CHAPTER II

EVALUATION OF LINE PARAMETERS

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2.1 INTRODUCTION:-

In view of the ever increasing demand for the electric power, the High Phase Order Transmission System (HPOTS) is catching exponential attention, and in order to cope with the growing demand, it is now being considered to be an effective alternative to the existing Three Phase Double Circuit System (TPDCS) owing to its several advantages over the latter. For example, it provides a unique technique for reducing physical space requirements and at the same time extends means for increasing power transfer capability of a new or existing transmission line and as such it has been emerging as a potential alternative to its Three-Phase counterpart. Proper designing of such system is based upon an accurate mathematical modeling of various system elements. Attempts for the 93 KV phase to ground Six-Phase transmission as commercially viable project is undertaken by New-York State Electric and Gas Corporation (NYSEG), Goudey-Oakdale line near Binghamton, New York.

Some of the technical and economical aspects as well as suitability of HPOTS for circuit up-rating [1-5] ; Parameter computation for 138KV Six-Phase [6] ; system component parameters [7] ; and sequence inductance and capacitance in [8] have been discussed earlier by researchers but not adequately. Discussions regarding the various configurations suitable to be used in practice and the comparative study of the HPOTS with the existing GETCO'S 400 KV, TPDCS line model, have not been made earlier so far.

In view of the pressing need to transfer more and more power from the large and remote power plants to bulk load centre, a multi-phase transmission is emerging as a potential alternative to the conventional Three-Phase system in recent years. Out of the various multi-phase systems, Six-Phase and Twelve-Phase systems have been investigated [8-25, 30-72] for their various technical and economic aspects, as well as their suitability for circuit uprating. However, the evaluation of line parameters of multi-phase transmission for new lines or for the existing TPDCS lines is fundamental to the modeling and analyses of the systems. The attempts have been to compute the phase parameters of a 138 KV Six-Phase line [9] and the symmetrical component parameters of Six-Phase lines [12]. A computer program [65] for generating series, shunt parameter matrices, and component sequence parameters was also developed. Recently, the expressions for the sequence inductances and capacitances of a cyclically transposed Six-Phase line were also developed [10]. However, the expressions for phase inductances; capacitances; capacitances to neutral; complete line parameters; and component sequence parameters of multi-phase line employing conductor configurations suitable for use in practice, are not available in adequate details. This chapter, therefore, deals with the development of the material for studying the line parameters of multi-phase transmission system leading to the better understanding and modeling of the line for various system studies as well as network/digital simulations.

In Section 2.2, the expressions for inductance; capacitance, the Potential and Maxwell coefficients describing the capacitance and inductance matrices of multi-phase lines (covering the transposed as well as untransposed situations) have been derived. Section 2.3 is concerned with the discussion of sequence parameters. Diagonalising transformation matrices for Six-Phase lines are derived for the purpose. Complete line parameters with the effect of ground return are developed in Section 2.5. The effect of lightning shield wires on line parameters is discussed in Section 2.6. Different illustrative calculations have been worked out in Section 2.6 to validate the expressions derived and giving a comparative view of the multi-phase line parameters with their Three-Phase counterparts. Lastly, the computations and conclusions derived from this study have been summarized in Section 2.7.

2.2 LINE PARAMETERS OF MULTI-PHASE LINES:

Multi-phase line has four parameters similar to the conventional Three-Phase system, namely, resistance, inductance, capacitance and shunt conductance. The procedure for calculating the resistance and conductance is similar to that of conventional lines and is discussed in [84, 85]. The expressions for inductance and capacitance parameters, whose values depend upon the conductor configuration and geometry of the line, are derived in this section for both transposed and untransposed cases of multi-phase lines. Since the full transposition with the multi-phase line is difficult to obtain and at the same time likely to destroy the phase relationship between adjacent conductors, only the cyclic transposition (obtained by rotating the entire conductor array over the length of the line allowing each conductor to occupy each location on the structure for $(1/N)^{th}$ distance, but maintaining the correct relative phasing.) is considered.

