CHAPTER III

MODELLING OF ELEMENTS OF MULTI-PHASE TRANSMISSION NETWORK

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3.1 INTRODUCTION

Analysis of a transmission network is based on the mathematical representations of the various elements. Since the transmission of power only by multi-phase lines is envisaged in near future, the integration of multi-phase systems with the existing three-phase network (viz., sources, transmissions, distributions and loads) can be achieved through a variety of three-phase/multi-phase transformers at various levels. The suitable mathematical representation of such interfacing transformer is of a major concern as it forms an essential aspect of analyses of multi-phase transmission systems as well as of a composite (mixed three-phase and high-phase order) network. By employing suitable representation of these transformers, it is possible to represent and analyse a multi-phase transmission network for load flow.

Modeling of suitable transformers for multi-phase conversion, multi-phase lines and loads, has evoked considerable interest in the recent past, as evident from several significant contributions available in the literature [25, 31-38]. This chapter is, therefore, aimed at reviewing the efforts made in this direction in the past. Equivalent circuits of a multi-phase line for steady state as well as for transient analysis are discussed with relational equations for obtaining the required parameters. Utilizing the parameters and the concepts developed in the present work, certain characteristics of multi-phase lines are brought out with the help of "Test System" considered in chapter II section 2.6.3.

3.2 TRANSFORMERS FOR THREE-PHASE / N-PHASE CONVERSION:

The transformers associated with the multi-phase systems are basically required to obtain high phase order (5, 9, 12 etc.) conversions from the three-phase systems. A three-phase to six-phase conversion is relatively easier, and it is achieved through a variety of connection schemes by employing the suitable three-phase transformer units. Various three-phase / six-phase connections schemes (viz. wye/star, delta/star, Wye/hexagon and delta / hexagon transformers) have been considered and extensively discussed in the literature [10, 25, 31-38]. However, the higher-phase order conversions require specially built transformer units. Such conversions have been earlier used to employ synchronous converters and valves [26-29].

3.3 THREE-PHASE/MULTI-PHASE TRANSFORMER MODELS :

Three-phase/six-phase transformers have been modeled as ideal transformers by Willems [25]. An improved model incorporating leakage impedance/ admittance of windings and off-nominal tappings on one of the windings was obtained by Tiwari et al. [31-33]. Later, similar representations were developed for wye/star three-phase/twelve-phase transformers by Swarup et al. [38], and even generalized to an N-phase conversion by choudhary et al. [37]. The three-phase/N-phase transformer was represented as an ideal transformer in series with leakage impedance/admittance measured in per-unit. The terminal relationships across the ideal transformer (Fig. 3.1) are given by:

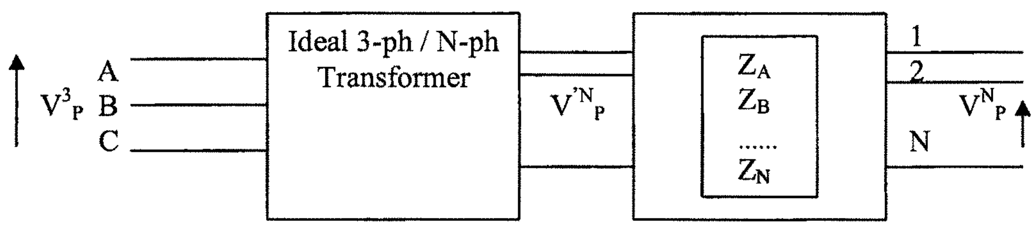

Fig. 3.1 Schematic representation of a 3-ph / N-ph Transformer

$$V_P'^N = C_1 V_P^3 \qquad V_P^3 = C_2 V_P'^N \tag{3.1}$$

$$I_P^N = C_3 I_P^3 \qquad I_P^3 = C_4 I_P^N \tag{3.2}$$

$$V_P^N = V_P'^N - [z] I_P^N \tag{3.3}$$

Where, C_1, C_2, C_3 and C_4 are the connection matrices relating voltages and currents at the appropriate sides of three-phase/ N-phase ideal transformers. These connection matrices may be modified to include off-nominal tappings (say on 3-phase side) as follows:

$C_1 = K_1 T_1 \qquad C_2 = K_2 T_2$

$C_3 = K_3 T_1 \qquad C_4 = K_4 T_2 \qquad (3.4)$

Wherein, the value of the constants K_1, K_2, K_3, K_4 and matrices T_1 and T_2 for the different transformers are consolidated as follows for ready references.

3-phase/ 6-phase transformers [25,32]

- **wye/star:-**

  $K_1 = 1/\alpha \qquad K_2 = \alpha/2 \qquad K_3 = \alpha \qquad K_4 = 1/2\ \alpha \qquad T_1 = K \qquad T_2 = K^t$

- **delta / star:-**

  $K_1 = 1/\sqrt{3}\ \alpha \qquad K_2 = \alpha\ /\ 2\sqrt{3} \qquad K_3 = \alpha\ /\ \sqrt{3} \qquad K_4 = 1/2\sqrt{3}\ \alpha$

  $T_1 = KP \qquad T_2 = P^t\ K^t$

- **wye/hexagon:-**

  $K_1 = 1/\alpha \qquad K_2 = \alpha/2 \qquad K_3 = \alpha \qquad K4 = 1/2\alpha$

  $T1 = Q^t K \qquad T_2 = K^t Q$

- **delta/hexagon:-**

  $K_1 = 1/\sqrt{3}\ \alpha \qquad K_2 = \alpha\ /\ 2\sqrt{3} \qquad K_3 = \alpha/\sqrt{3} \qquad K_4 = 1/2\sqrt{3}\ \alpha$

