of the line. This is more in high-voltage long transmission lines. Ferranti effect can be understood as follows.

Under no-load ($I_R = 0$), we can write Eq. (3.50) as

$$\overline{V_S} = \overline{V_R}\cosh(\gamma l) \tag{3.66}$$

Or

$$\overline{V_R} = \frac{\overline{V_S}}{\cosh(\gamma l)} \tag{3.67}$$

From Eq. (3.67), it is seen that the value of V_R is always greater or equal to V_S because the value of $cosh(\gamma l)$ is always less than or equal to unity. Actual value depends on the γl, which is a function of inductance, capacitance and length of the line.

3. Power flow through a transmission line

Fig. shows the transmission line connected with load. At sending end, a power source is supplying the power to the load. Receiving end is assumed as reference. The sending-end angle δ should be positive because real power flows from higher angle to lower angle. It is also true that reactive power always flows from higher voltage to lower voltage, which varies throughout the line. The direction of real power flow is same throughout the line, however, reactive power depends on the voltage profile of the line.

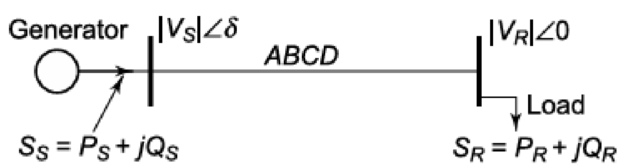

Fig. 3.17: Power flow through a transmission line

Let us take receiving-end voltage as a reference phasor ($\overline{V_R} = V_R\angle 0°$) and let the sending-end voltage lead it by an angle d ($\overline{V_S} = V_S\angle\delta$). Let also $A = |A|\angle\alpha$ and $B = |B|\angle\beta$.

We can derive receiving- and sending-end currents expressions in terms of receiving- and sending-end voltages as

$$\overline{V_S} = A.\overline{V_R} + B.\overline{I_R} \quad \rightarrow \quad \overline{I_R} = \frac{\overline{V_S} - A.\overline{V_R}}{B}$$

$$\overline{I_S} = C.\overline{V_R} + D.\frac{\overline{V_S} - A.\overline{V_R}}{B} = \frac{D.\overline{V_S}}{B} - \frac{(AD - BC)\cdot\overline{V_R}}{B} = \frac{A.\overline{V_S}}{B} - \frac{\overline{V_R}}{B}$$

Therefore, we can write

$$\overline{I_R} = \frac{V_S}{|B|}\angle\delta - \beta - \frac{|A|.V_R}{|B|}\angle\alpha - \beta \tag{3.68}$$

$$\overline{I_S} = \frac{A \cdot V_S}{|B|}\angle\delta + \alpha - \beta - \frac{V_R}{|B|}\angle - \beta \tag{3.69}$$

Receiving-end complex power

$$\overline{S_R} = P_R + jQ_R = \overline{V_R}.\overline{I_R}^* = \frac{V_S V_R}{|B|}\angle\beta - \delta - \frac{|A|V_R^2}{|B|}\angle\beta - \alpha \tag{3.70}$$

Similarly,

$$\overline{S_S} = P_S + jQ_S = \overline{V_S}.\overline{I_S}^* = \frac{|A|V_S^2}{|B|}\angle\beta - \alpha - \frac{V_S V_R}{|B|}\angle\beta + \delta \tag{3.71}$$

In the above equations S_R and S_S are per phase complex voltamperes, while V_R and V_S are expressed in per phase volts. If V_S and V_R are replaced by line voltages in kV, the complex power will be a three phase power in MVA.

Real power (P_R) and reactive power (Q_R) at receiving end can be written as

$$P_R = \frac{V_S V_R}{|B|}\cos(\beta - \delta) - \frac{|A|V_R^2}{|B|}\cos(\beta - \alpha) = V_R I_R cos\varphi_R \tag{3.72}$$

$$Q_R = \frac{V_S V_R}{|B|}\sin(\beta - \delta) - \frac{|A|V_R^2}{|B|}\sin(\beta - \alpha) = V_R I_R sin\varphi_R \tag{3.73}$$

Similarly, the real and reactive powers at sending-end are

$$P_S = \frac{|A|V_S^2}{|B|}cos(\beta - \alpha) - \frac{V_S V_R}{|B|}cos(\beta + \delta) \tag{3.74}$$

$$Q_S = \frac{|A|V_S^2}{|B|}sin(\beta - \alpha) - \frac{V_S V_R}{|B|}sin(\beta + \delta) \tag{3.75}$$

From Eq. (3.72), it can be seen that the maximum power P_{max} (keeping voltages constant) received by the load will be at $\delta = \beta$, because α and β are constants and depend on the line configuration and design. Therefore, we get

$$P_{Rmax} = \frac{V_S V_R}{|B|} - \frac{|A|V_R^2}{|B|}\cos(\beta - \alpha) \tag{3.76}$$

The corresponding Q_R (at max P_R) is

$$Q_R = -\frac{|A|V_R^2}{|B|}\sin(\beta - \alpha) \tag{3.77}$$

Thus, the load must draw this much leading reactive power in order to receive the maximum real power.

