2.1 CLASSIFICATION OF OVERHEAD TRANSMISSION LINES

A transmission line has *three constants *R*, *L* and *C* distributed uniformly along the whole length of the line. The resistance and inductance form the series impedance. The capacitance existing between conductors for 1-phase line or from a conductor to neutral for a 3- phase line forms a shunt path throughout the length of the line. Therefore, capacitance effects introduce complications in transmission line calculations. Depending upon the manner in which capacitance is taken into account, the overhead transmission lines are classified as :

(i) Short transmission lines.

When the length of an overhead transmission line is upto about 50 km and the line voltage is comparatively low (< 20 kV), it is usually considered as a short transmission line. Due to smaller length and lower voltage, the capacitance effects are small and hence can be neglected. Therefore, while studying the performance of a short transmission line, only resistance and inductance of the line are taken into account.

(ii) Medium transmission lines.

When the length of an overhead transmission line is about 50-150 km and the line voltage is moderatly high (>20 kV < 100 kV), it is considered as a medium transmission line. Due to sufficient length and voltage of the line, the capacitance effects are taken into account. For purposes of calculations, the distributed capacitance of the line is divided and lumped in the form of condensers shunted across the line at one or more points.

(iii) Long transmission lines.

When the length of an overhead transmission line is more than 150 km and line voltage is very high (> 100 kV), it is considered as a long transmission line. For the treatment of such a line, the line constants are considered uniformly distributed over the whole length of the line and rigorous methods are employed for solution.

It may be emphasised here that exact solution of any tranmission line must consider the fact that the constants of the line are not lumped but are distributed unfiormly throughout the length of the line.

2.7 CORONA

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called critical disruptive voltage, the conductors are surrounded by a faint violet glow called corona.

The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. The higher the voltage is raised, the larger and higher the luminous envelope becomes, and greater are the sound, the power loss and the radio noise. If the applied voltage is increased to breakdown value, a flash-over will occur between the conductors due to the breakdown of air insulation If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductor, otherwise the rough points will appear brighter. With d.c. voltage, there is difference in the appearance of the two wires. The positive wire has uniform glow about it, while the negative conductor has spotty glow.

2.7.1 Theory of corona formation

Some ionisation is always present in air due to cosmic rays, ultraviolet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionised particles and neutral molecules. When p.d. is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons. When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which is turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cummulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

2.7.2 Factors Affecting Corona

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. The following are the factors upon which corona depends:

(i)Atmosphere

As corona is formed due to ionsiation of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

(ii) Conductor size.

The corona effect depends upon the shape and conditions of the conductors. The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona that a solid conductor.

(iii) Spacing between conductors.

If the spacing between the conductors is made very large as compared to their diameters, there may not be any corona effect. It is because larger distance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.

(iv) Line voltage.

The line voltage greatly affects corona. If it is low, there is no change in the condition of air surrounding the conductors and hence no corona is formed. However, if the line voltage has such a value that electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

2.7.3 Advantages and Disadvantages of Corona

Corona has many advantages and disadvantages. In the correct design of a high voltage overhead line, a balance should be struck between the advantages and disadvantages.

Advantages

(i) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.

(ii) Corona reduces the effects of transients produced by surges.

Disadvantages

(i) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.

(ii) Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.

(iii) The current drawn by the line due to corona is non-sinusoidal and hence no sinusoidal voltage drop occurs in the line. This may cause inductive interference with neighboring communication lines.

2.7.4 Methods of Reducing Corona Effect

It has been seen that intense corona effects are observed at a working voltage of 33 kV or above. Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33 kV and higher voltages otherwise highly ionized air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment. The corona effects can be reduced by the following methods

(i) By increasing conductor size.

By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced. This is one of the reasons that ACSR conductors which have a larger cross-sectional area are used in transmission lines.

(ii) By increasing conductor spacing

By increasing the spacing between conductors, the voltage at which corona occurs is raised and hence corona effects can be eliminated. However, spacing cannot be increased too much otherwise the cost of supporting structure (e.g., bigger cross arms and supports) may increase to a considerable extent.

2.5 LONG TRANSMISSION LINES

It is well known that line constants of the transmission line are uniformly distributed over the entire length of the line. However, reasonable accuracy can be obtained in line calculations for short and medium lines by considering these constants as lumped. If such an assumption of lumped constants is applied to long transmission lines (having length excess of about 150 km), it is found that serious errors are introduced in the performance calculations. Therefore, in order to obtain fair degree of accuracy in the performance calculations of long lines, the line constants are considered as uniformly distributed throughout the length of the line. Rigorous mathematical treatment is required for the solution of such lines. Fig.2.5.1 shows the equivalent circuit of a 3-phase long transmission line on a phase-neutral basis. The whole line length is divided into n sections, each section having line constants 1 /n th of those for the whole line.