2.2.1 **Inductance Calculation.:-**

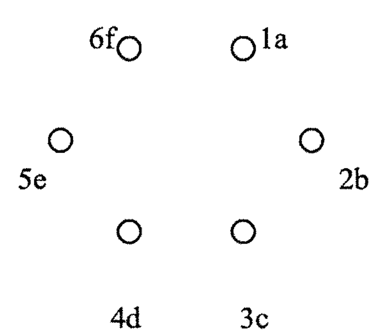
The flux linkage (in weber / metre) of conductor "i" in a multi-conductor transmission line may be written as [15]:

$$\lambda_i = \sum_{j=1}^{n} I_{ij} \ln(1/D_{ij}) \qquad (2.1)$$

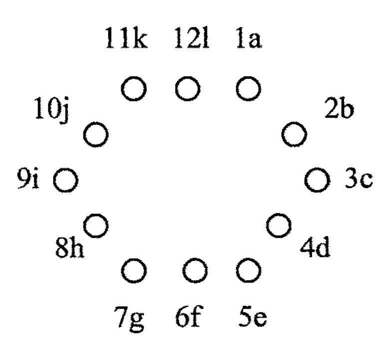
With, i=j , $D_{ij}=r' = r\exp(-\mu r/4)$ for solid conductors, which is to be substituted by G.M.R. for stranded conductors as well as for bundle conductors.

$$L_i=\lambda_i/I_i \qquad \text{H/m} \qquad (2.2)$$

Where, L_i, be the inductance of i^{th} conductor, by employing the above equation (2.2), the inductance for Twelve-Phase and Six-Phase lines will be derived assuming all the phase currents to be balanced (with phase "a" as reference).



Six-Phase configuration
Fig. 2.1(a)



Twelve-Phase configuration
Fig. 2.1(b)

(A) Inductance of Twelve-Phase line:-

By employing the above equation (2.2) the expressions for the inductances of all Twelve-Phases, for the general case of asymmetrical arrangement of the conductor can be obtained as follows.

For Twelve-Phase Inductance of i^{th} conductor can be given as:

Generalized equation is....

With, i = j = 1;

$$L_i=10^{-7}[\ \ln(D_{i,j+4}(D_{i,j+6})^2(D_{i,j+8})/D_{i,j+2}D_{i,j+10}r'^2)\ (D_{i,j+5}D_{i,j+7}/D_{i,j+1}D_{i,j+11})^{1.73} + j\ln(D_{i,j+1}(D_{i,j+3})^2D_{i,j+5}/D_{i,j+7}(D_{i,j+9})^2D_{i,j+11})(D_{i,j+2}D_{i,j+4}/D_{i,j+8}D_{i,j+10})^{1.73}] \quad \textbf{(2.3)}$$

$$L_a=10^{-7}[\ \ln(D_{15}(D_{17})^2(D_{19})/D_{13}D_{1,11}r'^2)\ (D_{16}D_{18}/D_{12}D_{1,12})^{1.73} + j\ln(D_{12}(D_{14})^2D_{16}/D_{18}(D_{1,10})^2D_{1,12})(D_{13}D_{15}/D_{19}D_{1,11})^{1.73}] \quad (2.3.1)$$

$$L_b=10^{-7}[\ \ln(D_{26}(D_{28})^2(D_{2,10})/D_{24}D_{2,12}r'^2)(D_{27}D_{29}/D_{23}D_{21})^{1.73} + j\ln(D_{23}(D_{25})^2D_{27}/D_{29}(D_{2,11})^2D_{21})(D_{24}D_{26}/D_{2,10}D_{2,12})^{1.73}] \quad (2.3.2)$$

$$L_c=10^{-7}[\ \ln(D_{37}(D_{39})^2(D_{3,11})/D_{35}D_{31}r'^2)\ (D_{38}D_{3,10}/D_{34}D_{32})^{1.73} + j\ln(D_{34}(D_{36})^2D_{38}/D_{3,10}(D_{3,12})^2D_{32})(D_{35}D_{37}/D_{3,11}D_{31})^{1.73}] \quad (2.3.3)$$

$$L_d=10^{-7}[\ \ln(D_{48}(D_{4,10})^2(D_{4,12})/D_{46}D_{42}r'^2)\ (D_{49}D_{4,11}/D_{45}D_{43})^{1.73} + j\ln(D_{45}(D_{47})^2D_{49}/D_{4,11}(D_{41})^2D_{43})(D_{46}D_{48}/D_{4,12}D_{42})^{1.73}] \quad (2.3.4)$$