The transmission real power loss,

$$P_L = P_S - P_R \tag{3.78}$$

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 during transmitting power from sending end to receiving end. Hence, performance of transmission line can be determined by its efficiency. The efficiency of the line is defined as follows:

$$\eta = \frac{P_R}{P_S} = \frac{P_S - P_L}{P_S} \tag{3.79}$$

Case of lossless short line

For a short line, $A = D = 1$ and $B = \overline{Z} = Z\angle\varphi$. Substituting these values in Eq. (3.72), we get

$$P_R = \frac{V_S V_R}{Z}\cos(\varphi - \delta) - \frac{V_R^2}{Z} \tag{3.80}$$

Normally the resistance of a transmission line is small compared to its reactance $R \ll X$ (since it is necessary to maintain a high efficiency of transmission), so that $\overline{Z} = jX = X\angle 90°$. The receiving end Eqs (3.72) and (3.73) can then be approximated as

$$P_R = \frac{V_S V_R}{X}\cos(90° - \delta) = \frac{V_S V_R}{X}\sin\delta \tag{3.81}$$

$$Q_R = \frac{V_S V_R}{X}\sin(90° - \delta) - \frac{V_R^2}{X}\sin(90°) = \frac{V_S V_R}{X}cos\delta - \frac{V_R^2}{X} \tag{3.82}$$

For fixed voltage magnitudes V_S and V_R, the phase angle δ increases from 0 to 90 as the real power delivered increases (Fig. 3.18). The maximum power that the line can deliver, which occurs when $\delta = 90°$, is given by

$$P_{max} = \frac{V_S V_R}{X} \tag{3.83}$$

P_{max} represents the theoretical steady-state stability limit of a lossless line. If an attempt were made to exceed this steady-state stability limit, then synchronous machines at the sending end would lose synchronism with those at the receiving end.

We can make following observations:

1. Receiving-end power will be maximum at $\delta = 90°$.
2. Receiving-end power can be increased by increasing sending-end voltage magnitude V_S and/or receiving-end voltage magnitude V_R.
3. Reducing reactance of the line can increase receiving-end power.

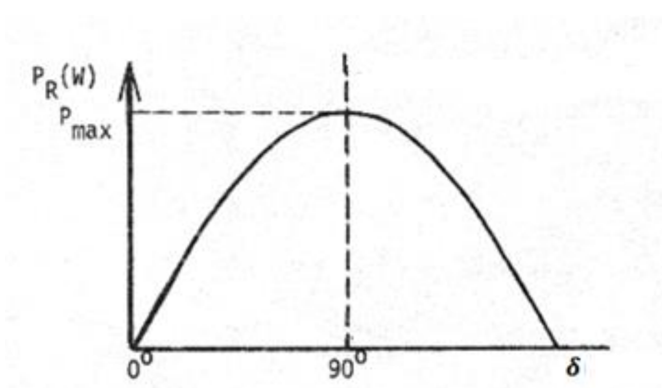

Fig. 3.18: Real power delivered by a lossless line versus voltage angle across the line

For $\delta > 90°$, the system becomes unstable, and the line cannot transmit any more power. In practice, a much lower static stability limit is used for the stable operating range: $|\delta| < \delta_{max} \approx 45°$.
If $\delta > 0$: Active power flows from end S to end R
If $\delta < 0$: Active power flows from end R to end S

Normally, angle δ is very small; Eq. (3.82) can be further simplified by assuming $cos\delta = 1$. Thus,

$$Q_R = \frac{V_R}{X}(V_S - V_R) \tag{3.84}$$

Let $\Delta V = V_S - V_R$, the magnitude of voltage drop across the transmission line

$$Q_R = \frac{V_R}{X}\Delta V \tag{3.85}$$

From Eq. (3.85), it can be observed that the reactive power is directly proportional to the difference in the voltage magnitudes. It also indicates that the reactive power is mainly dependent on the voltage however real power is mainly dependent on the angle δ.

Several important conclusions are enumerated below:
1. For $R = 0$ (which is a valid approximation for a transmission line) the real power transferred to the receiving-end is proportional to sin δ (i.e. δ for small values of δ), while the reactive power is proportional to the magnitude of the voltage drop across the line.
2. The real power received is maximum for $\delta = 90°$. Of course, δ is restricted to values well below 90º from considerations of stability.
3. Maximum real power transferred for a given line (fixed X) can be increased by raising its voltage level. It is from this consideration that voltage levels are being progressively pushed up to transmit larger chunks of power over longer distances warranted by large size generating stations. For very long lines, voltage level cannot be raised beyond the limits placed by present-day high voltage technology. To increase power transmitted in such cases, the only choice is to reduce the line reactance. This is accomplished by adding series capacitors in the line. Series capacitors would of course increase the severity of line over voltages under switching conditions.
4. The VARs (lagging reactive power) delivered by a line is proportional to the line voltage drop and is independent of δ. Therefore, in a transmission system if the VARs demand of the load is large, the voltage profile at that point tends to sag rather sharply. To maintain a desired voltage profile, the VARs demand of the load must be met locally by employing positive VAR generators (compensation).