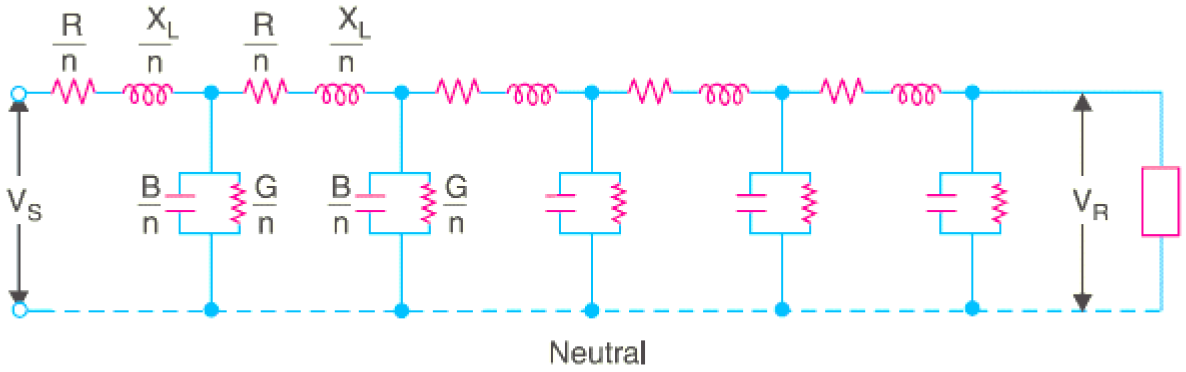

Figure 2.5.1 Long Transmission Line - Rigorous Method

[Source: "Principles of Power System" by V.K.Mehta Page: 251]

The following points may by noted :

(i) The line constants are uniformly distributed over the entire length of line as is actually the case.

(ii) The resistance and inductive reactance are the series elements.

(iii) The leakage susceptance (B) and leakage conductance (G) are shunt elements. The leakage susceptance is due to the fact that capacitance exists between line and neutral. The leakage conductance takes into account the energy losses occurring through leakage over the insulators or due to corona effect between conductors. Admittance

(iv) The leakage current through shunt admittance is maximum at the sending end of the line and decreases continuously as the receiving end of the circuit is approached at which point its value is zero.

2.5.1 ANALYSIS OF LONG TRANSMISSION LINE (RIGOROUS METHOD)

Fig.2.5.2 shows one phase and neutral connection of a 3-phase line with impedance and shunt admittance of the line uniformly distributed.

Consider a small element in the line of length dx situated at a distance x from the receiving end.

Let

z = series impedance of the line per unit length

y = shunt admittance of the line per unit length

V = voltage at the end of element towards receiving end

V + dV = voltage at the end of element towards sending end

I + dI = current entering the element dx

I = current leaving the element dx

Then for the small element dx,

z dx = series impedance

y dx = shunt admittance

Obviously, dV = I z dx

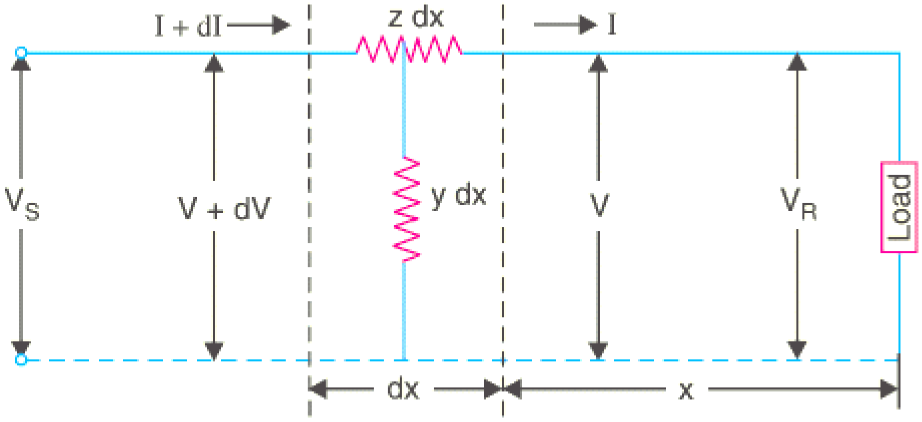

Figure 2.5.2 Equivalent Circuit Rigorous Method

[Source: "Principles of Power System" by V.K.Mehta Page: 252]

Now, the current entering the element is *I* + *dI* whereas the current leaving the element is *I*. The difference in the currents flows through shunt admittance of the element *i.e.*,

Current through shunt admittance of element,

$dI = V\,y\,dx$

Differentiating eq. (i) w.r.t. x, we get,

$$\frac{d^2V}{dx^2} = z\frac{dI}{dx}$$

$$\frac{d^2V}{dx^2} = yzV$$

$$V = k_1 \cosh\left(x\sqrt{y\,z}\right) + k_2 \sinh\left(x\sqrt{y\,z}\right)$$

$$\frac{dV}{dx} = k_1\sqrt{y\,z}\,\sinh\left(x\sqrt{y\,z}\right) + k_2\sqrt{y\,z}\,\cosh\left(x\sqrt{y\,z}\right)$$

$$\frac{dV}{dx} = I\,z$$

$$I\,z = k_1\sqrt{y\,z}\,\sinh\left(x\sqrt{y\,z}\right) + k_2\sqrt{z\,y}\,\cosh\left(x\sqrt{y\,z}\right)$$

$$I = \sqrt{\frac{y}{z}}\left[k_1 \sinh\left(x\sqrt{y\,z}\right) + k_2 \cosh\left(x\sqrt{y\,z}\right)\right]$$

From the above equations give the expressions for *V* and *I* in the form of unknown constants *k*1 and *k*2. The values of *k*1 and *k*2 can be found by applying end conditions as under : At *x* = 0, *V* = *VR* and *I* = *IR*