  $T_1 = Q^t KP \qquad T_2 = P^t\ K^t Q$

Where:

$$P = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \qquad Q = \left[\begin{array}{c|c} Q_1 & -Q^t_1 \\ \hline -Q^t_1 & Q_1 \end{array}\right] \qquad Q_1 = \begin{bmatrix} 0 & 1 & -1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$K^t = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ 0 & -1 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$L^t = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & -1 & -1 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & -1 & -1 & -1 \\ 0 & -1 & -1 & -1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \end{bmatrix}$$

$$M = 1/2\begin{bmatrix} 2 & 1 & -1 & 0 & 1 & -1 & -2 & -1 & 1 & 0 & -1 & 1 \\ 1 & 0 & -1 & 1 & 2 & 1 & -1 & 0 & 1 & -1 & -2 & -1 \\ 1 & -1 & -2 & -1 & -1 & 0 & -1 & 1 & 2 & 1 & -1 & 0 \end{bmatrix}$$

and [z] is the equivalent p.u. leakage impedance matrix of the windings .

$[z] = (N \times N)$ diagonal matrix $=[Y]^{-1}$

(I) Transformer Representation I

Using the terminal relationships given in (3, 1-3.3), a modal representation in the general form may be obtained as follows:

$$\begin{bmatrix} I_P^3 \\ -I_P^N \end{bmatrix} = \begin{bmatrix} Y_{TR1} & -Y_{TR2} \\ -Y_{TR3} & [Y] \end{bmatrix} \begin{bmatrix} V_P^3 \\ V_P^N \end{bmatrix} \quad (3.5)$$

Where, the sub-matrices $Y_{TR1}(3x3)$, $Y_{TR2}(3xN)$ and Y_{TR3} (Nx3), for different transformers, are given in Table 3.1.

(II) Transformer Representation II:

An alternative transformer model employing symmetrical lattice equivalent circuit of a single phase unit representing parallel windings of multi-phase transformers, may find considerable applications in studies involving imbalances in the networks [34-36]. The equivalent circuit representation of transformers utilizes the general symmetrical lattice equivalent circuit of a single phase transformer where both primary and secondary windings may have either actual or equivalent variable turns' ratio or both. The parallel transformer windings of a three-phase or multi-phase transformer, are taken to represent an equivalent single phase transformer.

Transformer Type	**Connection scheme**	**Y_{TR1}**	**Y_{TR2}**	**Y_{TR3}**
3-ph/6-ph [25,32]	wye/star	$Yii=y/\alpha^2$ $Yij=0$	$(y/2\ \alpha)\ K^t$	$(y\ /\ \alpha)\ K$
	delta/star	$Yii=2y/3\ \alpha^2$ $Yij=y/3\ \alpha^2$	$(y/2\sqrt{3}\ \alpha)\ [KP]^t$	$(y/\sqrt{3}\ \alpha)\ [KP]$
	Wye/Hexagon	$Yii=2y/\ \alpha^2$ $Yij=y/\ \alpha^2$	$(y/2\alpha)\ [Q^t K]^t$	$(y/\ \alpha)\ Q^t K$
	Delta/Hexagon	$Yii=2y/3\ \alpha^2$ $Yij=y/3\ \alpha^2$	$(y/2\sqrt{3}\ \alpha)\ [Q^t KP]^t$	$(y/\sqrt{3}\ \alpha)\ [Q^t KP]$

Table 3.1 Values of Submatrices for Different Transformers

The method which was originally developed for Three-phase two winding as well as three winding transformer by Laughton [34], has been employed to obtain representation for Three-phase/Six-phase transformer by Tiwari et al [31]. Subsequently, the above method has been generalized to M/N phase transformers by Saleh et al [36]. The equivalent circuit and the corresponding connection table for a wye/star transformer [36] are given in Fig. 3.2, 3.3 and Table 3.2 respectively, as an illustration.

Table 3.2
Connection Table for Wye/Star Transformer, with Equivalent Circuit (Fig.3.3)

Admittances	**Between nodes**
$2y/\ \alpha^2$	A-N, B-N, C-N A-a_1, B-b_1, C-c_1
$y/\ \beta^2$	a_1-n, b_1-n, c_1-n a_2-n, b_2-n, c_2-n
$y/\alpha\ \beta$	A-a_1, B-b_1, C-c_1 a_2-N, b_2-N, c_2-N
$-\ y/\alpha\ \beta$	A-a_2, B-b_2, C-c_2 a_1-N, b_1-N, c_1-N

The nodal representation of the transformer can then be built from the connection table in the following form;