Voltage stability

On the other hand, by using the identity $sin^2\delta + cos^2\delta = 1$, we can eliminate δ from eq. (3.81) and eq. (3.82):

$$\left(\frac{XP_R}{V_S V_R}\right)^2 + \left(\frac{X}{V_S V_R}\right)^2 \left(Q_R + \frac{V_R^2}{X}\right)^2 = 1$$

Which is quadratic equation in V_R^2 that yields to two solutions:

$$V_R^2 = \frac{V_S^2}{2} - Q_R X \pm \sqrt{\frac{V_S^4}{4} - X(Q_R V_S^2 + P_R^2 X)} \tag{3.86}$$

The shape of the voltage-power curve, also known as the PV curve, is shown in the Fig. 3.19. The figure illustrates an inverse relationship between load power and voltage: as the load increases, the voltage decreases gradually, until a limit point is reached where the voltage collapses. This limit point, or maximum load point, represents the limit of voltage stability. There is a maximum amount of power that the system can transmit. The margin, in terms of additional load, between the operating point and the maximum point can be used as a measure of proximity to voltage instability. This margin defines the static voltage stability margin. Another characteristic of the system is that a specific power level can be transmitted at two different voltage levels. The high voltage/low current solution is the normal operating mode for a power grid due to lower transmission losses. The other solution corresponds to an unstable operating point. The nature of the load, or any load compensation, can result in different curves, as shown in the Fig. 3.19.

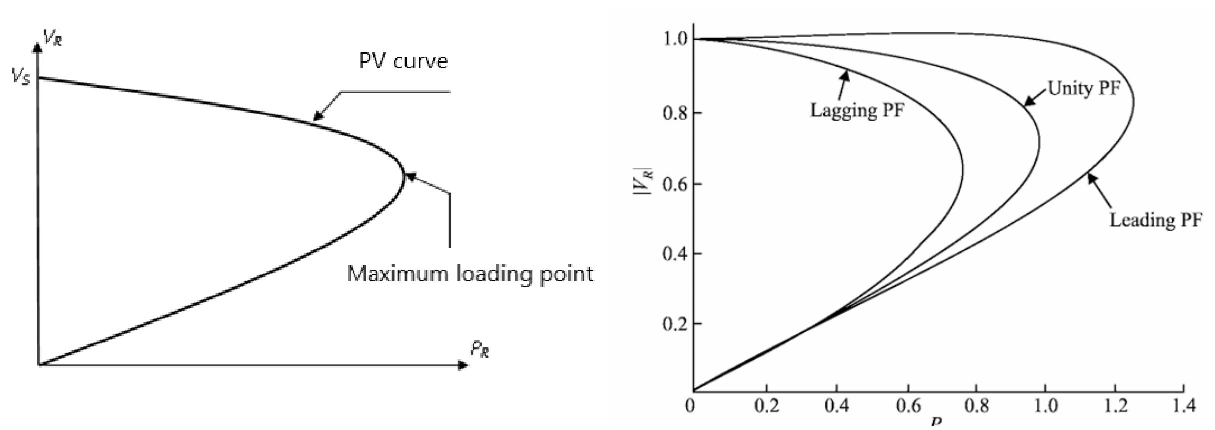

Fig. 3.19: Load voltage magnitude versus varying load (PV curve)

Power transmission capability

Power transfer capability of transmission lines is restricted mainly due to three reasons: thermal limit, voltage-drop limit and stability limit.

1. Thermal limit is due to heat generated when current flows in the conductor. Heat generated by line losses (I^2R) causes a temperature rise. Since line temperature of overhead lines must be kept within a safe limit to prevent excessive line sag between transmission towers and to prevent irreversible stretching, the ground clearance must be maintained in the case of overhead transmission lines. This imposes condition on the maximum safe current in a line. Several factors other than the current flowing in conductor are responsible for increase in the temperature such as design conditions (conductor size and geometry, spacing between towers, etc.) and operating conditions (ambient temperature, wind velocity, etc.). Cables are even more prone to thermal limit because of limited possibilities for heat transfer. However, there is no problem of sag in cables. But if the cable gets too hot, the insulation will begin to deteriorate and may fail in future.

2. In case of short lines, the ultimate transmission capability, using Eq. (3.81), is corresponding to $\delta = 90°$. But to have reasonable expectation of maintaining the synchronism, δ is limited to 30 to 60°. In this case, the stability limit is 60 to 70% of the ultimate capability. In short lines, the power handling capability is set by thermal limit rather than stability limit. However, it is reverse in the case of long transmission lines.

3. In medium transmission lines, the voltage drop is the main criterion for transferring maximum power over the lines. A line has current rating which provides the safe operation and above which it is not recommended for operation especially for long duration of time. Since lines are designed to operate at certain voltage level (restricted due to string insulators and clearances), sometimes rating is also given in terms of power which is multiplication of current and voltage. Extra-high voltage lines normally operate near to unity, the rating in MVA is almost the same as MW. Fig. 3.20 shows the limits with length of lines.