$$L_e=10^{-7}[\ \ln(D_{59}(D_{5,11})^2(D_{51})/D_{57}D_{53}r'^2)\ (D_{5,10}D_{5,12}/D_{56}D_{54})^{1.73} + j\ln(D_{56}(D_{58})^2D_{5,10}/D_{5,12}(D_{52})^2D_{54})(D_{57}D_{59}/D_{51}D_{53})^{1.73}] \quad (2.3.5)$$

$$L_f=10^{-7}[\ \ln(D_{6,10}(D_{6,12})^2(D_{62})/D_{68}D_{64}r'^2)\ (D_{6,11}D_{61}/D_{67}D_{65})^{1.73} + j\ln(D_{67}(D_{69})^2D_{6,11}/D_{61}(D_{63})^2D_{65})(D_{68}D_{6,10}/D_{62}D_{64})^{1.73}] \quad (2.3.6)$$

$$L_g=10^{-7}[\ \ln(D_{7,11}(D_{71})^2(D_{73})/D_{79}D_{75}r'^2)\ (D_{7,12}D_{72}/D_{78}D_{76})^{1.73} + j\ln(D_{78}(D_{7,10})^2D_{7,12}/D_{72}(D_{74})^2D_{76})(D_{79}D_{7,11}/D_{73}D_{75})^{1.73}] \quad (2.3.7)$$

$$L_h=10^{-7}[\ln(D_{8,12}(D_{82})^2(D_{84})/D_{8,10}D_{86}r'^2)(D_{81}D_{83}/D_{89}D_{87})^{1.73} + j\ln(D_{89}(D_{8,11})^2D_{81}/D_{83}(D_{85})^2D_{87})(D_{8,10}D_{8,12}/D_{84}D_{86})^{1.73}] \quad (2.3.8)$$

$$L_i=10^{-7}[\ln(D_{91}(D_{93})^2(D_{95})/D_{9,11}D_{97}r'^2)(D_{92}D_{94}/D_{9,10}D_{98})^{1.73} + j\ln(D_{9,10}(D_{9,12})^2D_{92}/D_{94}(D_{96})^2D_{98})(D_{9,11}D_{91}/D_{95}D_{97})^{1.73}] \quad (2.3.9)$$

$$L_j=10^{-7}[\ln(D_{10,2}(D_{10,4})^2(D_{10,6})/D_{10,12}D_{10,8}r'^2)(D_{10,3}D_{10,5}/D_{10,11}D_{10,9})^{1.73} + j\ln(D_{10,11}(D_{10,1})^2D_{10,3}/D_{10,5}(D_{10,7})^2D_{10,9})(D_{10,12}D_{10,2}/D_{10,6}D_{10,8})^{1.73}] \quad (2.3.10)$$

$$L_k=10^{-7}[\ln(D_{11,3}(D_{11,5})^2(D_{11,7})/D_{11,1}D_{11,9}r'^2)(D_{11,4}D_{11,6}/D_{11,12}D_{11,10})^{1.73} + j\ln(D_{11,12}(D_{11,2})^2D_{11,4}/D_{11,6}(D_{11,8})^2D_{11,10})(D_{11,1}D_{11,3}/D_{11,7}D_{11,9})^{1.73}] \quad (2.3.11)$$

$$L_l=10^{-7}[\ln(D_{12,4}(D_{12,6})^2(D_{12,8})/D_{12,2}D_{12,10}r'^2)(D_{12,5}D_{12,7}/D_{12,1}D_{12,11})^{1.73} + j\ln(D_{12,1}(D_{12,3})^2D_{12,5}/D_{12,7}(D_{12,9})^2D_{12,11})(D_{12,2}D_{12,4}/D_{12,8}D_{12,10})^{1.73}] \quad (2.3.12)$$

The inductances of the Twelve-Phase line presented in (2.3) are complex quantities and are different for different phases. The conductor configuration shown in Fig. 2.1 (b), for the Twelve-Phase line employed in practices [70], there are two groups of inductances; and within each group the inductances have the same value, as given by equations (2.4) and (2.5).