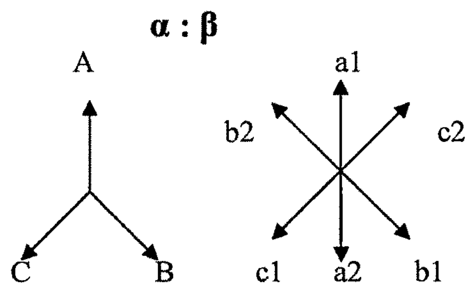

Fig. 3.2 Wye / Star Connection

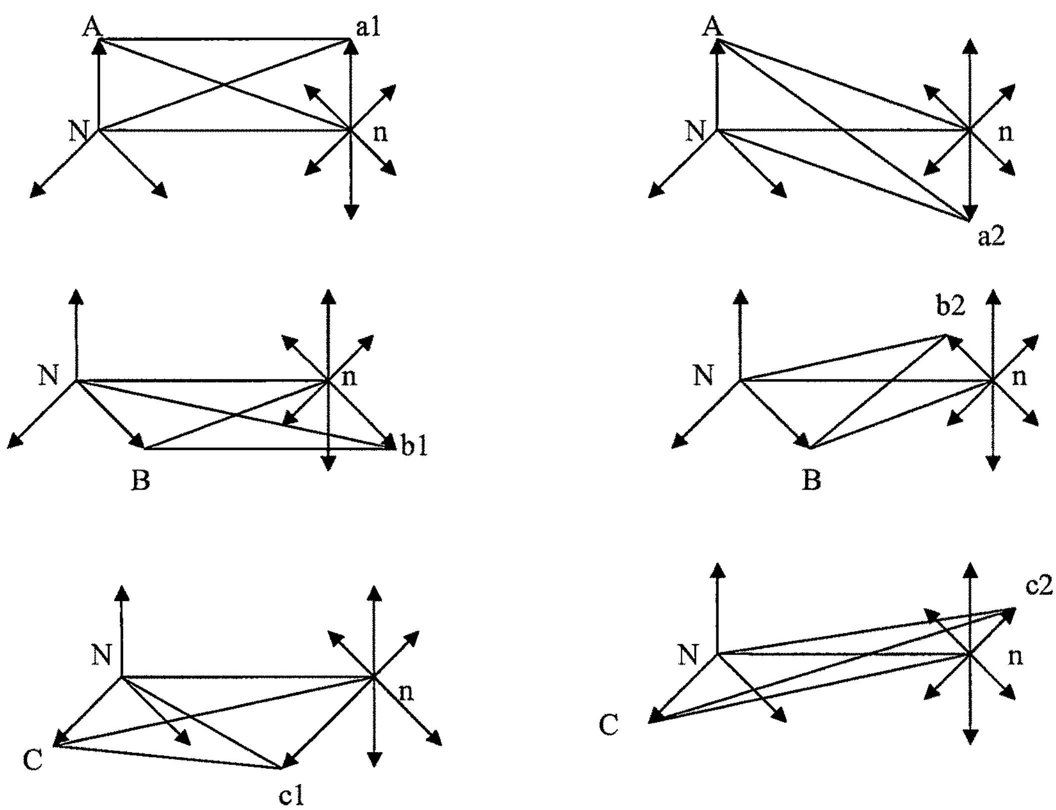

Fig. 3.3 Equivalent Circuit of Wye / Star Transformer

$$Y_{TR} = \begin{bmatrix} Y_{TR1} & Y_{TR2} \\ Y_{TR3} & Y_{TR4} \end{bmatrix} \quad (3.6)$$

Where, the values of the submetrices Y_{TR1}.............YT_{R4} will depend upon the phases and also upon the necessity to retain neutral connection in the representation. Such equivalent circuit representations are, of course, extremely valuable in the unbalanced network analysis, but they can not be so easily derived for various transformer connections, particularly in the case of twelve-phase transformers.

(iii) Transformer Representation III

The symmetrical component method is employed to obtain a description of a composite (3-phase and multi-phase) system, either in terms of symmetrical components at three-phase sequences or in terms of symmetrical components at multi-phase sequences. This method requires the identification of the correspondences between N multi-phase sequences representing the multi-phase side and the 3, three-phase sequences representing the three-phase side of the system.

These correspondences are achieved through the determination of the equivalent circuits of 3-phase to multi-phase interconnecting transformers. However, the terminal relationships (Fig. 3.1) with respect to symmetrical components of both voltages and currents for different transformer schemes, are given by:

$$V`_S^N = K_1 T_{S1} V_S^3 \qquad V_S^3 = K_2 T_{S2} V`_S^N \quad (3.7)$$

$$I_S^N = K_3 T_{S1} I_S^3 \qquad I_S^3 = K_4 T_{S2} I_S^N \quad (3.8)$$

Where T_{S1} and T_{S2} are the connection matrices transformed into symmetrical components. The expansion of the voltage expressions in (3.7) leads to an equivalent diagram shown in (Fig. 3.4) for Three-phase / Six-phase transformers [25]. Equations (3.7) and (3.6) can be used for studying the behaviour of composite power systems in the steady-state or fault conditions or also during electromechanical transients.

Nevertheless, any problem concerning power systems can be effectively handled by following the traditional methods used for the three-phase systems.

3.4. TRANSMISSION LINE MODELS :

Representations of Multi-phase lines suitable for the balanced as well as the unbalanced analysis were derived earlier by several authors [25, 31-33, 38]. In this section, the description of Multi-phase lines in terms of phase impedance/admittance, π-circuit and ABCD-parameters generalized as a whole to an N-phase order system, is reviewed.

3.4.1 Phase Impedance, pi and ABCD-parameter Model [32]

(i) Impedance/admittance matrix:-

An untransposed multi-phase line of N-phase order is described by its phase impedance matrix as:

$$Z_P^N = \begin{bmatrix} Z_{11} & Z_{12} \ldots\ldots Z_{1N} \\ Z_{21} & Z_{22} \ldots\ldots Z_{2N} \\ & . \quad \ldots \\ . \; . & \\ Z_{i1} & Z_{i2} \ldots \ldots Z_{iN} \\ . & \ldots\ldots \\ Z_{N1} & Z_{N2} \quad \ldots\ldots Z_{NN} \end{bmatrix} \quad (3.9).$$

Where, Z_{ii} = Self impedance of phase "i" of transmission line.

Z_{ij} = Mutual impedance between phases i and j of transmission line.