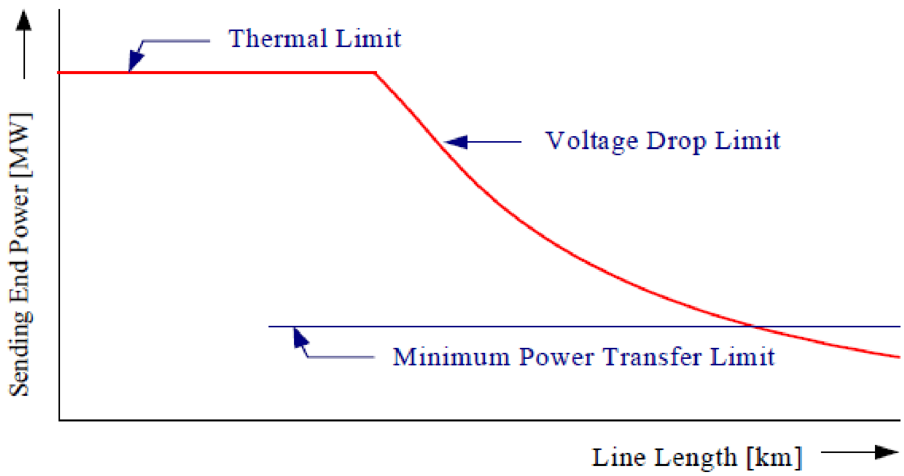

Fig. 3.20: Capability limits of lines

4. Transmission line transients

4.1. Interpretation of the long line equations

As already said in Eq. (3.46), γ is a complex number which can be expressed as $\gamma = \alpha + j\beta$

The real part α is called the attenuation constant and the imaginary part β is called the phase constant. Now $V(x)$ of Eq. (3.46) can be written as

$$V(x) = \left|\frac{V_R + Z_c I_R}{2}\right| e^{\alpha x} e^{j(\beta x + \varphi_1)} + \left|\frac{V_R - Z_c I_R}{2}\right| e^{-\alpha x} e^{-j(\beta x - \varphi_2)} \tag{3.87}$$

Where

$$\varphi_1 = \angle(V_R + Z_c I_R)$$
$$\varphi_2 = \angle(V_R - Z_c I_R)$$

The instantaneous voltage $v(x,t)$ can be written from Eq. (3.87) as

$$v(x,t) = \Re e\left[\sqrt{2}\left|\frac{V_R + Z_c I_R}{2}\right| e^{\alpha x} e^{j(\omega t + \beta x + \varphi_1)} + \sqrt{2}\left|\frac{V_R - Z_c I_R}{2}\right| e^{-\alpha x} e^{-j(\omega t + \beta x - \varphi_2)}\right] \tag{3.88}$$

The instantaneous voltage consists of two terms each of which is a function of two variables—time and distance. Thus they represent two travelling waves, i.e.,

$$v(x) = v_1(x) + v_2(x) \tag{3.89}$$

Now,

$$v_1(x) = \sqrt{2}\left|\frac{V_R + Z_c I_R}{2}\right| e^{\alpha x} cos(\omega t + \beta x + \varphi_1) \tag{3.90}$$

At any instant of time t, $v_1(x)$ is sinusoidally distributed along the distance from the receiving end with amplitude increasing exponentially with distance, as shown in Fig. 3.21 ($\alpha > 0$ for a line having resistance). After time Δt, the distribution advances in distance phase by $(\omega\Delta t/\beta)$. Thus, this wave is travelling towards the receiving-end and is the incident wave. Line losses cause its amplitude to decrease exponentially in going from the sending to the receiving-end.

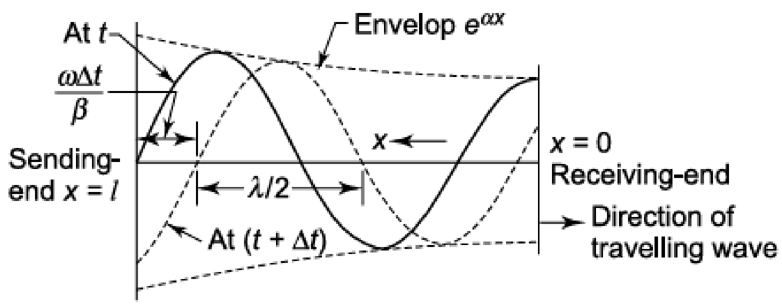

Fig. 3.21: Incident wave

Now,

$$v_2(x) = \sqrt{2}\left|\frac{V_R - Z_c I_R}{2}\right| e^{-\alpha x} cos(\omega t - \beta x + \varphi_2) \tag{3.91}$$

After time Δt the voltage distribution retards in distance phase by $(\omega\Delta t/\beta)$. This is the reflected wave travelling from the receiving end to the sending-end with amplitude decreasing exponentially in going from the receiving-end to the sending-end, as shown in Fig. 5.22.

At any point along the line, the voltage is the sum of incident and reflected voltage waves present at the point [Eq. (3.89)]. The same is true of current waves. Expressions for incident and reflected current waves can be similarly written down by proceeding from Eq. (3.47). If Z_c is pure resistance, current waves can be simply obtained from voltage waves by dividing by Z_c.

If the load impedance $Z_L = V_R/I_R = Z_c$, i.e., the line is terminated in its characteristic impedance, the reflected voltage wave is zero ($V_R - Z_c I_R = 0$). A line terminated in its characteristic impedance is called the infinite line. The incident wave under this condition cannot distinguish between a termination and an infinite continuation of the line.