(1) <u>first group:</u> (inductances of the phase conductors situated at the corners of a regular hexagon) :

$$L_a = L_c = L_e = L_g = L_i = L_k$$

$$= 2 \times 10^{-7} \ln (4\sqrt{3}\,(13)^{0.866}\ D/r`) \quad H/m \quad (2.4)$$

(2) <u>Second group:</u> (inductances of the phase conductors situated mid-way between the corners of a regular hexagon) :

$$L_b = L_d = L_f = L_h = L_j = L_l$$

$$= 2 \times 10^{-7} \ln (6(13)^{0.866}\ D/r`) \quad H/m \quad (2.5)$$

This difference results in an unbalanced network; the balance can be restored by the cyclic transposition of the line, which yields in an effective inductance per phase as follows:

$$L=2x10^{-7}\ln[(2\sqrt{3})^{1.5}(13)^{0.866}D/r'] \quad H/m \qquad (2.6)$$

If the cyclic transposition is not adopted, the conductor group at the corners and the conductor group mid-way between the corners of a regular hexagon, would have different inductances.

(B) Inductance for Six-Phase line:-

Similarly, the inductances of all the Six-Phases for a general case of asymmetrical arrangement of conductors, are obtained as;

General equation is…..

With i = j = 1;

$$L_i=2x10^{-7}[\ln(D_{i,j+3}/r')(D_{i,j+2}D_{i,j+4}/D_{i,j+1}D_{i,j+5})^{0.5}+j0.866\ln(D_{i,j+2}D_{i,j+3}/D_{i,j+4}D_{i,j+5})] \qquad (2.7)$$

$$L_a = 2x10^{-7} [\ln (D_{14} /r')(D_{13}D_{15} / D_{12} D_{16})^{0.5} +j0.866 \ln (D_{13}D_{14} /D_{15} D_{16})] \qquad (2.7a)$$

$$L_b = 2x10^{-7} [\ln (D_{25} /r')(D_{24} D_{26} / D_{12}D_{23})^{0.5} +j 0.866 \ln (D_{23}D_{24} / D_{12} D_{26})] \qquad (2.7b)$$

$$L_c = 2x10^{-7} [\ln (D_{36} /r')(D_{13}D_{35} / D_{23}D_{34})^{0.5} +j 0.866 \ln (D_{34}D_{35} / D_{13} D_{32})] \qquad (2.7c)$$

$$L_d = 2x10^{-7}[\ln (D_{14} /r') (D_{24}D_{46}/ D_{34}D_{45})^{0.5} +j 0.866 \ln (D_{45}D_{46} / D_{24}D_{34})] \qquad (2.7d)$$

$$L_e = 2x10^{-7} [\ln (D_{25}/r')(D_{15}D_{35} /D_{45}D_{56})^{0.5}+j0.866 \ln (D_{15}D_{56} / D_{35}D_{45})] \qquad (2.7e)$$

$$L_f = 2x10^{-7}[\ln(D_{36}/r')(D_{26}D_{46}/D_{16}D_{56})^{0.5}+j0.866 \ln (D_{46}D_{56} / D_{16}D_{26})] \qquad (2.7f)$$

The cyclic transposition of the line yields the following effective inductance per phase;

$$L=2x10^{-7}[\ln (1/r')(D_{14}D_{24}/D_{12})^{2/3}(D_{13}D_{25}/D_{16})^{1/3}] \quad H/m \qquad (2.8)$$

However, the symmetrical arrangement of conductors on a regular hexagon configuration yields a cyclic symmetry without transposition. The inductance per phase under this condition is shown by equation (2.9).

$$L = 2x10^{-7} \ln [(2\sqrt{3}) D/r'] \quad H/m \qquad (2.9)$$

2.2.2 Inductance Matrix of Multi-phase Lines :

The flux linkages for a multi-phase line given by (2.2) can be expressed in matrix form as;

$$\lambda = [L][I] = 2x10^{-7} [M][I] \qquad (2.10)$$

Where, [L] is (N x N) inductance matrix for N-phase line whose elements (in N/m) are given by:

$$L_{ii} = 2x10^{-7} \ln (1/r') \quad \text{for inductance} \qquad (2.11a)$$

$$l_{ij} = 2x10^{-7} \ln (1/D_{ij}) \quad \text{for mutual inductance where } i \neq j \qquad (2.11b)$$

$$i , j = 1.2......N$$

Thus, for the conductor configuration of the Twelve-Phase line (Fig. 2.1(b)) the Twelve-Phase line has eight different types of mutual inductances and all equal self inductances. The eight mutual inductances are shown in the appropriate off-diagonal locations in matrix [L] in (2.12a). However, the cyclic transposition of the Twelve-Phase line yields the matrix [L] in (2.12a) with only the different types of mutual inductance, as described in (2.12b). The inductance matrix elements in (2.12) can be computed to include the effect of earth when the ground is required to be represented as flux line. For the conductor configuration, as shown in Fig. 2.1(a, & b) the elements of [M] which are known as Maxwell's coefficients, can be obtained from the following;

