CHAPTER: VI

COMPARATIVE LOAD FLOW STUDY

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6.1 INTRODUCTION:-

Because of the ever increasing power supply requirements, increased transmission capability and efficient utilization of right of way are some of the most common concerns of the present day electric power utilities. The multi-phase transmission offers an appealing and unique solution to the problem. At present Six-phase transmission appears most promising amongst multi-phase systems for its possible realization in future.

Multi-phase transmission, if ever realized, will always be integrated with three-phase system. For the said purpose three-phase to multi-phase transformers will be required to connect multi-phase system to the existing network at all levels viz. stepping up generated voltages to multi-phase and vise-versa. Therefore, suitable representation of multi-phase lines and associated transformers are required for analyzing impact of multi-phase system in existing three-phase networks for effective planning and realization.

Multi-phase transmission system, particularly the six-phase lines have been modeled by their phase impedance matrices [17, 21, 23, 25, 44], ABCD parameters [25], Л-representations [83]. The associated transformers (three-phase / six-phase) have been modelled by Willems [25] without considering leakage impedance of the windings. An improved model incorporating leakage impedance / admittance was later presented by Tiwari and Singh [31]. The three-phase / six-phase transformer models [25] suitable for imbalance analysis were developed employing symmetrical lattice equivalent circuits. Employing the realistic model of transformers, three-phase equivalent of six-phase line obtained for performing analysis of composite three-phase and multi-phase system on three-phase basis [31]. Multi-phase loads (connected to the three-phase buses via three-phase / six-phase transformers) representations as equivalent three-phase impedance / admittance [25] were modified to include transformer winding leakage impedances [31].

Here, the transformer models are further improved by considering off-nominal tappings on one of the windings. Three-phase equivalents suitable for imbalance analysis and single phase equivalents of multi-phase elements are systematically derived. The phase co-ordinate representation for analyzing a composite system retaining physical identities of three-phase and multi-phase elements is also discussed briefly. Since a multi-phase transmission line can be viewed as a network between three-phase buses at sending and receiving ends, its three-phase equivalent impedance is different for the different types of transformers connected at two ends. An effort has been made to obtain the model in a unified general format to tide over this difficulty.

Employing the equivalent on single-phase basis of representation of multi-phase system along with the usual three-phase elements, the impact of replacing certain existing three-phase double circuit lines by six-phase is investigated for load flow analysis. As more and more multi-phase (six-phase) lines are introduced, an overall improvement in system conditions in terms of voltage magnitudes and phase angles, transmission efficiencies and transmission capabilities, is obtained. Taking a test system (fig 6.4) consisting *of* 6-buses and 8-lines, it is shown that by replacing all existing three-phase double circuit lines by six-phase lines, the system can deliver about 1.67 times the original load and still maintaining the benefits of better voltage regulation and transmission efficiencies, if additional generation at nodes 3 and 6 could be added.

Before performing the Load Flow Analysis on a sample system, it is imperative to briefly outline the Mathematical Modelling of the Transmission Lines with a view to providing a quick reference to readers.

6.2 MULTI-PHASE LINE TRANSMISSION PARAMETER CALCULATIONS:-

A programme entitled "Line parameter calculation" in ETAP software, calculates the line parameters viz. series impedance, shunt admittance to ground for n-phase system incorporating the features of bundle conductors, ground wires and transposition in actual and also in per unit values for multi circuit configurations. The programme provides sequence impedances, phase impedance matrix, π and T equivalent parameters values as well. These results are later required for the representation of multi-phase transmission system in balanced as well as unbalanced conditions.

6.2.1 THE THREE-PHASE / MULTI-PHASE TRANSFORMER MODELS:

The transformers associated with multi-phase transmission systems are required to obtain 6,9,12 and higher order phase conversions from three-phase systems. A Six-phase conversion can be obtained from commonly available three-phase units employing different connection schemes: Wye / Star , Delta / Star, Wye / Hexagon, Delta / Hexagon etc. [10], whereas still higher order phase conversions need specially constructed transformer units. For the present purpose, only six-phase conversion transformer models are discussed; and it is assumed that the higher phase units can be treated in a similar manner.