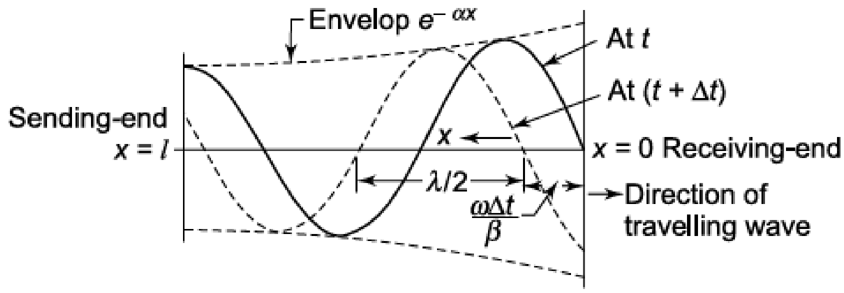

Fig. 3.22: Reflected wave

4.2. Natural Load and surge impedance

The characteristic impedance Z_C is known as the surge impedance if the line is considered to be lossless and all resistances are neglected. When a line is terminated in its characteristic impedance the power delivered is known as the natural load. For a loss-free line supplying its natural load the reactive power absorbed by the line is equal to the reactive power generated, that is.

$$\frac{V^2}{X_C} = I^2 X_L \tag{3.92}$$

At this load, V and I are in phase all along the line and optimum transmission conditions are obtained. In practice, however, the load impedances are seldom in the order of Z_C. Z_C has a value of about 400 Ω for an overhead line and its phase angle normally varies from 0° to –15°. For underground cables, Z_C is roughly one-tenth of the value for overhead lines. Lines are operated above the natural loading, whereas cables operate below this loading. The term surge impedance is, however, used in connection with surges (due to lightning or switching) or transmission lines, where the line loss can be neglected such that

$$Z_c = \sqrt{\frac{j\omega L}{-j\omega C}} = \sqrt{\frac{L}{C}} \tag{3.93}$$

which is a pure resistance.

Surge Impedance Loading (SIL) of a transmission line is defined as the power delivered by a line to purely resistive load equal in value to the surge impedance of the line.

At any time the voltage and current vary harmonically along the line with respect to x, the space coordinate. A complete voltage or current cycle along the line corresponds to a change of 2π rad in the angular argument βx. The corresponding line length is defined as the wavelength.

$$\lambda = \frac{2\pi}{\beta} \tag{3.94}$$

Velocity of propagation of wave,

$$v = \frac{\lambda}{\frac{1}{f}} = f\lambda \tag{3.95}$$

which is a well-known result.

For a lossless transmission line ($R = 0, G = 0$),

$$\gamma = \sqrt{yz} = j\omega\sqrt{LC} \tag{3.96}$$

So that $\alpha = 0$ and $\beta = \omega\sqrt{LC}$

$$\lambda = \frac{2\pi}{\beta} = \frac{2\pi}{\omega\sqrt{LC}} = \frac{1}{f\sqrt{LC}} \quad (m) \tag{3.97}$$

and

$$v = f\lambda = \frac{1}{\sqrt{LC}} \quad (m/s) \tag{3.98}$$

Using expressions of L and C established for transmission lines

$$v = \frac{1}{\sqrt{\frac{\mu_0}{2\pi} Ln\left(\frac{D}{r'}\right) \frac{2\pi\varepsilon_0}{Ln\left(\frac{D}{r}\right)}}} \quad (m/s) \tag{3.99}$$

Since r and r' are quite close to each other, when log is taken, it is sufficiently accurate to assume that $Ln\left(\frac{D}{r'}\right) \approx Ln\left(\frac{D}{r}\right)$.

$$v = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = 3.10^8 \quad (m/s) \tag{3.100}$$

The actual velocity of the propagation of wave along the line would be somewhat less than the velocity of light.

4.3. Surge phenomena and travelling waves

The ultra-fast transient overvoltages occur on a power system either originated externally by atmospheric lightning discharges on the exposed transmission lines or generated internally by the abrupt but normal network changes resulting from regular switching operations. These transients, termed surge phenomena, are entirely electric in nature and involve, essentially, only the transmission lines. Physically, a disturbance of this type causes an electromagnetic wave that travels with almost the speed of light along the lines, giving rise to reflected waves at the line terminations. The surge phenomena associated with these waves take place, therefore, during the first few milliseconds after their initiation. Due to the line losses, the travelling waves attenuate fast and die out after a few reflections. Also, the series inductances of transformer windings effectively block the disturbances, thereby preventing them from entering generator windings. However, due to the reinforcing action of several reflected waves, it is possible for voltages to build up to a level that could destroy the insulation of the high-voltage equipment. Lightning strokes hitting either ground wires or power conductors cause an injection of current, and divides the current into half, in two directions. The crest value of current along the struck conductor varies widely because of the wide variation in the intensity of the strokes; typical values being 10 kA and above.