[L] =

Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1
Lm1	Ls	Lm1	Lm7	Lm3	Lm6	Lm5	Lm4	Lm5	Lm6	Lm3	Lm7
Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3
Lm3	Lm7	Lm1	Ls	Lm1	Lm7	Lm3	Lm8	Lm5	Lm4	Lm5	Lm8
Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5
Lm5	Lm8	Lm3	Lm7	Lm1	Ls	Lm1	Lm7	Lm3	Lm8	Lm5	Lm4
Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5
Lm5	Lm4	Lm5	Lm8	Lm3	Lm7	Lm1	Ls	Lm1	Lm7	Lm3	Lm8
Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3
Lm3	Lm8	Lm5	Lm4	Lm5	Lm6	Lm3	Lm7	Lm1	Ls	Lm1	Lm7
Lm2	Lm3	Lm4	Lm5	Lm5	Lm6	Lm4	Lm3	Lm2	Lm1	Ls	Lm1
Lm1	Lm7	Lm3	Lm8	Lm5	Lm4	Lm5	Lm8	Lm3	Lm7	Lm1	Ls

(2.12a)

[L]=

Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1
Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2
Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3
Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4
Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5
Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5	Lm6
Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4	Lm5
Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3	Lm4
Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2	Lm3
Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1	Lm2
Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls	Lm1
Lm1	Lm2	Lm3	Lm4	Lm5	Lm6	Lm5	Lm4	Lm3	Lm2	Lm1	Ls

(2.12b)

$$\mathbf{M_{ii} = \ln (2H_i/r')} \qquad \textbf{(2.13a)}$$

$$\mathbf{M_{ij} = \ln (I_{ij}/A_{ij}) \quad \text{where } i \neq j} \qquad \textbf{(2.13b)}$$

i,j = 1,2,3……12

Where,

Hi = Height of conductor "i" above ground.

Aij = Distance between conductor "i" and "j".

Iij = Distance between conductor "i" and image of conductor "j".

The matrix [M] for the Twelve-Phase untransposed line is, therefore, different from matrix (2.12a), and even its diagonal elements differ from each other. This is due to the different heights of the individual conductors above ground. This asymmetry of the N-matrix is improved by transposing the line cyclically, so that the M-matrix will have the form of (2.12b) and its elements can be expressed with the help of equations 2.13a and 2.13b, as follows;

$$M_S = 1/6 \ln 2[(H_1 H_5)^3 (H_2H_3H_4)^2]/r' \qquad (2.14a)$$

$$M_{m1} = 1/6 \ln [(I_{12} I_{23}I_{34}I_{45}I_{56}I_{12,1})/(A_{12}A_{23}A_{34}A_{45}A_{56}A_{12,1})] \qquad (2.14b)$$

$$M_{m2} = 1/6 \ln [\{(I_{13} I_{24}I_{35}I_{46}I_{12,2})/(A_{13}A_{24}A_{35}A_{46}A_{12,2})\}^2 (I_{57}I_{11,1})/(A_{57}A_{11,1})] \qquad (2.14c)$$

$$M_{m3} = 1/6 \ln [(I_{14} I_{25}I_{36}I_{47}I_{9,12}I_{10,1})/(A_{14}A_{25}A_{36}A_{47}A_{9,12}A_{10,1})] \qquad (2.14d)$$

$$M_{m4} = 1/6\ln[\{(I_{15} I_{26}I_{37}I_{8,12}I_{9,1})/(A_{15}A_{26}A_{37}A_{8,12}A_{9,1})\}^2 (I_{4,8}I_{10,2})/(A_{48}A_{10,2})] \qquad (2.14e)$$

$$M_{m5} = 1/6 \ln [(I_{16} I_{27}I_{38}I_{7,12}I_{81}I_{92})/(A_{16}A_{27}A_{38}A_{7,12}A_{81}A_{92})] \qquad (2.14f)$$

$$M_{m6} = 1/6\ln [\{(I_{17} I_{28})/(A_{17}A_{28})\}^2 (I_{39}I_{6,12})/(A_{39}A_{6,12})] \qquad (2.14g)$$