Putting these values we have,

$$V_R = k_1 \cosh 0 + k_2 \sinh 0 = k_1 + 0$$

$$V_R = k_1$$

$$I_R = \sqrt{\frac{y}{z}}\left[k_1 \sinh 0 + k_2 \cosh 0\right] = \sqrt{\frac{y}{z}}\left[0 + k_2\right]$$

$$k_2 = \sqrt{\frac{z}{y}}\,I_R$$

$$V = V_R \cosh(x\sqrt{y\,z}) + \sqrt{\frac{z}{y}}\, I_R \sinh(x\sqrt{y\,z})$$

$$I = \sqrt{\frac{y}{z}} V_R \sinh(x\sqrt{y\,z}) + I_R \cosh(x\sqrt{y\,z})$$

$$V_S = V_R \cosh(l\,\sqrt{y\,z}) + \sqrt{\frac{z}{y}} I_R \sinh(l\sqrt{y\,z})$$

$$I_S = \sqrt{\frac{y}{z}}\, V_R \sinh(l\sqrt{y\,z}) + I_R \cosh(l\sqrt{y\,z})$$

2.4 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.

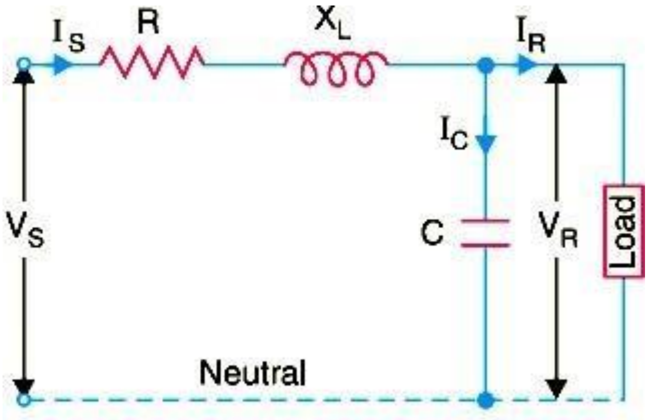

Figure 2.4.1 Equivalent Circuit End Condenser Method

[Source: "Principles of Power System" by V.K.Mehta Page: 253]

Let

I_R= load current per phase

R = resistance per phase

X_L= inductive reactance per phase

C = capacitance per phase

cos □$_R$= receiving end power factor (lagging)

V_S= sending end voltage per phase

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

we have,

$V_R = V_R + j\,0$

Load current, $I_R = I_R\,(\cos \emptyset_R - j \sin \emptyset_R)$

Capacitive current, $I_C = j\,V_R\,\omega\,C = j\,2\,\pi\,f\,C\,V_R$

The sending end current I_S is the phasor sum of load current I_R and capacitive current I_C *i.e.*,

$$\begin{aligned} I_S &= I_R + I_C \\ &= I_R\,(\cos \emptyset_R - j \sin \emptyset_R) + j\,2\,\pi\,f\,C\,V_R \\ &= I_R \cos \emptyset_R + j\,(-I_R \sin \emptyset_R + 2\,\pi\,f\,C V_R) \end{aligned}$$

Voltage drop/phase = $I_S\,Z = I_S\,(R + j\,X_L)$

Sending end voltage, $V_S = V_R + I_S\,Z = V_R + I_S\,(R + j\,XL)$

% Voltage regulation = $\frac{V_S - V_R}{V} \times 100$

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.

Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

cos φ_R = receiving end power factor (lagging)

V_S= sending end voltage/phase

V_1 = voltage across capacitor C

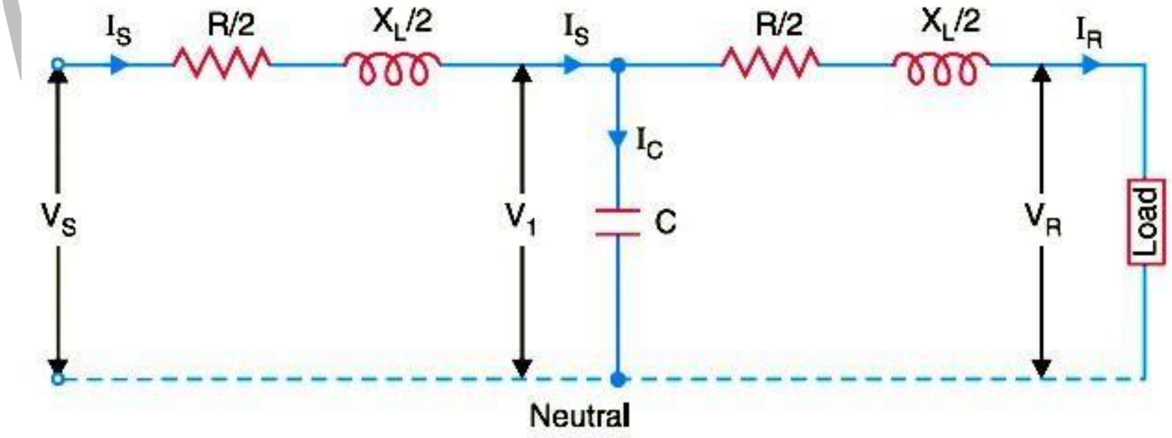

Figure 2.4.2 Equivalent Circuit Nominal - T Method

[Source: "Principles of Power System" by V.K.Mehta Page: 243]