In a case where a power line receives a direct stroke, the damage to equipment at line terminals is caused by the voltages between the line and the ground resulting from the injected charges, which travel along the line as current. These voltages are typically above 10^6 V. Strokes to the ground wires can also cause high- voltage surges on the power lines by electromagnetic induction. Transient overvoltages due to the surges provide a basis for selection of equipment insulation levels and surge-protection devices. At voltages up to about 220 kV, the insulation level of the lines and equipment is determined from the point of view of lightning protection. For voltages above 220 kV but less than 700 kV, switching operations as well as lightning are potentially damaging to insulation. At voltages above 700 kV, the level of insulation is decided mainly by the magnitude of switching surges. Overhead lines can be protected from direct strokes of lightning, in most cases, by one or more wires at ground potential strung at the highest point above the power-line conductors. These protecting wires, called ground wires, or shield wires, are connected to ground through the transmission towers supporting the line. The ground wires, rather than the power line, receive the lightning strokes in most cases. Fastest circuit breakers that operate within a few cycles (1 cycle = 20 ms) are too slow to protect against lightning or switching surges. Lightning surges can rise to peak levels within a few microseconds and switching surges within a few hundred microseconds, which is fast enough to destroy insulation before a circuit breaker could open. Surge arresters are used to protect equipment insulation against transient overvoltages. These devices limit voltage to a ceiling level and absorb the energy from lightning and switching surges.

The study of transmission-line surges, regardless of their origin, is very complex. For lightning surges on transmission lines, the study of a lossless line is usually considered. This simplification enables understanding of some of the phenomena without involving complicated theory. Here, voltages and current waveforms travelling along the line are of interest. The voltage and current distribution are propagated as travelling waves, and may consist of forward waves if moving in the direction of positive x and backward waves moving in the direction of negative x, both waves having the same velocity . As mentioned earlier, the velocity of propagation of voltage and current waves for an overhead line is approximately equal to $v = 3.10^8\ m/s$, the speed of light in free space. For undergraound cables, the speed of propagation is much lower than for overhead lines.
Travelling wave on a lossless line of the form is shown in Fig. 3.23. Since the argument $(x - tv)$ will not change if t and x are increased by the amounts Δt and $v\Delta t$, respectively, it is clear that the wave of the form represents a wave travelling in positive x direction with a velocity $v = \Delta x/\Delta t$.

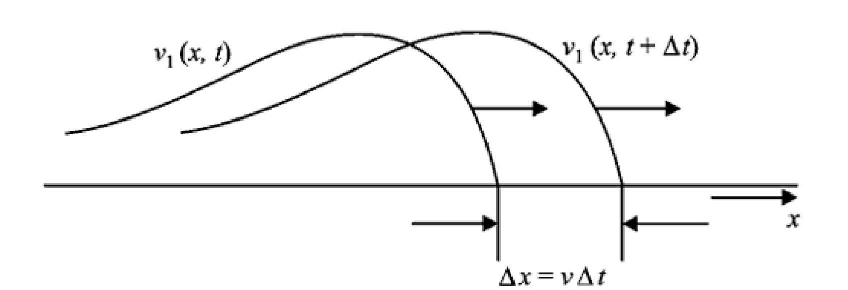

Fig. 3.23: Travelling voltage wave

5. High Voltage DC (HVDC) Transmission

The established method of transmitting large quantities of electrical energy is to use three-phase alternating-current. However, there is a limit to the distance that bulk ac can be transmitted unless some form of reactive compensation is employed. For long overhead lines either alternating current with reactive compensation (connected in shunt or series) or direct current may be used. If undersea crossings greater than around 50km are required, then, because of the capacitive charging current of ac cables, dc is the only option. Fig. 3.24 shows the distances at which dc becomes cheaper than ac for overhead line and submarine cable transmission. The terminal converter stations of a dc scheme are more expensive than ac substations but the overhead line is cheaper. The choice of whether to use ac or dc is usually made on cost. With the increasing use of high-voltage, high-current semiconductor devices, converter stations and their controls are becoming cheaper and more reliable, so making dc more attractive at shorter distances.

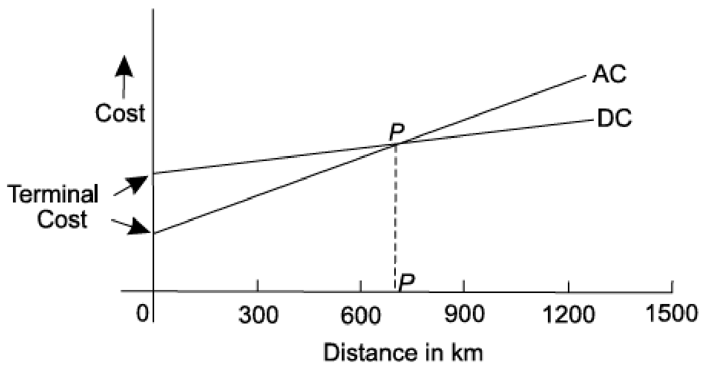

Fig. 3.24: Costs of dc and ac transmission

The main technical reasons for high-voltage direct-current (HVDC) transmission are for the:

1. Interconnection of two large ac systems without having to ensure synchronism and be concerned over stability between them (for example, the UK-France cross channel link of 2000MW);
2. interconnection between systems of different frequency (for example, the connections between north and south islands in Japan, which use 50 and 60Hz systems);
3. long overland transmission of high powers where ac transmission towers, insulators, and conductors are more expensive than using HVDC (for example, the Nelson River scheme in Manitoba– a total of 4000MW over more than 600km).