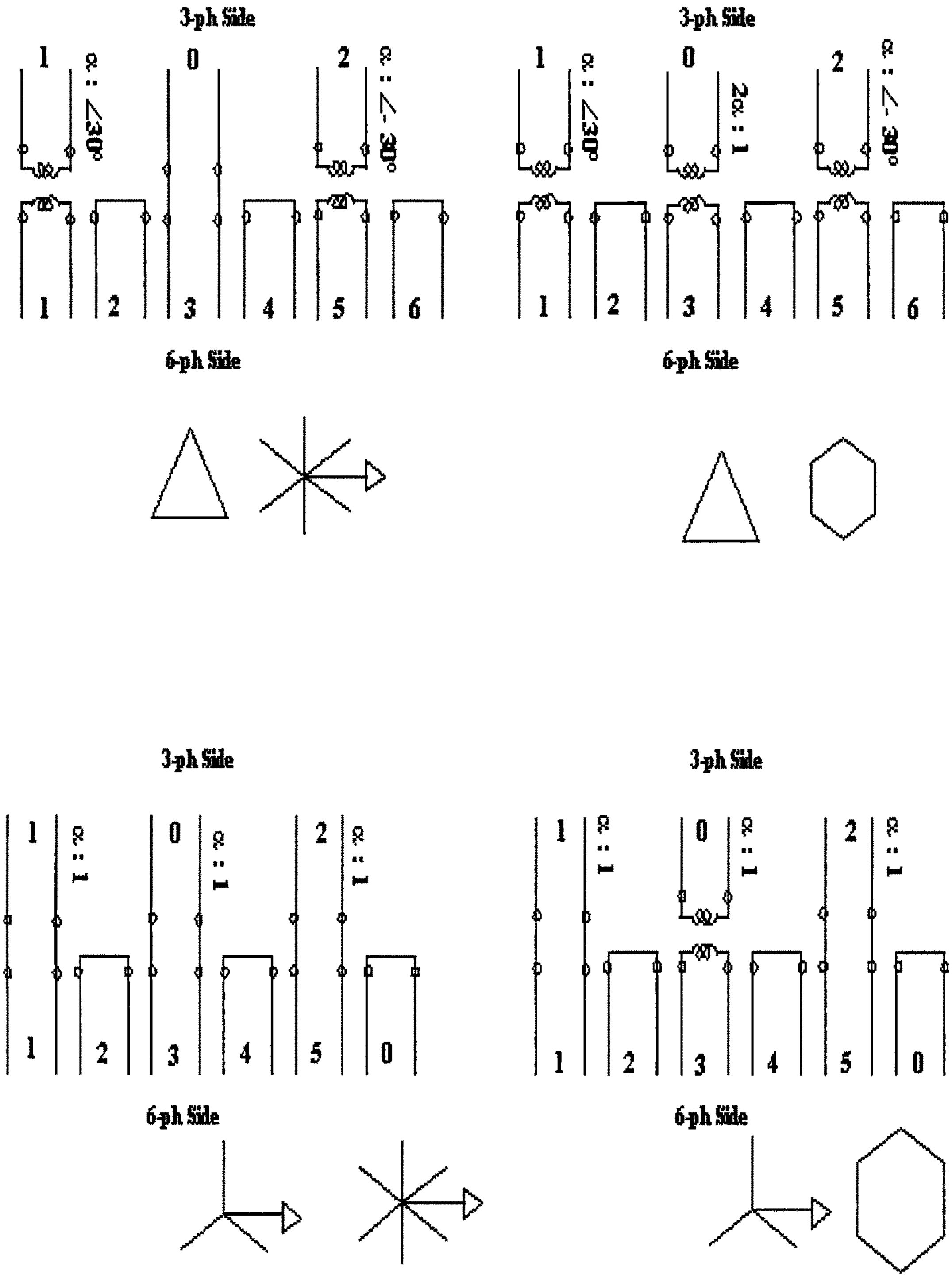

Fig. 3.4 Equivalent diagrams of different 3-phase/6-phase Transformer schemes

(ii) Pi model:

Equation (3.9) is used to represent a short line. Medium and long lines may be adequately represented by nominal and equivalent π-circuit, as:

$$\begin{bmatrix} I_{pS}^{N} \\ I_{pR}^{N} \end{bmatrix} = \begin{bmatrix} Y_p^{N}+(1/2)Y_{Sh}^{N} & -Y_p^{N} \\ -Y_p^{N} & Y_p^{N}+(1/2)Y_{Sh}^{N} \end{bmatrix} \begin{bmatrix} V_{pS}^{N} \\ V_{pR}^{N} \end{bmatrix} \qquad (3.10)$$

Where, Y_{Sh}^{N} is the shunt admittance matrix of transmission line.

(iii) ABCD-Parameters model:

Another useful representation of the transmission lines in terms of ABCD parameters, is given by:

$$\begin{bmatrix} V_{pS}^{N} \\ I_{pS}^{N} \end{bmatrix} = \begin{bmatrix} A^{N} & B^{N} \\ C^{N} & D^{N} \end{bmatrix} \begin{bmatrix} V_{pR}^{N} \\ I_{pR}^{N} \end{bmatrix} \qquad (3.11)$$

Where, A, B, C and D (with A=D) are the square matrices of order (NxN). The constants A and D are the functions of line length (l) and propagation constant (γ) of the transmission line; while B and C are the functions of length (l), propagation constant (γ), and the characteristic impedance (Z_C) of the line.