6.2.2 THE THREE-PHASE / MULTI-PHASE TRANSFORMER MODEL-I:

Consider Wye / Star, three-phase / six-phase transformer in series with the equivalent series impedance / admittance in p.u. (fig. 6.1). The terminal relationships across the ideal transformer [25] are given by:

$$\alpha\, V'^{6}_{P} = N\, V^{3}_{P} \qquad\qquad \alpha\, I^{3}_{P} = (\,\tfrac{1}{2}\,)N^{T}\, I^{6}_{P} \tag{6.1}$$

$$V^{3}_{P} = (\,\tfrac{1}{2}\,)\,\alpha\, N^{T}\, V'^{6}_{P} \qquad\qquad I^{6}_{P} = \alpha\, N\, I^{3}_{P} \tag{6.2}$$

Where,

$$N^{T} = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ 0 & -1 & 0 & 0 & 1 & 0 \end{bmatrix}$$

The terminal voltage vector V^{6}_{P} on the six-phase side is given by

$$V^{6}_{P} = V'^{6}_{P} - [\,z\,]\, I^{6}_{P} \tag{6.3}$$

From equations (6.1) to (6.3), the nodal representation of the transformer can be obtained as:

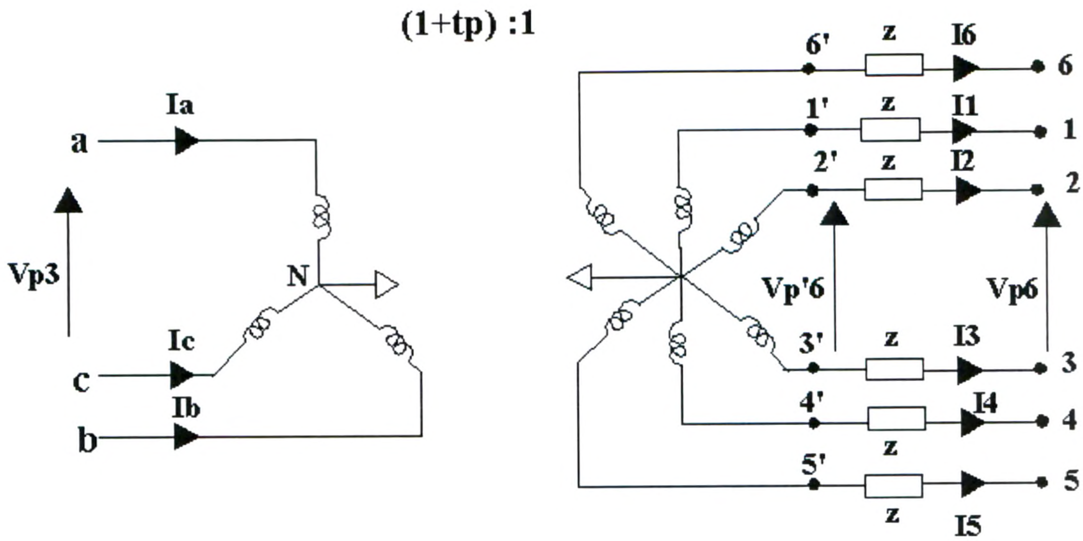

Fig. 6.1 A Wye / Star transformer of turns ratio ($1 + t_p$) : 1

$$\begin{bmatrix} I^3{}_P \\ I^6{}_P \end{bmatrix} = \begin{bmatrix} K_1 H^T [y] H & -K2\ H^T [y] \\ -K_3 [y] H & [y] \end{bmatrix} \begin{bmatrix} V^3{}_P \\ V^6{}_P \end{bmatrix} \tag{6.4}$$

Where, the constants K_1, K_2, and K_3, and matrix H for different types of transformer connections are summarized as under:

Wye / Star transformer:

$K_1 = 1 / 2\alpha^2$ $K_2 = 1 / 2\alpha$ $K_3 = 1 / \alpha$ $H = N$

Delta / Star transformer:

$K_1 = 1 / 6\alpha^2$ $K_2 = 1 / 2\sqrt{3}\alpha$ $K_3 = 1 / \sqrt{3}\alpha$ $H = NP$

Wye / Hexagon transformer:

$K_1 = 1 / 2\alpha^2$ $K_2 = 1 / 2\alpha$ $K_3 = 1 / \alpha$ $H = Q^T N$

Delta / Hexagon transformer:

$K_1 = 1 / 6\alpha^2$ $K_2 = 1 / 2\sqrt{3}\alpha$ $K_3 = 1 / \sqrt{3}\alpha$ $H = Q^T NP$

Where,

$$P = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \qquad Q = \begin{bmatrix} 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ -1 & 0 & 0 & 0 & 0 & 1 \\ 1 & -1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

6.2.3 THREE-PHASE / SIX-PHASE TRANSFORMER MODEL – II

An alternative transformer model suitable for unbalanced network analysis can be derived including off-nominal tappings. A three-phase / six-phase transformer can be conceptualized as a three winding transformer having (1) A three-phase winding P with terminals a-b-c (2) a secondary winding S with terminals 1-3-5, and (3) tertiary equivalent three-phase winding T with winding S for the purpose of deriving equivalent circuit representation [83].