DC transmission requires a convertor at each end of the line. The sending end convertor act, as a rectifier converting ac to dc and the receiving end converter acts as an inverter converting dc to ac. The rectifier is fed from an ac source through a transformer and the inverter feeds ac load through a transformer. As we shall see later, the role of the converter is easily reversed from rectifier to inverter and vice versa, thereby, reversing the flow of dc power on the line. Modern day converters are thyristor based.

5.1. Types of dc links (transmission modes)

The dc links can be classified into the following types:

1. Monopolar Link: It has only one energised conductor normally of negative polarity and uses ground or sea water as the return path. It may be noted that earth has a much lower resistance to dc as compared to ac. The negative polarity is preferred on overhead lines due to lesser radio interference. Figure 3.25 shows a monopolar link.

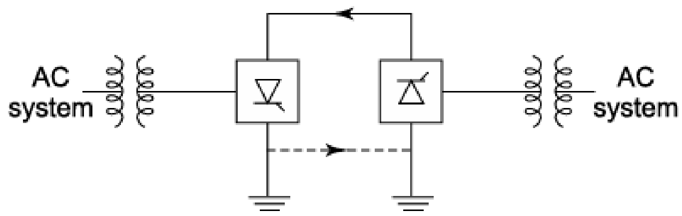

Fig. 3.25: Monopolar Link

2. Bipolar Link: This link has two conductors (Fig. 3.26), one positive and the other negative potential of the same magnitude (e.g., ±650 kV). At each terminal, two converters of equal rated voltages are connected in series on the dc side. The neutral points (i.e., the junctions between converters) are grounded, at one or both ends. If both the neutrals are grounded, the two poles operate independently. If the currents in the two conductors are equal, the ground current is zero. If one conductor has a fault, the other conductor (along with ground return) can supply half the rated load. The rated voltage of bipolar link is given as (say) ±650 kV.

A bipolar transmission has two circuits which are almost independent of each other. A bipolar line can be operated as a monopolar line in an emergency. In some applications continuous current through earth is not permitted, and a bipolar arrangement is the natural solution.

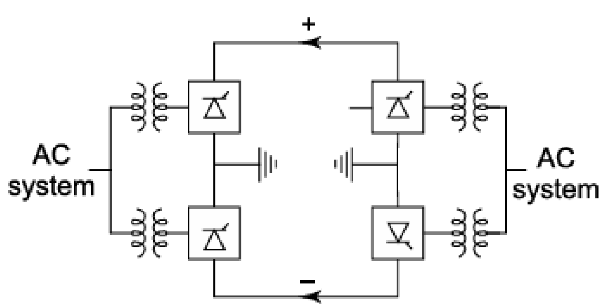

Fig. 3.26: Bipolar Link

3. Homopolar Link: A homopolar link (Fig. 3.27) has two or more conductors, all having the same polarity (usually negative), as the corona loss and radio interference get reduced, and it always operates with ground as the return. If one of the conductors develops a fault, the converter equipment can be reconnected so that the healthy conductor (with some overload capacity) can supply more than 50% of the rated power.

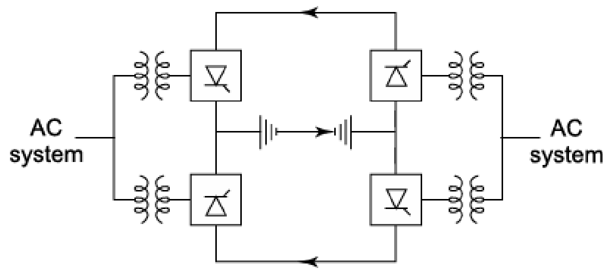

Fig. 3.27: Homopolar Link

A two-conductor dc line is more reliable than a three-conductor ac line, because in the event of a fault on one conductor, the other conductor can continue to operate with ground return during the fault period. The same is not possible with the ac line. Furthermore, if a two pole (homopolar) dc line is compared with a double-circuit three-phase ac line, the dc line costs would be about 45% less than the ac line. In general, the cost advantage of the dc line increases at higher voltages.

5.2. Structure of HVDC transmission

Transmission consists of two converter stations which are connected to each other by a dc cable or an overhead dc line. A typical arrangement of main components of an HVDC transmission is shown in Fig. 3.28.