3.4.2 Equivalent Network Representation :

(i) Three-phase equivalent representation:

A multi-phase transmission line may be represented by the three-phase equivalent impedance/admittance for carrying out the analysis of a composite three-phase and multi-phase system (Fig. 3.6) on three-phase basis. As shown in Fig. 3.6, the equivalent three-phase impedance/admittance of a multi-phase line (by employing different three-phase/six-phase connection) can be written in a general form as:

$$Z_{p,eq}^{3} = K_5 T_2 [Z_p^N + [Z_1] + [Z_2]] T_1 \quad (3.12)$$

And

$$Y_{p,eq}^{3} = [U + K_6 T_2 Y_p^N [Z_1 + Z_2] T_1]^{-1} [K_7 T_2 Y_p^N T_1] \quad (3.13)$$

Where K_5, K_6, and K_7 for different transformer connections are consolidated as follows:

Transformer type	**Connection Scheme**	**K_5**	**K_6**	**K_7**
3- ph/6-ph [32]	wye/star wye/hexagon	$\alpha^2/2$	1/2	$1/2\ \alpha^2$
	delta/star delta/hexagon	$\alpha^2/6$	1/6	$1/6\ \alpha^2$

The equivalent three-phase network replacing multi-phase line cyclically transposed results in a balanced network. The equivalent impedance matrix of multi-phase transmission system is given hereunder, as an example:

6-phase line employing wye-star identical transformers:

$$Z_{ii} = \alpha^2 (Z_S + 2z - Z_{m3}) \quad \text{and} \quad Z_{ij} = \alpha^2 (Z_{m2} - Z_{m1}) \quad (3.14)$$

The equivalent three-phase matrices (3.12, 3.13) will hence be decoupled by means of symmetrical component transformation. However, their sequence elements will be different for different transformer connection schemes employed.

(ii) Three-phase equivalent ABCD-Parameters:

Three-phase equivalent ABCD-parameters of multi-phase transmission line (Fig.3.5) may be obtained between bus bars S and R from cascading of the three networks of transformer T_1; multi-phase transmission line; and transformer T_2. Assuming identical transformers at the two ends, the ABCD-Parameters obtained by:

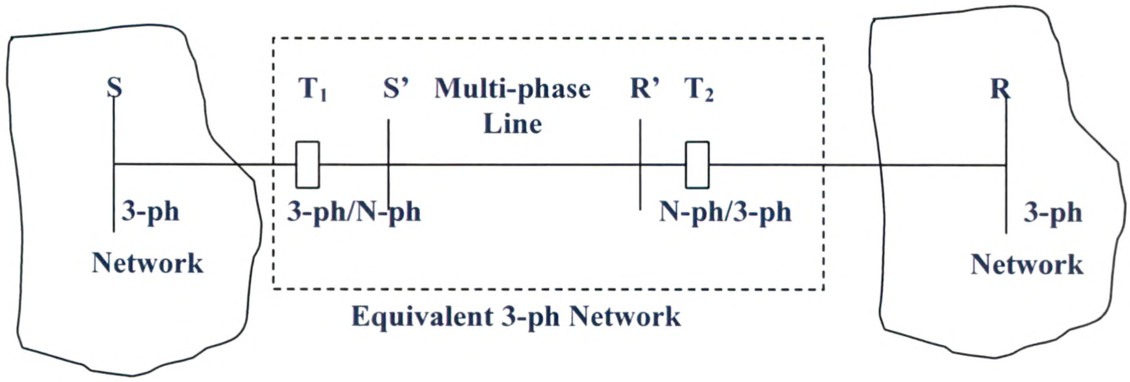

Fig.3.5 Schematic Diagram of Multi-phase Line Connected via 3-ph / N-ph Transformers to 3-ph Network

$$A^3eq = K_6T_2 [A^N + [z] C^N] T_1$$

$$B^3eq = K_5 T_2 [B^N + [2z] A^N + [z] C^N [z]] T_1$$

$$C^3eq = K_7 T_2 C^N T_1$$

$$D^3eq = K_6 T_2 [D^N + [z] C^N]T_1 \quad (3.15)$$

ABCD-parameters for different transformer connections can be obtained by putting respective values of constants K_5, K_6 and K_7 as well as the values of the connection matrices T_1 and T_2 in equation (3.15).

(iii) Single-Phase equivalent representation:

A single phase equivalent of a multi-phase line for the analysis of the system entirely on three-phase basis may be conveniently derived from the equivalent three-phase ABCD-parameter (3.15). For a π–circuit representation the following familiar relations can be written as:

$$A^1_{eq} = 1 + 0.5 Z^1_{p, eq} Y^1_{sh, eq} \quad (3.16)$$

$$B^1_{eq} = Z^1_{p,eq} \quad (3.17)$$

Where, $Z^1_{p,eq}$ and $Y^1_{sh,eq}$ represent the equivalent single phase Series impedance and Shunt admittance of multi-phase line respectively.

Equating the values of the diagonal entries of A^3_{eq} and B^3_{eq} from (3.15) with A^1_{eq} and B^1_{eq} in (3.16) and (3.17) respectively, the $Z^1_{p,eq}$ and $Y^1_{p,eq}$ can be related to per phase series impedance (z^1_p) and shunt admittance (Y^1_{sh}) respectively .

3.4.3 Equivalent Multi-Phase Representation :

In a composite three-phase and multi-phase system, if our interest of investigation lies chiefly in the multi-phase part of the network, a multi-phase equivalent description is required to be developed for carrying out the analysis entirely on the multi-phase basis, as discussed hereunder.

(i) Equivalent impedance/admittance model :

By employing the terminal relations of the transformers and by relating the currents and voltages across the bus bars S and R (Fig.3.6), a multi-phase equivalent impedance representation of the network can be given as:

$$Z^N_{p,eq} = K_5\, T_2\, Z^3_p\, T_1 + [2z]$$

$$Y^N_{p,eq} = [U + K_6\, T_2\, Y^3_p\, T_1\, [2z]\,]^{-1} \quad [K_7\, T^3_p\, T_1\,] \tag{3.18}$$

For a balanced three-phase line, the equation (3.18) yields a balanced circulant impedance matrix which corresponds to a balanced multi-phase network where all non-diagonal elements are not equal. However, this matrix shows coupling between symmetrical components and has only the symmetrical properties of a line with cyclic transposition. This gives an additional motivation for considering multi-phase network with cyclic tranposition [25].