TABLE: 6.1

Connection table for Wye / Star transformer with equivalent windings P,S and T characterized by $\alpha = (1+t_p)$, $\beta = 1$, $\gamma = -1$

Admittances	Between Nodes
$(y_{PS} + y_{PT}) / \alpha^2$	N-a, N-b, N-c
$(y_{PS} + 2y_{ST})$	n-1, n-2, n-3
$(y_{PT} + 2y_{ST})$	n-4, n-6, n-2
$(y_{PT} + y_{PS}) / \alpha$	n-a, n-b, n-c
Y_{PS} / α	a-1, b-3, c-5
$-y_{PS} / \alpha$	a-4, b-6, c-2
Y_{PT} / α	N-4, N-6, N-2
$-y_{ST}$	1-4, 3-6, 5-2

Similar connection table can be prepared for other types of transformers. The nodal admittance representation of transformers either from (6.4) or connection table can be written compactly as:

$$Y_{TR} = \begin{bmatrix} Y_{TR1} & Y_{TR2} \\ Y_{TR3} & Y_{TR4} \end{bmatrix} \tag{6.5}$$

Where, sub-matrices Y_{TR1}, Y_{TR2}, Y_{TR3} and Y_{TR4}, in this case are of the dimension 3 x 3, 3 x 6, 6 x 3 and 6 x 6 respectively.

6.2.4 THREE-PHASE EQUIVALENT IMPEDANCE / ADMITTANCE OF MULTI-PHASE (SIX-PHASE) ELEMENTS:-

In a composite system, for the analysis of the three-phase part of system phenomena, such as calculation of fault currents or load flows, it is convenient to convert multi-phase part or element to equivalent three-phase element [25]. Consider a multi-phase element connected via three-phase / six-phase transformer to three-phase bus bar as shown in fig. 6.2. The three-phase equivalent impedance / admittance of six-phase element can be derived by substituting appropriate voltage and current relationship similar to (1)-(3) for particular transformer in the following relations:

$$V^6_P = Z^6_P\, I^6_P \tag{6.6}$$

And

$$I^6_P = Y^6_P\, V^6_P \tag{6.7}$$

Where,

$$Y^6_P = [Z^6_P]^{-1}$$

The general form of the expression for equivalent three-phase impedance is obtained as:

$$Z^3_{P,eq} = KH^T\,[\,Z^6_P + Z]\,H \tag{6.8}$$

And $Y^3_{P,eq}$ can either be found out by inverting $Z^3_{P,eq}$ or can be obtained as:

$$Y^3_{P,eq} = [\,U + K''\,H^T\,Y^6_P\,[Z]H]^{-1}\,[\,K'\,H^T\,Y^6_P\,H] \tag{6.9}$$

Where, the values of K, K' and K" for different transformers are:

- Wye / Star and Wye / Hexagon transformer

  $K=\alpha^2/2$ $\quad K' = 1/2$ $\quad K'' = 1/2\alpha^2$

- Delta / Star and Delta / Hexagon transformer

  $K=\alpha^2/6$ $\quad K' = 1/6$ $\quad K'' = 1/6\alpha^2$

The three-phase equivalent impedance / admittance of multi-phase (six-phase) lines employing the transformer representations given by [17] and derived from connection tables, may also be obtained. A procedure discussed in 6.3.2 in connection with transmission system representations may be utilized for the purpose.

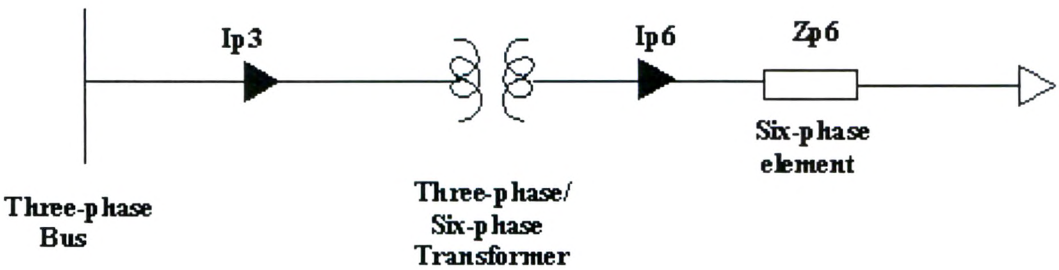

Fig. 6.2 A multi-phase (six-phase) element connected to three-phase bus bar

6.3 MULTI-PHASE TRANSMISSION LINE MODEL:-

An untransposed multi-phase transmission line possessing cyclic symmetry [18] is described by its phase impedance matrix for a general N-phase system as under:

$$Z_P^N = \begin{bmatrix} Z_{11} & Z_{12} \ldots\ldots & Z_{1N} \\ Z_{21} & Z_{22} \ldots\ldots & Z_{2N} \\ & . & \ldots \\ . & . & \\ Z_{i1} & Z_{i2} \ldots & \ldots Z_{iN} \\ . & & \ldots\ldots \\ Z_{N1} & Z_{N2} & \ldots Z_{NN} \end{bmatrix} \qquad (6.10)$$

If assumption of complete transposition of conductors (although difficult to realize in practice) is made, then the power invariant transformation matrices may be constructed for six-phase and higher order systems employing group theoretic techniques [18,19], which will fully diagonalize the matrix in [31].