The phasor diagram for the circuit is shown in Fig.2.4.3, Taking the receiving end voltage V_R as the reference phasor, we have,

$$\text{Receiving end voltage,} \quad \vec{V_R} = V_R + j\,0$$

$$\text{Load current,} \quad \vec{I_R} = I_R\,(\cos\phi_R - j\sin\phi_R)$$

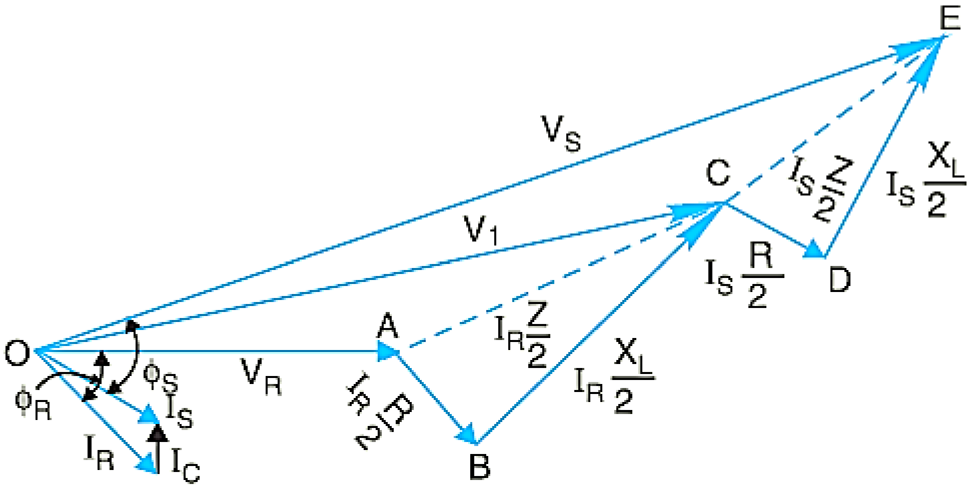

Figure 2.4.3 Phasor Diagram Nominal - T Method

[Source: "Principles of Power System" by V.K.Mehta Page: 243]

Voltage across C, $\vec{V_1} = \vec{V_R} + \vec{I_R}\,\vec{Z}/2$

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

Capacitive current, $\vec{I_C} = j\,\omega\,C\,\vec{V_1} = j\,2\pi f\,C\,\vec{V_1}$

Sending end current, $\vec{I_S} = \vec{I_R} + \vec{I_C}$

Sending end voltage, $\vec{V_S} = \vec{V_1} + \vec{I_S}\,\frac{\vec{Z}}{2} = \vec{V_1} + \vec{I_S}\left(\frac{R}{2} + j\frac{X_L}{2}\right)$

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.

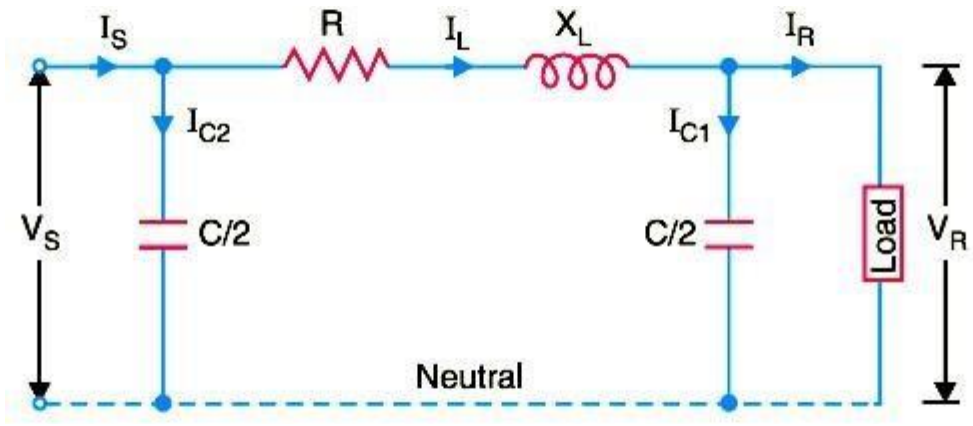

Figure 2.4.4 Equivalent Circuit Nominal - π Method

[Source: "Principles of Power System" by V.K.Mehta Page: 246]

Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

cos φ_R = receiving end power factor (lagging)

VS= sending end voltage per phase

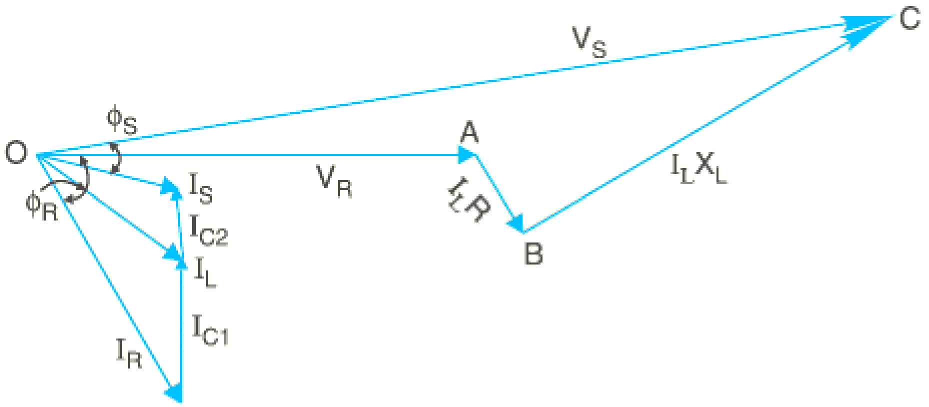

Figure 2.4.5 Phasor Diagram Nominal - π Method

[Source: "Principles of Power System" by V.K.Mehta Page: 243]