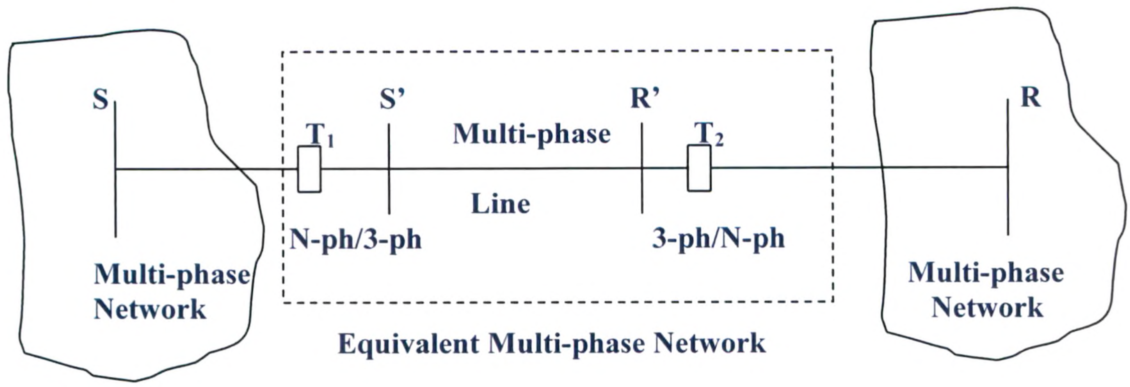

Fig.3.6 Schematic Diagram of 3-phase Line Connected via N-ph / 3-ph Transformers to Multi-phase Network

(ii) Multi-phase equivalent ABCD-parameter:

Multi-phase equivalent ABCD-parameters may also be derived by following the procedure similar to that required for solving three-phase equivalent ABCD-parameters. The multi-phase equivalent ABCD-parameters, as given in a general form below, are valid for different transformer schemes (assuming identical transformers with negligible leakage impedances) and for different phase order.

$$\begin{aligned} A^N{}_{eq} &= K_6\, T_1\, A^3\, T_2 \\ B^N{}_{eq} &= K_7\, T_1\, B^3\, T_2 \\ C^N{}_{eq} &= K_5\, T_1\, C^3\, T_2 \\ D^N{}_{eq} &= K_6\, T1\ \ D^3\, T_2 \end{aligned} \qquad (3.19)$$

3.5 LOAD MODELS:

Loads on a multi-phase system may be represented by constant impedances/admittances in the balanced as well as the imbalanced conditions as the case may be. Loads in the form of multi-phase machines may be represented in a similar way as given in [31]. In some cases, it may be necessary to represent a multi-phase load by an equivalent three-phase load for carrying out the analysis of a composite system on the basis of three-phase system.

Referring to Fig. 3.7, the load current can be expressed as:

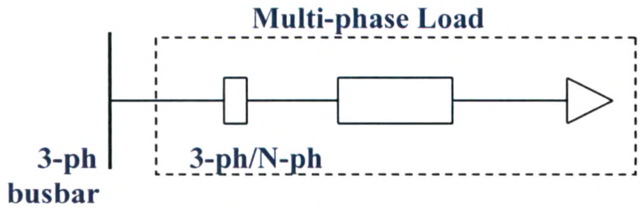

Fig. 3.7 A Multi-phase Load Connected to 3-phase bus bar

$$I^N_p = Y^N_L \; V^N_p \tag{3.20}$$

Using the voltage and current relations of transformers as given in (3.1) and (3.2); and the load current equation in (3.20), the current of three-phase side of the transformer can be expressed in a general form as:

$$I^3_p = [U + (K_6)\, T_2 \; Y^N_L \,[z]\, T_1]^{-1} \, [(K_7) T_2 \, Y^N_L \, T_1 \,] \, V^3_p \tag{3.21}$$

Hence, the equivalent three-phase admittance of multi-phase load can be expressed by:

$$Y^3_{L,\,eq} = [U + (K_6)\, T_2 \, Y^N_L [z]\, T_1]^{-1} \; [K_7 \, T_2 \, Y^N_L T_1] \tag{3.22}$$

Similarly, the equivalent representation in the impedance form can be obtained by:

$$Z^3_{L\,,eq} = K_5 \, T_2 \, [\, Z_L + [z] \,] T_1 \tag{3.23}$$

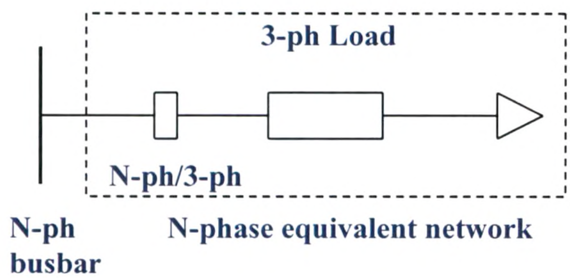

Fig. 3.8 A three-phase Load Connected to N-phase bus bar

One of the possible schemes to tap a multi-phase line at some location would be to employ a multi-phase / three-phase transformer as shown in Fig. 3.8. By using the terminal relations of transformer (3.1) and (3.2), the load voltage can be representation can be expressed as:

$$V^3_p = Z^3_L \; I^3_p \tag{3.24}$$

The equivalent multi-phase load arranged in a general form is obtained by:

$$Y^{N}_{L,eq} = [U + K_5\, T_1\, Y^{3}_{L} T_2\ [z]\,]^{-1}\ [\,K_5\, T_1\, Y^{3}_{L}\ T_2] \tag{3.25}$$

$$Z^{N}_{L,eq} = [K_7\, T_1\, Z^{3}_{L}\ T_2\ + [z]\,] \tag{3.26}$$

In the above equations, the values of the constants K_5, K_7, and the matrices T_1, T_2, have been expressed in the foregoing sections 3.3 and 3.4.2.