Medium and long length lines may be adequately represented by nominal and equivalent π-models respectively as:

$$\begin{bmatrix} I_{PS}^{N} \\ I_{PR}^{N} \end{bmatrix} = \begin{bmatrix} Y_P^N+(1/2)Y_{Sh}^N & -Y_P^N \\ -Y_P^N & Y_P^N+(1/2)Y_{Sh}^N \end{bmatrix} \begin{bmatrix} V_{PS}^{N} \\ V_{PR}^{N} \end{bmatrix} \quad (6.11)$$

Where, the second subscripts S and R denote sending and receiving ends respectively. The matrix Y_P^N in (6.11) is related to its symmetrical component matrix Y_S^N as:

$$Y_P^N = [T_S^N][Y_S^N][T_S^{N*}]^T \quad (6.12)$$

Another useful representation, in terms of ABCD-parameters, popularly used with several systems studies may be written as:

$$\begin{bmatrix} V_{PS}^{N} \\ I_{PS}^{N} \end{bmatrix} = \begin{bmatrix} A^N & B^N \\ C^N & D^N \end{bmatrix} \begin{bmatrix} V_{PR}^{N} \\ I_{PR}^{N} \end{bmatrix} \quad (6.13)$$

Where, $A^N B^N C^N$ and D^N are square matrices of order N.

6.3.1 EQUIVALENT THREE-PHASE REPRESENTATIONS:

To carry out the analysis of composite system as a three phase network, the multi-phase transmission systems may be represented by their three-phase equivalents. For example, consider a multi-phase (six-phase) transmission line connected between three-phase bus bars S and R via transformers T_1 and T_2 as shown in figure 6.3. Let the multi-phase (six-phase) transmission line be represented between S' and R' as:

$$V^6_{S}{}' - V^6_{R}{}' = Z^6_P \, I^6_P \tag{6.14}$$

Fig 6.3 Schematic diagram of a multi-phase (six-phase) transmission Line

Assuming the transformer T_1 and T_2 of the same type and employing the relations similar to (6.1 and 6.2) for relating V^3_S and V^6_S' and V^6_R' and V^3_R' the voltage drop vector (V^3_S – V^3_R) is obtained as:

$$V^3_S - V^3_R = K\, H^T [Z^6_P + Z_1 + Z_2]\, H \;\; I^3_P \tag{6.15}$$

Thus from (6.15), the equivalent three-phase impedance is given by:

$$Z_{p\,,eq}^{3} = K\, H^T [Z^6_P + Z_1 + Z_2]\, H \tag{6.16}$$

The equivalent admittance matrix may be either obtained by inverting Zp^3,eq or may be derived to yield,

$$Y_{p\,,eq}^{3} = [\, U + K''\, H^T\, Y^6_P\, [Z_1 + Z_2]\,]^{-1} \quad [K'\, H^T\, Y^6_P\, H] \tag{6.17}$$

It is to be noted that when the transformer leakage impedances are negligible the equivalent impedances and admittances are the same as given by (6.8 and 6.9).

Similarly the three-phase equivalent ABCD – parameter of a multi-phase (six-phase) line may be obtained between bus bars S and R from cascading of the three networks of transformers T_1, line, and transformer T_2 as:

$$A^3_{eq} = K\,H^T\,[A^6 + [Z_1]\,C^6\,]\,H$$

$$B^3_{eq} = K\,H^T\,[B^6 + [Z_1+Z_2]\,A^6 + [Z_1]\,C^6\,[Z_2]\ ]\,H$$

$$C^3_{eq} = K\,H^T\,C^6\,H$$

$$D^3_{eq} = K\,H^T\,[D^6 + [Z_2]\,C^6\,]H \qquad (6.18)$$

For identical transformers implying $[Z_1] = [Z_2]$, the equivalent A and D parameters, as usual become equal. Further, when the impedance of transformers is negligible, the equivalent parameters in (6.18) simplify to the form:

$$A^3_{eq} = K\,H^T A^6\,H \qquad B^3_{eq} = K\,H^T B^6\,H$$

$$C^3_{eq} = K\,H^T\,C^6\,H \qquad D^3_{eq} = K\,H^T D^6\,H \qquad (6.19)$$

The equivalent three-phase representations obtained in (6.16 – 6.19) employing transformer models given by (6.4) are not suitable for unbalanced network analysis. However an equivalent representation employing transformer model in section 6.2.2 and described by 6.5 may be derived as under. Consider the multi-phase (six-phase) transmission line of figure 6.3. The nodal admittance description of transformers T_1,T_2 and transmission line may be written as;