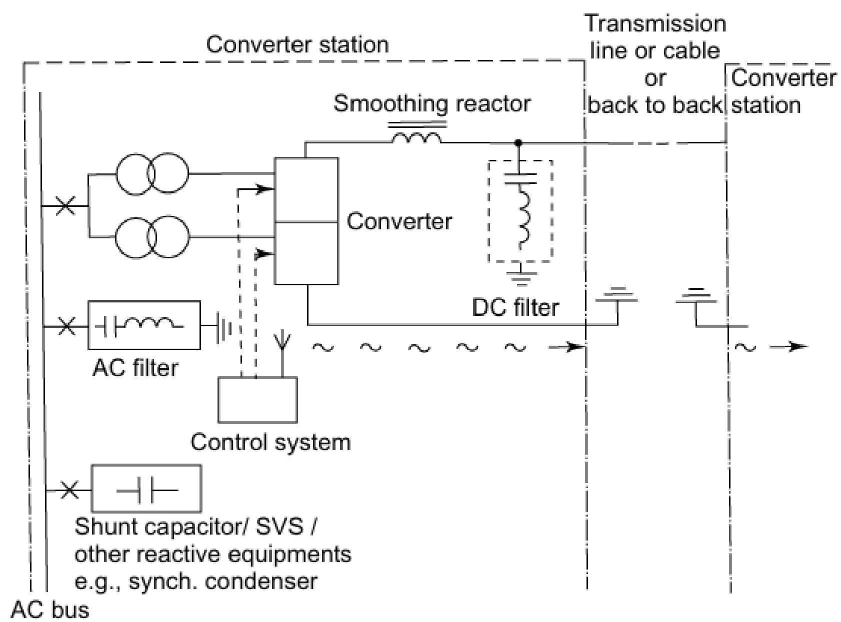

Fig. 3.28: Main components of a HVDC transmission—a typical arrangement

Two series connected 6-pulse converters (12-pulse bridge) consisting of valves and converter transformers are used. The valves convert ac to dc, and the transformers provide a suitable voltage ratio to achieve the desired direct voltage and galvanic separation of the ac and the dc systems. A smoothing reactor in the dc circuit reduces the harmonic currents in the dc line, and possible transient overcurrents. Filters are used to take care of harmonics generated at the conversion. Thus we see that, in an HVDC transmission, power is taken from one point in an ac network, where it is converted to dc in a converter station (rectifier), transmitted to another converter station (inverter) via line or a cable and injected into an ac system. By varying the firing angle α (point on the voltage wave when the gating pulse is applied and conduction starts) the dc output voltage can be controlled between two limits, $+v_e$ and $-v_e$. When α is varied, we get

Maximum dc voltage when $\alpha = 0°$
Rectifier operation when $0 < \alpha < 90°$
Inverter operation when $90° < \alpha < 180°$

5.3. Principles of HVDC control

One of the most important aspects of HVDC systems is its fast and stable controllability. In dc transmission, the current and power flows from higher voltage (rectifier side) to lower voltage (inverter side) and is proportional to the voltage difference between the two sides as shown in Fig. 3.29. The amount of power transmitted is, therefore, easily controlled by adjusting the two voltages. For reversal of power flow, the roles of rectifier and inverter are interchanged by adjusting their firing angles. This automatically causes the reversal of dc polarity.

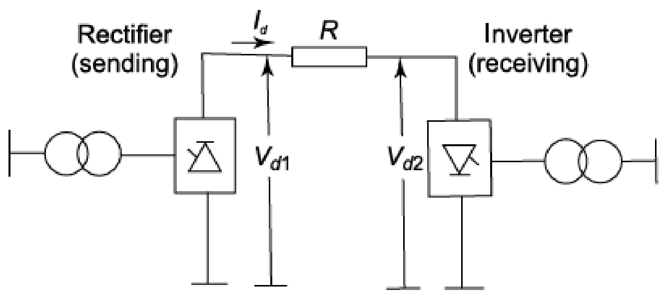

Fig. 3.29: HVDC control

In an HVDC transmission, one of the converter stations, generally the inverter station, is so controlled that the direct voltage of the system is fixed and has a rigid relation to the voltage on the ac side. Tap changers take care of the slow variations on the ac side. The other terminal station (rectifier) adjusts the direct voltage on its terminal so that the current is controlled to the desired transmitted power.

In Fig 3.29

$$I_d = \frac{V_{d1} - V_{d2}}{R} \tag{3.101}$$

where R is the resistance of link and includes loop transmission resistance (if any), and resistance of smoothing reactors and converter valves. The power received is, therefore, given as

$$P = I_d V_{d2} = \left(\frac{V_{d1} - V_{d2}}{R}\right) V_{d2} \tag{3.102}$$

From Eq. (3.102) it is clear that the dc power per pole is controlled by relative control of dc terminal voltages, V_{d1} and V_{d2}. Control on dc, voltage is exercised by the converter control angles α. Normal operating range of control angles is:

$$\alpha_{min} = 5° \ , \ \alpha_{max} = (15 \pm 3)°$$

The prime considerations in HVDC transmission are to minimise reactive power requirement at the terminals and to reduce the system losses. For this, dc voltage should be as high as possible and α should be as low as possible.

5.4. Advantages and disadvantages of HVDC systems

The main advantages of HVDC compared with HVAC are:

1. two conductors, positive and negative to ground, are required instead of three, thereby reducing tower or cable costs;
2. the direct voltage can be designed equivalent to the peak of the alternating voltage for the same amount of insulation to ground;
3. there is no charging current and skin effect.
4. the voltage regulation problem is much less serious for DC, since only the IR drop is involved. For the same reason steady-state stability is no longer a major problem.
5. the voltage stress at the conductor surface can be reduced with dc, thereby reducing corona loss, audible emissions, and radio interference;
6. HVDC in feeds do not increase significantly the short-circuit capacity required of switchgear in the ac networks;
7. fast control of converters can be used to damp out oscillations in the ac system to which they are connected.

Disadvantages of HVDC are:

1. the higher cost of converter stations compared with an ac transformer substation;
2. the need to provide filters and associated equipment to ensure acceptable wave form and power factor on the ac networks;
3. limited ability to form multi-terminal dc networks because of the need for coordinated controls and the present lack of commercially available dc circuit breakers.