3.6 CERTAIN CHARACTERISTICS OF MUTI-PHASE LINE:-

It has been shown earlier that a multi-phase line can be represented as an equivalent of three-phase network between the three-phase buses connecting the multi-phase line with interfacing transformers at either ends. In the multi-phase dominated networks, it would be advantageous to represent a three-phase line by the multi-phase equivalent representation. Assumptions of full transposition of lines and ideal wye/star transformers of nominal turns' ratio are made for the simplicity. The three-phase equivalent impedance matrices for six-phase lines, and the multi-phase equivalent impedance matrices of three-phase lines, are obtained and consolidated in Table 3.3.

3.6.1 EQUIVALENT REPRESENTATIONS :

The equivalent three-phase impedance matrices of multi-phase lines (as in Table 3.3) resemble the balanced three-phase lines having no mutual coupling between the phases. The matrices are characterised by lower diagonal and zero mutual impedances. Further, it is noticed that the symmetrical component transformation of these matrices produces equal sequence impedances.

The six-phase equivalent impedance matrix (Table 3.3) of three-phase lines is a circulant matrix, and its non-diagonal elements are not all equal.

Table 3.3
Computation of certain equivalent impedance matrices
(With wye/star terminal transformers)

Line type Impedance matrix Elements (Ω / Km)	**Equivalent impedance matrix elements (Ω /Km)**	**Remarks**
6-ph line: Zs = j1.007 Zm = j0.534	**3-ph equivalent** Zs = j0. 473 Zm= j0.0	This matrix is diagonal
3-ph line: Zs=j0.908 Zm = j0.51	**6-ph equivalent** Zs = j0.454 , Zm1=j0.255 Zm2=j0.255, Zm3=j0.454 Zm4=j0.255, Zm5=j0.255	This matrix is circulant

However, the multi-phase impedance matrices show coupling between their symmetrical components. Equivalent impedance matrices in the cases of other transformer connection schemes can be analyzed, and treated in a similar manner.

3.6.2 Charging Current :

The conductors of transmission line togetherwith the ground plane, behave like a large capacitor. When the transmission line is energized, a capacitive line charging current is generated. Since the RMS voltage varies along the line, the charging current is not the same everywhere along the line.

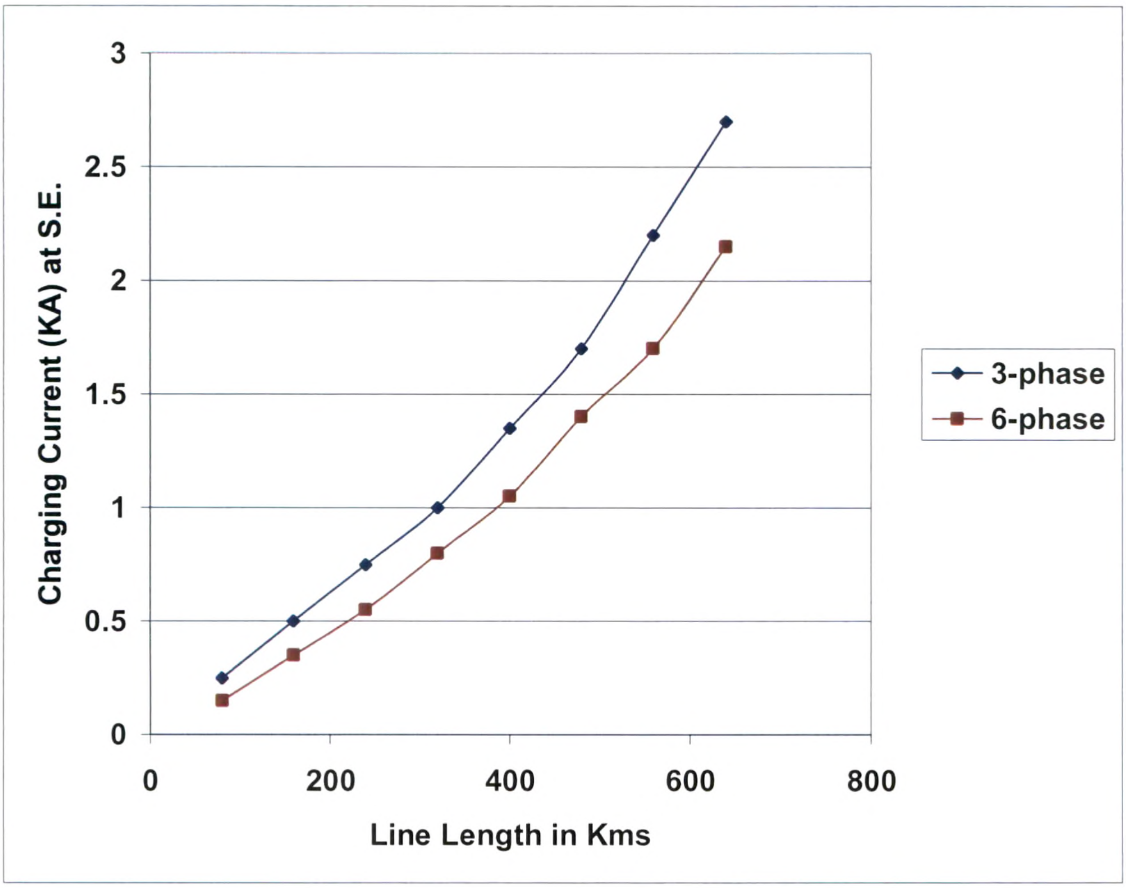

Fig. 3.9 Charging Current at S.E. V/S Line Length

The charging current at the sending end for each of the two alternative transmission lines (as described in chapter II) represented by equivalent π-circuit has been computed and plotted versus line length as shown in Fig.3.9. It can be observed from the curves (Fig. 3.9), that the charging currents for the two transmission lines are of negligible values for short lengths. As the line length increases, the charging current also increases in values for all the lines in a similar manner. However, the multi-phase lines are characterized by lower charging currents as compared to their lower phase order counterparts. This lower charging current associated with the multi-phase lines, appears to indicate a reduced Ferranti effect on multi-phase lines. However, the lower capacitance and somewhat higher inductance associated with multi-phase lines (making the product LC =constant) produce somewhat enhanced Ferranti effect, as shown in the next section.