$$\begin{bmatrix} I_S^3 \\ -I_S^{6'} \end{bmatrix} = \begin{bmatrix} Y_{TR1}^{(1)} & Y_{TR2}^{(1)} \\ Y_{TR3}^{(1)} & Y_{TR4}^{(1)} \end{bmatrix} \begin{bmatrix} V_S^3 \\ V_S^{6'} \end{bmatrix} \tag{6.20}$$

$$\begin{bmatrix} I_R^{6'} \\ -I_R^3 \end{bmatrix} = \begin{bmatrix} Y_{TR1}^{(2)} & Y_{TR2}^{(2)} \\ Y_{TR3}^{(2)} & Y_{TR4}^{(2)} \end{bmatrix} \begin{bmatrix} V_R^{6'} \\ V_R^3 \end{bmatrix} \tag{6.21}$$

And

$$\begin{bmatrix} I_S^{6'} \\ -I_R^{6'} \end{bmatrix} = \begin{bmatrix} Y_{TL1} & Y_{TL2} \\ Y_{TL3} & Y_{TL4} \end{bmatrix} \begin{bmatrix} V_S^{6'} \\ I_R^{6'} \end{bmatrix} \tag{6.22}$$

Where, (6.22) is exactly similar to (6.11) except that it is written in compact form. The elimination of intermediate nodes, corresponding to bus bar groups S' and R' utilizing (6.20-6.22) leads to the relationships between currents and voltages of bus bars S and R as:

$$\begin{bmatrix} I_S^3 \\ -I_R^3 \end{bmatrix} = \begin{bmatrix} Y^3_{p,eq} \end{bmatrix} \begin{bmatrix} V_S^3 \\ V_R^3 \end{bmatrix} \tag{6.23}$$

From (6.23), the desired equivalent three-phase nodal admittance representation follows as:

$$Y^{3}_{p,eq} = \begin{bmatrix} Y_{TR1}^{(1)} - Y_{TR2}^{(1)} X_1 Y_{TR3}^{(1)} & -Y_{TR2}^{(2)} X_2 Y_{TR3}^{(2)} \\ -Y_{TR1}^{(2)} X_3 Y_{TR3}^{(1)} & Y_{TR1}^{(2)} - Y_{TR1}^{(2)} X_4 Y_{TR4}^{(2)} \end{bmatrix} \tag{6.24}$$

Where,

$$\begin{bmatrix} X_1 & X_2 \\ X_3 & X_4 \end{bmatrix} = \begin{bmatrix} Y_{TR4}^{(1)} + Y_{TL1} & Y_{TR2}^{(1)} \\ Y_{TL3} & Y_{TL4} + Y_{TR4}^{(2)} \end{bmatrix} \tag{6.25}$$

Alternatively, the nodal admittance matrix of the network between S and R may be assembled [31] as,

$$Y = \begin{bmatrix} Y_{TR1}^{(1)} & Y_{TR3}^{(1)} & \multicolumn{2}{c}{\multirow{2}{*}{Y_{TL2}}} \\ Y_{TR3}^{(1)} & Y_{TR4}^{(1)} + Y_{TL1} & & \\ \multicolumn{2}{c}{\multirow{2}{*}{Y_{TL3}}} & Y_{TL4} + Y_{TR1}^{(2)} & Y_{TR2}^{(2)} \\ & & Y_{TR3}^{(2)} & Y_{TR4}^{(2)} \end{bmatrix} \tag{6.26}$$

And the intermediate nodes corresponding to S' and R' may be eliminated by usual elimination subroutine. The equivalent three-phase nodal admittance matrix once calculated may be used as and when required for subsequent analysis.

6.3.2 EQUIVALENT SINGLE-PHASE REPRESENTATION:

A single phase equivalent of a multi-phase (six-phase) line can be conveniently derived from ABCD-parameters in (6.18). Note that A^{3}_{eq}, B^{3}_{eq}, C^{3}_{eq} and D^{3}_{eq} are square diagonal matrices with A^{1}_{eq}, B^{1}_{eq}, C^{1}_{eq} and D^{1}_{eq} as the diagonal entries respectively. If, $Z^{1}_{p,eq}$ and $Y^{1}_{sh,eq}$ and Z^{1}_{p} and Y^{1}_{sh} are equivalent single phase and per phase Series impedance and Shunt admittance of the multi-phase (six-phase) line, then for a π-circuit representation, we have the familiar relations as:

$$A^{1}_{eq} = 1 + 0.5\, Z^{1}_{p,eq}\; Y^{1}_{sh,eq} \tag{6.27}$$

$$B^{1}_{eq} = Z^{1}_{eq} \tag{6.28}$$

Equating the values of A^{1}_{eq} and B^{1}_{eq} from (6.18) with (6.27 and 6.28) $Z^{1}_{p,eq}$ and $Y^{1}_{sh,eq}$ can be related to Z^{1}_{p} and $Y^{1}_{sh.}$ The equations given below are given as an illustration for identical Wye / star transformers T_1 and T_2 connected at the two ends of line.