The phasor diagram for the circuit is shown in Fig 2.4.5 Taking the receiving end voltage as the reference phasor, we have,

$$\overrightarrow{V_R} = V_R + j\,0$$

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

Charging current at load end is

$$\overrightarrow{I_{C1}} = j\,\omega\,(C/2)\,\overrightarrow{V_R} = j\,\pi\,f\,C\,\overrightarrow{V_R}$$

Line current, $\overrightarrow{I_L} = \overrightarrow{I_R} + \overrightarrow{I_{C1}}$

Sending end voltage, $\overrightarrow{V_S} = \overrightarrow{V_R} + \overrightarrow{I_L}\,\overrightarrow{Z} = \overrightarrow{V_R} + \overrightarrow{I_L}\,(R + jX_L)$

Charging current at the sending end is

$$\overrightarrow{I_{C2}} = j\,\omega\,(C/2)\,\overrightarrow{V_S} = j\,\pi\,f\,C\,\overrightarrow{V_S}$$

$\therefore$ Sending end current, $\overrightarrow{I_S} = \overrightarrow{I_L} + \overrightarrow{I_{C2}}$

Problem 1

Determine the efficiency and regulation of a 3-phase, 100 km, 50 Hz transmission line delivering 20 MW at a p.f. of 0.8 lagging and 66 kV to a balanced load. The conductors are of copper, each having resistance 0.1 ohm per km, 1.5 cm outside dia, spaced equilaterally 2 metres between centres. Neglect leakance and use (*i*) nominal-*T*, and (*ii*) nominal- π method.

Solution:

Total resistance of line 100 × 0.1 = 10 ohms.

The inductance of the line $= 2 \times 10^{-7} \times 100 \times 1000 \ln\left(\frac{200}{0.75}\right)$

$= 11.17 \times 10^{-2}$ H

$\therefore$ Inductive reactance $= 314 \times 11.17 \times 10^{-2} = 35.1$ ohm

The capacitance/phase $= \dfrac{2\square \times 8.854 \times 10^{-12}}{\ln\left(\frac{200}{0.75}\right)} \times 100 \times 1000$

$= 9.954 \times 10^{-7}$

$= 0.9954$ μF.

Nominal-T method: The nominal-*T* circuit for the problem is given below:

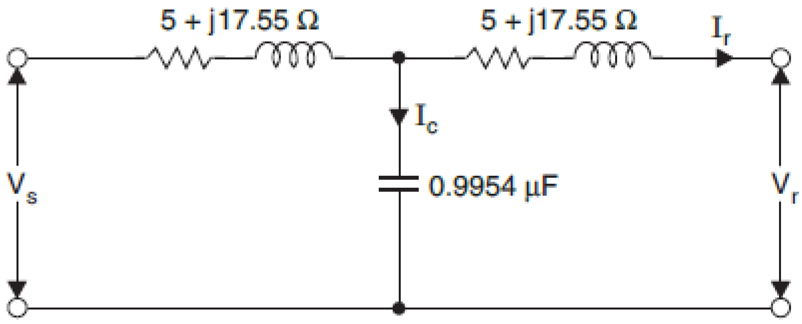

Figure 2.4.6 Nominal - T Method

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 73]

$$I_r = \frac{20 \times 1000}{\sqrt{3} \times 66 \times 0.8} = 218.68 \text{ amps}$$

$$V_r = \frac{66 \times 1000}{\sqrt{3}} = 38104 \text{ volts}$$

Taking I_r as the reference, the voltage across the condenser will be

$$V_c = (38104 \times 0.8 + 218.68 \times 5) + j(38104 \times 0.6 + 218.68 \times 17.55)$$

$$= 31576 + j26700$$

The current $\quad I_c = j\omega CV_c = j314(31576 + j26700) \times 0.9954 \times 10^{-6}$

$$= j9.87 - 8.34$$

$\therefore \quad I_s = 218.68 + j9.87 - 8.34 = 210.34 + j9.87$

$$= 210.57 \text{ amps}$$

$\therefore \quad V_s = V_c + I_s \frac{Z}{2}$

$$= 31576 + j26700 + (210.34 + j9.87)\,(5 + j17.53)$$

$$= 31576 + 1051 - 173 + j26700 + j3691 + j49.35$$

$$= 32454 + j30440$$

$\therefore \quad |V_s| = 44495 \text{ volts}$

The no load receiving end voltage will be

$$\frac{|V_s|\,(-\,j3199)}{5 + j17.55 - j3199} = \frac{44495\,(-\,j3199)}{5 - j3181} = 44746 \text{ volts}$$

$\therefore \quad \% \text{ regulation} = \frac{44746 - 38104}{38104} \times 100 = 17.4\%.$ **Ans.**