3.6.3 Voltage Gain for Open-Circuit Condition of Lines :

Voltage gain may be defined as the ratio of voltage at the receiving end to voltage at the sending end for an open circuit line end [86]. This voltage gain indicates the voltage rise at the receiving end of transmission line due to the line charging capacitance.
Employing the data for the alternative lines (chapter II), the open circuit voltage ratio has been computed and plotted against line length as shown in Fig, 3.10. From the curves (Fig. 3.10), the following observations can be made:

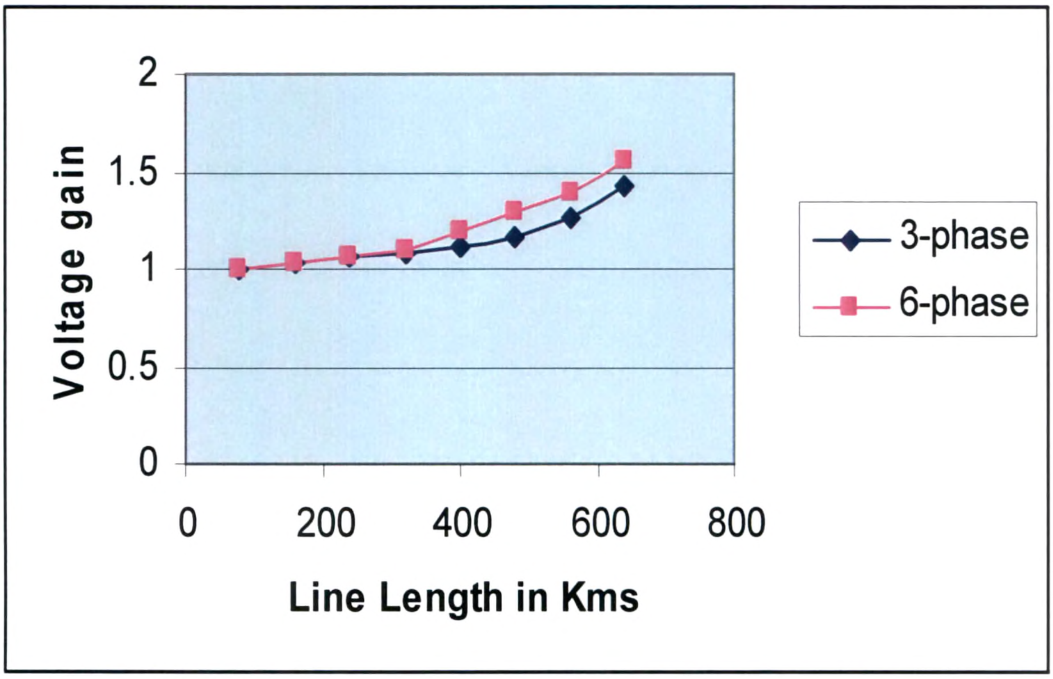

Fig. 3.10 Voltage Gain for (O.C. at R.E.) Line Represented by Equivalent π- Circuit

(i) The voltage gain is constant up to a length of 80 Kms. This is due to the fact that with a line up to such line length, the charging current has a negligible value.

(ii) The voltage gain is almost the same for both the alternative lines up to a length of 240 Kms, but beyond this length, the difference in voltage gain between both the lines increases with the increase in phase order. This can be explained by looking into the voltage gain that is numerically equal to reciprocal of generalized constant "A". Since "A" depends upon both inductance and capacitance which are somewhat higher and lower respectively for multi-phase lines, the voltage gain is higher (i.e. the Ferranti effect is enhanced) in the case of multi-phase lines.

3.7 CONCLUSIONS:

In this chapter an overview of certain transformers required for the six-phase conversion from the three-phase supply, has been presented. Mathematical representation of three-phase / multi-phase transformers has been reviewed. Mathematical models of the multi-phase transmission lines applicable to any phase order and suitable for the balanced as well as the unbalanced lines analyses have been discussed. Recognizing multi-phase transmission lines forming part of a three-phase power system network connected via three-phase / multi-phase interfacing transformers at either end has been illustrated briefly. The modeling of a multi-phase line as a part of three-phase network has been illustrated. Similarly, the multi-phase equivalent representation of a three-phase line for the analysis of a composite system on multi-phase basis, has been considered and dealt with in details. In both the cases of equivalent representations, the phase impedance matrix; ABCD parameters; sequence parameters; and equivalent single phase representations have been the main points of deliberations.

The various derivations in the chapter have been substantiated by taking into account the sample systems of chapter II. In this chapter, certain characteristics of multi-phase lines viz. charging current, voltage gain, and voltage regulation characteristics have been brought to light.

The study has revealed that the multi-phase lines are characterized by the lower charging current, a slightly higher voltage rise on an open circuit end, better voltage regulation, higher power transmission capacity and higher steady state stability limit, as against those of their lower phase order counterparts.