$$Z^{1}_{p,eq} = Z^{1}_{p} + 2Z\,(1 + 0.5\, Z^{1}_{p}Y^{1}_{sh}) + Z^{2}Y^{1}_{sh}(1 + 0.25\, Z^{1}_{p}Y^{1}_{sh}) \tag{6.29}$$

$$Y^{1}_{sh,eq} = (1/\, Z^{1}_{p,eq})(\, Z^{1}_{p}Y^{1}_{sh} + 2ZY^{1}_{sh}(1 + 0.25\, Z^{1}_{p}Y^{1}_{sh})) \tag{6.30}$$

6.4 SYSTEM REPRESENTATION AND ANALYSIS:

6.4.1 SYSTEM REPRESENTATION:-

The representation of multi-phase transmission line and the associated transformers and loads discussed in 6.3 and 6.2 may be employed to model the composite system consisting of an equivalent three phase and multi-phase elements as an equivalent single phase, a three-phase and also as a mixed three-phase and multi-phase (retaining physical identities of different elements) network. Single phase representation is widely used in several studies for balanced system conditions.

In the event of investigating phenomena on three-phase part of the network, the multi-phase network elements may be replaced by their three-phase equivalents discussed in the preceding sections. However, if the interest of investigation lies in the multi-phase part of the network, then a mixed phase representation in phase coordinates is preferred. In this case, each element is required to be represented in detail, and the models of multi-phase elements already discussed in sections 6.2 and 6.3 along with the usual three-phase elements [34], may be used. By making use of the phase coordinates representation [83] of the system, any type and any number of imbalances can be eliminated with the same ease as for the balanced system analysis.

In each case, the system may be represented in the following form.

$$[Y]\,\bar{V} = \bar{I} \tag{6.31}$$

The above equation relates the nodal voltages $\bar{V}$ and currents $\bar{I}$ at every bus in the network, and for each phase in the three-phase and mixed-phase representations. The procedure for assembling nodal admittance matrix and the suitability of phase coordinates representations are discussed in [83, 34, 36].

6.4.2 ANALYSIS:-

The nodal admittance equations (6.31) may be used for usual network solutions. With slight refinements, load flow and fault studies for balanced and unbalanced situation may be carried out using the well established balanced system techniques. Although no systematic study of Short circuit and load flow is intended here, the application of multi-phase transmission lines and the associated transformers representations will be illustrated by carrying out single phase load flow studies on a typical sample system to investigate the impact of converting certain double circuit three-phase lines to six-phase lines, in the next section.

6.5 IMPACT OF CONVERTING TPDC LINES TO SIX-PHASE – A CASE STUDY FOR LOAD FLOW

Taking in to the consideration the sample system as shown below in figure: 6.4, wherein, the lines 6,7 & 8 are TPDC lines. The conversion of TPDC line into six-phase would mean an increase in the line to ground voltage by √3 times. This is equivalent to up-rating the existing TPDC line by increasing voltage by √3 times. The effects of conversion of TPDC lines into six-phase lines are studied by NR load flow subroutines. The scope for the rise in system loading (after the line conversion) with required changes in the network, is investigated and studied. The necessary data for the load-flow study are given in table 3 and 4 and its results are consolidated in tables: 5 and 6.