The inductance matrix and the Maxwell's coefficients of Six-Phase line are obtained in the same manner as in the Twelve-Phase line. It has been found that for the asymmetrical configuration of Six-Phase conductors, the inductance matrix contains 5 mutual terms, all different in values; and the diagonal terms are characterized by equal magnitudes. The cyclic transposition yields the Six-Phase inductances as given in (2.15), which are in conformity with those obtained in reference [20].

$$[L]= \begin{bmatrix} Ls & Lm1 & Lm2 & Lm3 & Lm2 & Lm1 \\ Lm1 & Ls & Lm1 & Lm2 & Lm3 & Lm2 \\ Lm2 & Lm1 & Ls & Lm1 & Lm2 & Lm3 \\ Lm3 & Lm2 & Lm1 & Ls & Lm1 & Lm2 \\ Lm2 & Lm3 & Lm2 & Lm1 & Ls & Lm1 \\ Lm1 & Lm2 & Lm3 & Lm2 & Lm1 & Ls \end{bmatrix} \qquad (2.15)$$

The matrix [M] for cyclically transposed Six-Phase line has the same form as (2.15) for both symmetrical as well as asymmetrical configurations; and the elements of [M] can be calculated with the help of equations (2.13a) and (2.13b), for any specified configuration.

2.2.3 Capacitance Calculation :

The voltage nomenclature of multi-phase system has been discussed by Stewart et al, [11]. Among the various possible definitions of system voltages, the phase-to-ground voltage definition is favoured. This is in view of the fact that the adjacent phase-to-phase voltage decreases with phase-to-ground voltages. The number of phase-to-phase voltages for an N-phase system, can be obtained by;

Number of Phase to phase voltages = N [N-1] / 2 **(2.16)**

Contrary to the Three-Phase system, these phase-to-phase voltages of the multi-phase systems are characterized by a number of groups in which the magnitude and phase difference differ from one group to another. This results in unequal capacitances between one phase and the remaining ones. In this section, the expressions for the capacitances to neutral, (which find applications in most of the studies) and the expressions for capacitances between the phases for multi-phase lines are derived.

The potential difference (in Volts) between any two phases (say, "a" and "b") for N-phase line, is given by:

$$V_{ab}= 1 / 2\pi k\ [q_a \ln(D_{12}/r)+q_b \ln(r/D_{12})+q_c \ln(D_{23}/D_{13})+\ldots\ldots+Q_n \ln (D_{2,n}/D_{1,n})] \quad (2.17)$$

Capacitance between C_{ab} is given by..

$$C_{ab}=q_a/V_{ab} \quad (2.18)$$

The equations (2.16) to (2.18) will be employed in developing the expressions for the capacitance of multi-phase lines.

[a] Capacitance of Twelve-Phase Line:-

Twelve-Phase line has 12 phase-ground-voltages and 66 phase-to-phase voltages which are characterized by groups in which the magnitude and phase difference differ from one group to another as follows;

Group I ($V_{12}, V_{23} \ldots V_{12,1}$): the voltages are spaced by 30^0 .
Group II ($V_{13}, V_{24} \ldots V_{12,2}$): the voltages are spaced by 60^0,.
Group III ($V_{14}, V_{25} \ldots V_{12,3}$): the voltages are spaced by 90^0.
Group IV ($V_{15}, V_{26} \ldots V_{12,4}$): the voltages are spaced by 120^0.
Group V ($V_{16}, V_{27} \ldots V_{12,5}$): the voltages are spaced by 150^0.
Group VI (V_{17}, V_{28}, V_{39}, $V_{4,10}$, $V_{5.11}$, $V_{6,12}$): the voltages are spaced by 180^0 .

Applications of equations (2.17) and (2.18) to the line conductor configuration as shown in Fig.2.1 (b), yields 132 capacitances between phases. These capacitances can be characterized by a total of twelve groups; and within each group the capacitances are complex quantities having the same absolute value. Six of these groups (i.e. 66 capacitances) are related to the phase conductors situated at the corners of a regular hexagon (a, c, e, g, i, k) with the following capacitances.