To determine η we evaluate transmission line losses as follows:

$$3[218.68^2 \times 5 + 210.57^2 \times 5] = 1382409 \text{ watts} = 1.3824 \text{ MW}$$

$\therefore \quad \% \eta = \frac{20}{20 + 1.3824} \times 100 = 93.5\%.$ **Ans.**

Nominal-π method: The nominal-π circuit for the problem is as follows:

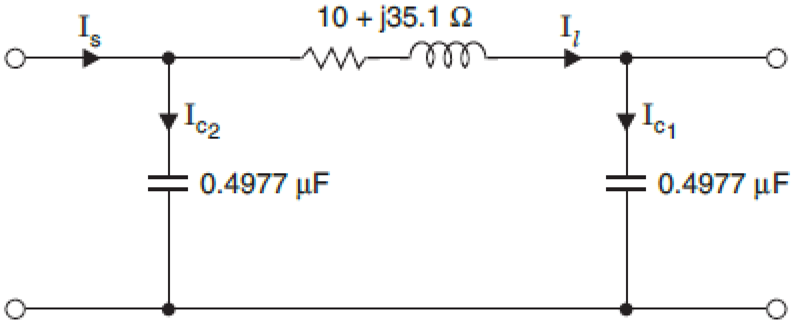

Figure 2.4.7 Nominal - π Method

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 74]

For nominal-π it is preferable to take receiving end voltage as the reference phasor. The current $I_r = 218.68\ (0.8 - j0.6)$.

Current $I_{c1} = j\omega CV_r = j314 \times 0.4977 \times 10^{-6} \times 38104 = j5.95$ amp

$I_l = I_r + I_{c1} = 174.94 - j131.20 + j5.95 = 174.94 - j125.25$

$\therefore\ V_s = V_r + I_l Z = 38104 + (174.94 - j125.25)\ (10 + j35.1)$

$= 38104 + 1749.4 - j1252.5 + j6140 + 4396$

$= 44249 + j4886$ volts

$|Vs| = 44518$ volts

The no load receiving end voltage will be

$$\frac{44518\,(-j6398)}{10 + j35.1 - j6398} = 44762 \text{ Volts}$$

$$\%\text{ voltage regulation} = \frac{44762 - 38104}{38104} \times 100$$

$$= 17.47\%$$

The line current $I_l = 215.15$

$\therefore$ Loss = 3 × 215.152 × 10 = 1.388 MW

$$\therefore\ \%\,\eta = \frac{20}{21.388} \times 100$$

$= 93.5\%$. **Ans.**

2.3 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 = load current

R = loop resistance i.e., resistance of both conductors

X_L= loop reactance

V_R = receiving end voltage

= receiving end power factor (lagging)

VS= sending end voltage

$\cos\phi_S$ = sending end power factor

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

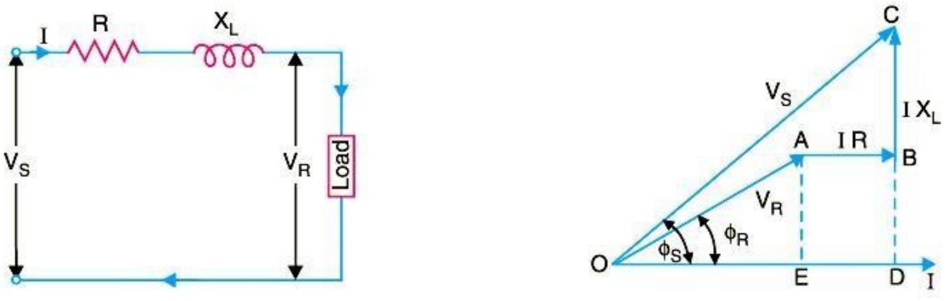

Figure 2.3 Equivalent Circuit of Short Line

[Source: "Principles of Power System" by V.K.Mehta Page: 230]

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.

$$\begin{aligned}
& & (OC)^2 &= (OD)^2 + (DC)^2 \\
\text{or} & & V_S^2 &= (OE + ED)^2 + (DB + BC)^2 \\
& & &= (V_R \cos\phi_R + IR)^2 + (V_R \sin\phi_R + IX_L)^2 \\
\therefore & & V_S &= \sqrt{(V_R \cos\phi_R + IR)^2 + (V_R \sin\phi_R + IX_L)^2} \\
(i) & & \text{\%age Voltage regulation} &= \frac{V_S - V_R}{V_R} \times 100 \\
(ii) & & \text{Sending end } p.f., \cos\phi_S &= \frac{OD}{OC} = \frac{V_R \cos\phi_R + IR}{V_S} \\
(iii) & & \text{Power delivered} &= V_R I_R \cos\phi_R \\
& & \text{Line losses} &= I^2 R \\
& & \text{Power sent out} &= V_R I_R \cos\phi_R + I^2 R \\
& & \text{\%age Transmission efficiency} &= \frac{\text{Power delivered}}{\text{Power sent out}} \times 100 \\
& & &= \frac{V_R I_R \cos\phi_R}{V_R I_R \cos\phi_R + I^2 R} \times 100
\end{aligned}$$