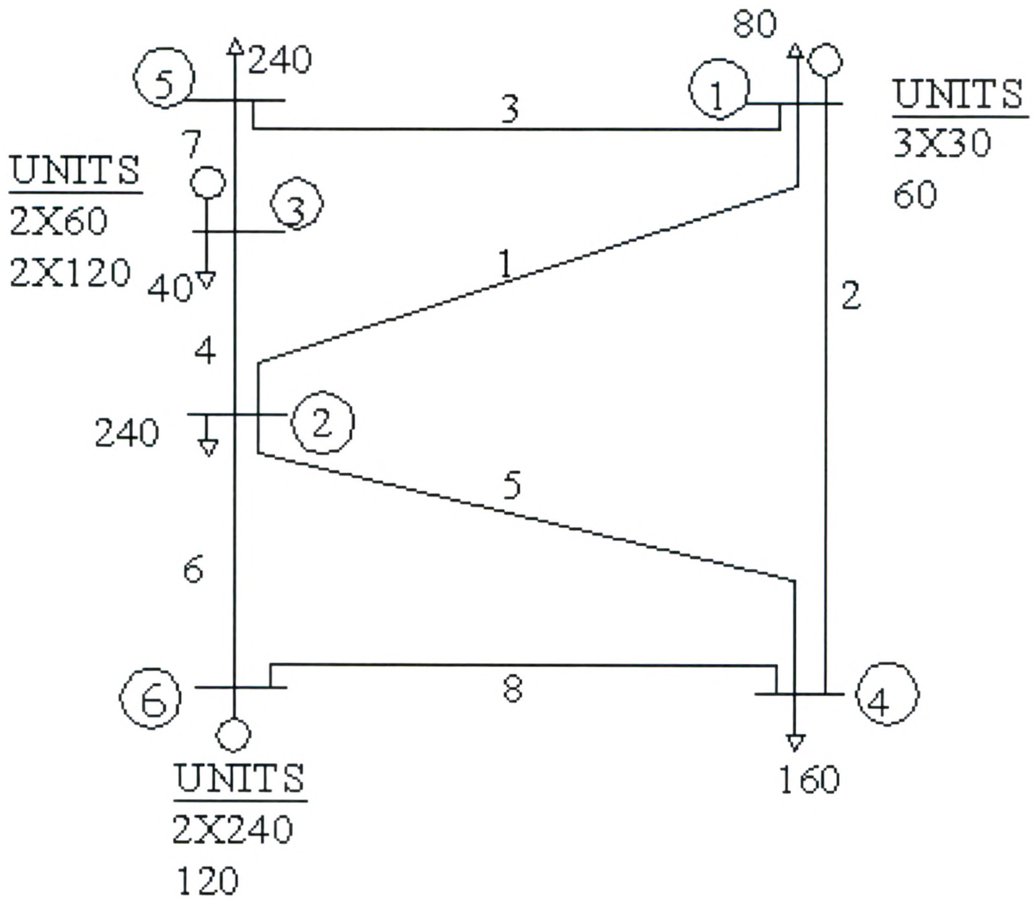

Fig. 6.4 Sample System having Three Phase Single and Double Circuits With Loads and Generations in MW

(Lines 6,7 and 8 are Three-phase Double Circuit Lines)

Line No	Type	R (p.u.)	X (p.u.)	Normal Capacity (MW)
1	1	0.1	0.4	100
2	1	0.15	0.6	80
3	1	0.05	0.2	100
4	1	0.05	0.2	100
5	1	0.1	0.4	100
6	2	0.01875	0.075	400
	3	0.00625	0.04357	692
7	2	0.025	0.1	200
	3	0.00833	0.07143	346
8	2	0.0375	0.15	200
	3	0.0125	0.08715	346
	Type			
	1	Single Ckt Three-Phase Line		
	2	Double-Ckt Three-Phase Line		
	3	Six-Phase Line coversion		

Table:6.2 Circuit Characteristics With 100 MVA Base

A.C. Load-flow Data					
Bus No	Type	Generation (MVA)	Load (MVA)	Voltage Mag.	Phase Angle
1	P, |V|	51 + j0.0	80 + j0.0	1.02	0.0
2	P , Q	0.0 + j0.0	240 + j0.0	1.04	0.0
3	P, |V|	168 + j0.0	39.7 + j0.0	1.04	0.0
4	P , Q	0.0 + j0.0	160 + j40	1.04	0.0
5	P , Q	0.0 + j0.0	240 + j0.0	1.04	0.0
6	Slack	0.0 + j0.0	0.0 + j0.0	1.04	0.0

Table: 6.3 A.C. Load Flow Data

A.C. Load-flow for increased Sysytem Loading					
Bus No	Type	Generation (MVA)	Load (MVA)	Voltage Mag.	Phase Angle
1	P, |V|	51 + j0.0	80 + j0.0	1.02	0.0
2	P , Q	0.0 + j0.0	530 + j0.0	1.04	0.0
3	P, |V|	240 + j0.0	111.7+ j0.0	1.04	0.0
4	P , Q	0.0 + j0.0	200 + j40	1.04	0.0
5	P , Q	0.0 + j0.0	240 + j0.0	1.04	0.0
6	Slack	0.0 + j0.0	0.0 + j0.0	1.04	0.0

Table:6.4 A.C. Load Flow Data for Increased System Loading

Voltage Magnitude & Phase Angles						
Bus No	Case:1 Original Network System Load=759.70 MW		Case:2 6,7 & 8 are Six-Phase Lines System Load=759.70 MW		Case:3 6,7 & 8 are Six-Phase Lines System Load=1261.7 MW	
	|V| p.u.	θ Deg	|V| p.u.	θ Deg	|V| p.u.	θ Deg
1	1.02	-31.42	1.02	-19.97	1.02	-28.88
2	0.96	-16.87	1.02	-8.75	0.98	-16.55
3	1.04	-26.59	1.04	-17.45	1.04	-26.28
4	0.9	-17.27	0.98	-8.98	0.94	-16.81
5	0.98	-37.29	1.01	-25.08	1.01	-33.93
6	1.04	0	1.04	0	1.04	0