First Group (capacitances between adjacent phases):

$$C_{ab} = C_{cd} = C_{gh} = C_{ij} = C_{kl}$$
$$= 2Пk / [0.134 \ln (161.68\ D/r) + j0.5 \ln (55.313\ D/r)] \ \text{F/m} \quad (2.19a)$$

$$C_{al} = C_{cb} = C_{ed} = C_{gf} = C_{ih} = C_{kj}$$
$$=2Пk / [0.134 \ln (161.68\ D/r) - j0.5 \ln (55.313\ D/r)] \ \text{F/m} \quad (2.19b)$$

These twelve capacitances $C_{ab}, \ldots\ldots, C_{kj}$ have the same absolute values :

$$C_{ab} = 2Пk / \{ [(0.134 \ln (161.68\ D/r)]^2 + [0.5 \ln (55.31\ D/r)]^2 \}^{1/2} \quad \text{F/m} \quad (2.19c)$$

Second Group :

(capacitances between phases separated by one intermediate conductor):

$C_{ac} = C_{eg} = C_{ik} = C_{ka} = C_{ak} = C_{ca} = C_{ec} = C_{ge} = C_{ig} = C_{ki}$

$= 2\text{ЛK} / [\ln (63.87D/r)]$ F/m (2.19d)

Third Group : (capacitances between phases separated by two conductors) :

$C_{ad} = C_{cf} = C_{eh} = C_{gj} = C_{il} = C_{kb} = C_{aj} = C_{ci} = C_{eb} = C_{gd} = C_{if} = C_{kh}$

$=2\text{Лk} / \{ (\ln (63.87D/r))^2 + (\ln (55.313\ D/r))^2 \}^{1/2}$ F/m (2.19e)

Fourth Group: (capacitances between phases separated by three conductors):

$C_{ae} = C_{eg} = C_{ei} = C_{gk} = C_{ia} = C_{kc} = C_{ai} = C_{ck} = C_{ea} = C_{gc} = C_{ie} = C_{kg}$

$= 2\text{Лk} / [\ 1.73\ \ln (63.87\ D/r)\ ]$ F/m (2.19f)

Fifth Group : (capacitances between phases separated by four conductors) :

$C_{af} = C_{ch} = C_{gi} = C_{ib} = C_{kd} = C_{ah} = C_{cj} = C_{el} = C_{gb} = C_{id} = C_{kf}$

$= 2\text{Лk} / \{ [1.866 \ln(59.75D/r)\ ]^2 + [0.5 \ln(55.313D/r)]^2 \}^{1/2}$ F/m (2.19g)

Sixth Group : (capacitances between opposite phases) :

$C_{ae} = C_{ag} = C_{ci} = C_{ek} = C_{ga} = C_{ic} = C_{ke}$

$= 2\text{Лk} / (2 \ln (63.87\ D/r)\}$ F/m (2.19h)

The remaining six groups are related to the phase conductors situated mid-way between the corners of the regular hexagon (b, d, f, h, j, i) characterized in a similar manner to the previous ones. The absolute values of the capacitances of the various groups are as follows:

Seventh Group:

$C_{bc} = C_{de} = C_{fg} = C_{hi} = C_{jk} = C_{la} = C_{ba} = C_{dc} = C_{fe} = C_{hg} = C_{ji} = C_{lk}$

=2Лk / $[\,(0.134 \ln (21.767\, D/r))^2 + (0.5 \ln (63.87 D/r))^2\,]^{1/2}$ F/m (2.20a)

Eighth Group:

$C_{bd} = C_{df} = C_{fh} = C_{hj} = C_{jl} = C_{lb} = C_{bl} = C_{db} = C_{fd} = C_{hf} = C_{jh} = C_{li}$

=2Лk / (ln 55.313 D/r)] F/m (2.20b)

Ninth Group:

$C_{be} = C_{dg} = C_{fi} = C_{hk} = C_{ja} = C_{lc} = C_{bk} = C_{da} = C_{fc} = C_{he} = C_{ig} = C_{li}$

= 2Лk /$[\,(\ln (55.313\, D/r\,))^2 + (\ln (63.87\, D/r))^2\,]^{1/2}$ F/m (2.20c)

Tenth Group:

$C_{bf} = C_{dh} = C_{fj} = C_{hl} = C_{jb} = C_{ld} = C_{bj} = C_{dl} = C_{fb} = C_{hd} = C_{jf} = C_{lg}$