An approximate expression for the sending end voltage Vs can be obtained as follows. Draw S perpendicular from B and C on OA produced as shown in Fig. Then OC is nearly equal to OF

$$OC = OF = OA + AF = OA + AG + GF$$

$$= OA + AG + BH$$

$$V_s = V_R + I_R \cos\varphi_R + I\, X_L \sin\varphi_R$$

2.3.1 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

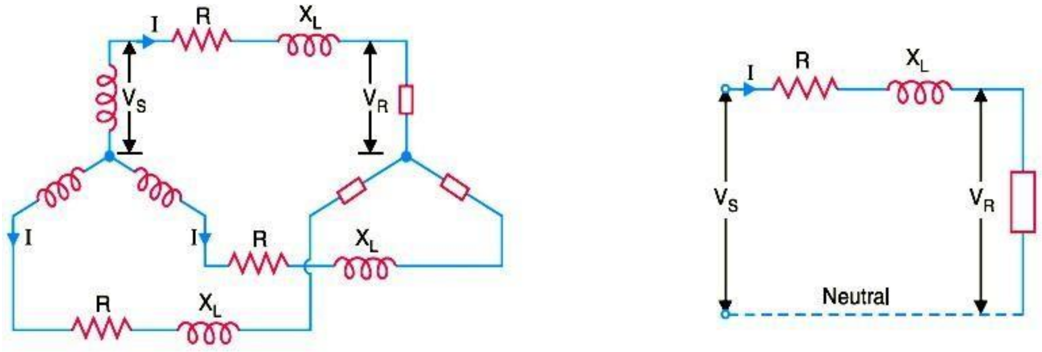

Figure 2.3 Equivalent Circuit of Three Phase Short Line

[Source: "Principles of Power System" by V.K.Mehta Page: 232]

2.3.2 Effect of Load p.f. On Regulation and Efficiency

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

The following conclusions can be drawn from the above expressions :

(*i*) When the load p.f. is lagging or unity or such leading that $I_R\cos\varphi_R > IX_L\sin\varphi_R$, then voltage regulation is positive *i.e.* , receiving end voltage V_R will be less than the sending end voltage V_S .

(*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 $IX_L\sin\varphi_R > I_R\cos\varphi_R$, then voltage regulation is negative *i.e*. the receiving end voltage V_R is more than the sending end voltage V_S .

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

2. Effect on transmission efficiency.

The power delivered to the load depends upon the power factor. 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. $\cos\varphi_R$.

$$P = V_R * I \cos\phi_R \quad \text{(For 1-phase line)}$$

$$I = \frac{P}{V_R \cos\phi_R}$$

$$P = 3\, V_R I \cos\phi_R \quad \text{(For 3-phase line)}$$

$$I = \frac{P}{3V_R \cos\phi_R}$$

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,

2.6 POWER CIRCLE DIAGRAM

Receiving End Power Circle Diagram:

Consider equation in general circuit constants

Vs = *AVr* + *BIr*

In phasor diagram except for *Ir* all other phasors represent voltages. We are interested in studying the power diagram, that too receiving end power diagram. The voltage phasor diagram must be multiplied by suitable value of current. If we multiply equation by *Vr*/*B* we get as,

$$\frac{V_sV_r}{B}=\frac{AV_r^{\,2}}{B}+V_rI_r$$

We find that the last term in the expression represents the volt-amperes at the receiving end; this is what is required. Since *Vr* is taken as the reference, the effect of multiplying the equation by *Vr*/*B* will be to change the magnitude of all the phasors in Fig. 2.6.1 by |*Vr*|/|*B*| and rotate them clockwise through an angle ∠(0 – β°) *i.e.*, – β°.Now when origin is shifted to *n* and phasor *BIr* is to be rotated through – β°, this phasor will subtend an angle – φ*r* with the horizontal axis. *Vr* 2/*B* will subtend an angle – β with the horizontal axis. Now with respect to *Vr* 2/*B* other phasors *AVr* 2/*B* and *VsVr*/*B* are drawn as shown in Fig.2.6.1.

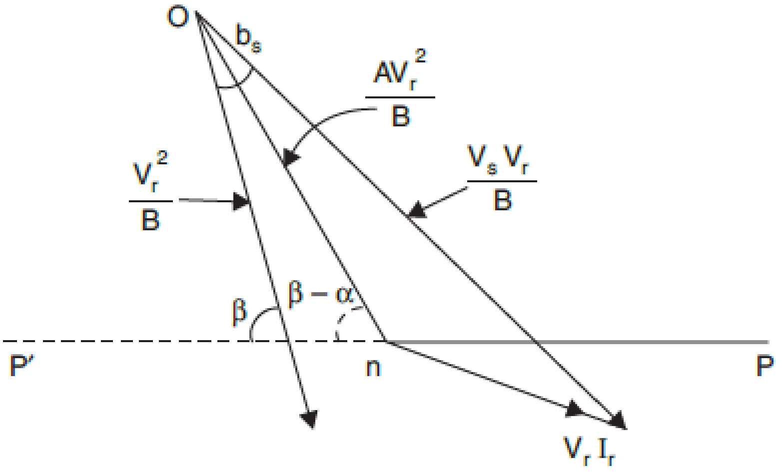

Figure 2.6.1 Phasor diagram

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 239]

Normally in a 3-phase system, 3-phase power is specified and *L-L* voltage is given. The power circle diagram that we have obtained we started with phase quantities. We could make use of 3-phase quantities also and in that case the power will be 3-phase power and voltage line to line. The procedure we are going to describe is say on per phase basis.