Table: 6.5 Voltage Magnitude & Phase Angles

Line Flows And Transmission Efficiencies											
Line No	From Bus i	To Bus j	Case:1 Original Network System Load=759.70 MW			Case:2 6,7 & 8 are Six-Phase Lines System Load=759.70 MW			Case:3 6,7 & 8 are Six-Phase Lines System Load=1261.7 MW		
			Pij (MW)	Qij (MVAR)	% Effi	Pij (MW)	Qij (MVAR)	% Effi	Pij (MW)	Qij (MVAR)	% Effi
1	1	2	-52.96	35.31	93.15	-46.08	17.454	95.16	-46.15	28.17	94.26
2	1	4	-29.64	31.76	91.59	-27.83	16.2	94.88	-27.26	24.26	93.38
3	1	5	53.6	10.31	97.33	44.91	-3.68	97.84	44.42	-3.62	97.83
4	2	3	72.8	-47.46	94.42	73.84	-24.47	95.96	75.29	-42.17	94.82
5	2	4	4.84	13.3	95.66	2.91	7.54	97.93	3.23	8.76	96.9
6	2	6	-374.5	53.9	92.84	-365.17	25.04	97.82	-657.48	5.34	98.85
7	3	5	197.04	32.27	95.32	199.2	34.59	98.41	199.69	34.56	98.41
8	4	6	-187.7	-6.68	92.06	-168.47	-22.48	97.61	-326.05	-15.02	95.56

Table: 6.6 Line Flows and Transmission Efficiencies

Salient features derived from Load flow study on a Sample System:

1) The voltage magnitude and phase angles of all nodes improve substantially (shown in Case:2, Tables: 5 & 6) as the lines 6,7 & 8 are converted into Six-phase lines maintaining the same line voltages and conductor configuration. Even with the increased loading of 1.67 times the original system load (As shown in Case:3, Tables:5 & 6), the benefit of the improved voltage magnitudes and phase angles are retained to an appreciable extent, as evident from the values for P and Q at nodes 2,4 & 5. This clearly states that the better voltage regulation or MVAR control is obtained by replacing TPDC line by six-phase line.

2) The real and reactive power loadings of most of the lines get reduced. The benefit is relatively more quantitative in reactive power flows.

3) The improvement in line efficiencies means the reduced line loss in the system. The lines 6, 7 & 8 retain marked efficiencies in all cases.

4) The system can transfer more load -a phenomenon that has been verified by increasing the system load from 759.70 MW to 1261.70 MW (i.e. 1.67 times the original loading) and for that an additional generating capacity at node 3 and at node 6 is provided. The data and results are given in table 4 and 5, 6 (case-3) respectively. It is evident from

the results that system load can be increased without overloading any of the lines and maintaining at the same time, an appreciable benefit in voltage regulation and efficiencies.

5) The conversion of the existing TPDC line in to six phase offers several advantages, such as, the enhanced loadability, better regulation, increased stability margin, less compensation required for the same rise in power transfer capability, enhanced power transmission efficiency, less space requirement for the same power transfer as compared to that of TPDCS, addressing biological problems (since there is no need to increase system voltage for up-rating the circuit.)

6.6 CONCLUSION:-

The above listed performance features can be explained by the per phase values of the line parameters for TPDCS and Six-phase, as given in Table: 2. For the purpose of calculating equivalent single phase parameters, 8 percent leakage impedance of each of the transformers (One at each end of the Six-phase line) was assumed. As the parameters of the six-phase are significantly lower than their values for TPDCS, the voltage drop in line reduces, leading to an improvement of the voltages of the nodes, both in magnitudes and phase angles. Lower values of resistance and current (i.e. lower real and reactive power flows) in Six-phase lines tend to improve transmission efficiency. The quantum of benefits accrued depends on the topology of the network, location of loads and generating units. The fact that line is up rated by $\sqrt{3}$ times i.e. 1.723 times, the six-phase conversion would transfer more power complying with this value, but the insertion of the two transformers, one at each end, modify this value a little lower. This establishes the fact that with the increase in number of Six-phase lines in the three phase network, the system performance would improve proportionately. The single phase basis load flow analysis and loadability results strongly justify the suitability of six-phase lines as potential Transmission Alternative for realizing the above discussed benefits. However, to gain more insight into the behaviour of the system, phase coordinate analysis to simulate various imbalances viz. unequal phase loadings, Single pole switching, Transformer imbalances such as open delta connection etc. should be investigated for effective planning and diagnosis of the operational problems.