(a) Let *P* be the 3-phase power and *VL* the line to line voltage at the receiving end, then

$$P_r = \frac{P}{3} \text{ and } V_r = \frac{V_L}{\sqrt{3}}$$

(b) Calculate

$$\frac{|A||V_r^2|}{|B|}$$

(c) Now looking at the relative values of P_r and $A\ V_r^2$ / B choose a suitable scale.

(d) Draw a horizontal line and fix a point *n* on this line. From this point draw a line subtending an angle φ*r* as shown in Fig.6.1.2 Then after reducing *Pr* to scale cut the horizontal line at *l* by an amount equal to *Pr*. Draw a vertical line such that it cuts the slanted line (at angle φ*r*) at *m*. Thus the operating point *m* is obtained.

(e) Now from the point *n*, draw a line *no* equal to $A\ V_r^2$ / B (reduced to scale) at angle (β – α) in the third quadrant.

(f) Measure the length *Om*. Convert this to MVA or kVA depending upon the scale chosen. Then

$$Om \times \text{scale} = \frac{|V_s||V_r|}{|B|}$$

The capacity of the phase modifier in all cases will be *mm*′. The VArs requirements of the load are fixed and are equal to *ml*. Therefore, the division of VArs in the three situations is as follows:

(*i*) When *m*′ is above *m*. The capacity of the phase modifier is *mm*′. The VArs transmitted over the line are *m*′*l*, *i.e.*, in order to have sending end voltage corresponding to this operating point, transmission line has to transmit not only the VArs required by the load but it has to supply VArs to the synchronous phase modifier equal to *mm*′ *i.e.*, the phase modifier takes the lagging VArs from the system which means it is under-excited.

(*ii*) When *m′* lies between *m* and *l*. In order to meet the VArs requirements of the load *mm′* is supplied by the phase modifier and *m′l* have to be transmitted over the line. The phase modifier is over-excited.

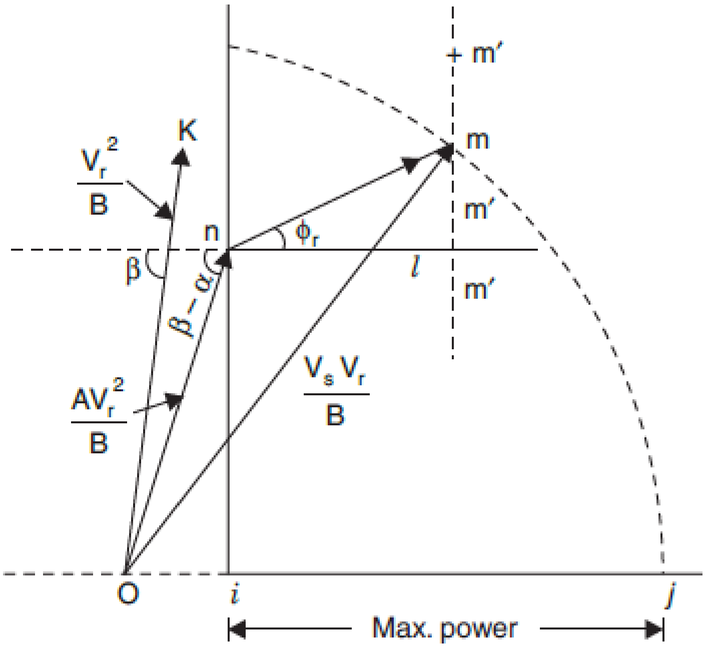

Figure 2.6.2 Power Circle diagram

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 242]

(*iii*) When *m′* lies below the horizontal axis. The capacity of the phase modifier is *mm′*. Here the phase modifier not only supplied VArs to the load but it supplies *lm′* VArs to the transmission line also to get this operating point. The phase modifier is over-excited.

The power factor of the load is fixed and is given by cos φ*r*. The power factor of the transmission line at the receiving end will depend upon the position of the operating point *m′* with respect to the horizontal axis. The power factor angle in all cases is the angle between the line *nm′* and the horizontal axis. If the point *m′* lies above the horizontal axis the power factor is lagging and if it lies below the horizontal axis it is leading.

To find out the load angle or torque angle δ*s*, draw a horizontal line passing through *O* and then from *O* draw a line subtending an angle β. This line corresponds to $|Vr^2|/|B|$. Cut this line to scale equal to $|Vr^2|/|B|$. The angle between *Ok* and *Om′* gives the torque angle for regulated systems and for unregulated systems the angle between *Ok* and *Om* is the torque angle δ*s*.

2.2 VOLTAGE REGULATION.

When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (V_R) of the line is generally less than the sending end voltage (V_S). This voltage drop ($V_s - V_R$) in the line is expressed as a percentage of receiving end voltage V and is called voltage regulation.

The difference in voltage at the receiving end of a transmission line between conditions of no load and full load is called voltage regulation and is expressed as a percentage of the receiving end voltage.

$$\% voltage regulation = \frac{V_S - V_R}{V_R} \times 100$$

2.2.1 Transmission efficiency.

The power obtained at the receiving end of a transmission line is generally less than the sending end power due to losses in the line resistance. The ratio of receiving end power to the sending end power of a transmission line is known as the transmission efficiency of the line

$$= \frac{V_R I_R cos\emptyset_R}{V_S I_S cos\emptyset_s} \times 100$$