=2Лk /(1.73 ln 55.313 D/r)] F/m (2.20d)

Eleventh Group:

$C_{bg} = C_{di} = C_{fk} = C_{ha} = C_{jc} = C_{le} = C_{bi} = C_{dk} = C_{fa} = C_{hc} = C_{je} = C_{lg}$

= 2Лk / $[(1.866\ \text{In}\ (59.135\, D/r\,))^2 + (0.5\ \text{In}\ (63.87\, D/r))^2\,]^{1/2}$ F/m (2.20e)

Twelfth Group:

$C_{bh} = C_{dj} = C_{fl} = C_{hb} = C_{jd} = C_{lf}$

= 2Лk /[2 In (55.313D/r) } F/m (2.20f)

However, when the line is cyclically transposed, these twelve groups of phase-to-phase capacitances get reduced to only Six-groups which are expressed as follows.

First Group:

$$C_{ab} = 2\pi k/[0.5176 \ln (59.44D/r)] \quad F/m \quad (2.21a)$$

Second Group:

$$C_{ac} = 2\pi k/[\ln (59.44D/r)] \quad F/m \quad (2.21b)$$

Third Group:

$$C_{ad} = 2\pi k/[1.414 \ln (59.44D/r)] \quad F/m \quad (2.21c)$$

Fourth Group:

$$C_{ae} = 2\pi k/[1.73 \ln (59.44D/r)] \quad F/m \quad (2.21d)$$

Fifth Group:

$$C_{af} = 2\pi k/[1.9318 \ln (59.44D/r)] \quad F/m \quad (2.21e)$$

Sixth Group:

$$C_{ag} = 2\pi k/[2 \ln(59.44D/r] \quad F/m \quad (2.21f)$$

The twelve capacitances-to-neutral (without considering the ground effect) are characterized by two groups. The first group consists of the phase conductors situated at the corners of a regular hexagon, while the second group consists of the conductors situated mid-way between the corners. Each capacitance of the first group has a value of $0.52C_{ab}$ as shown in the equation (2.19a), while each capacitance of the second group has a value of $0.52C_{bc}$ as shown in the equation (2.20a). The C_{ab} and C_{bc} are capacitances under untransposed condition, whereas with the cyclically transposed line all the capacitances to neutral have the same value equal to ($0.52C_{ab}$) as shown in equation (2.21a). The factor 0.52 is the ratio between Phase-to-Phase and Phase-to-Ground voltages for the Twelve-Phase system.

[b] Capacitance of Six-Phase Line:

Similar to the Twelve-Phase line, the Six-Phase line has 6, Phase-to-ground voltages and 15 phase-to-phase voltages. The phase-to-phase voltages are characterized by three groups, and the phase to ground voltage is equal to the adjacent phase to phase voltage. The application of general equations to line conductor configuration as shown in Fig.2.1 (a) yields the following phase-to-neutral capacitances (without considering the effect of ground) in F/m:

$$C_{an} = C_{dn}$$

$$= 2\pi k / [\ln (D_{13} D_{36}{}^{2} / r D_{16} D_{25} \}^{0.5} + j \ln (D_{13} D_{25}/r D_{16})^{0.866}] \quad (2.22a)$$

$$C_{bn} = C_{en}$$
$$= 2\pi k / [\ln (D_{13}D_{25}^2/r\, D_{16}\, D_{36})^{0.5} + j \ln (D_{13}D_{36}/r\, D_{16})^{0.866}] \quad (2.22b)$$
$$C_{cn} = C_{fn}$$
$$= 2\pi k / [\ln (D_{16}D_{36}D_{26}^{\,2}/r\, D_{13}\, D_{12}^2)\,] \quad (2.22c)$$

In the case of cyclic transposition, the effective phase-to-neutral capacitance is obtained as:

$$\mathbf{C_n = 2\pi k \;/\; [\,\ln (1/r)\, (D_{13}D_{25}D_{26}^2D_{36}^2 / D_{16}D_{12}^2\,)^{1/3}]} \qquad \mathbf{F/m} \qquad \mathbf{(2.23)}$$

However, in the case of symmetrical spacing (Fig 2.1(a)) the value of capacitance-to-neutral, (without the need for transposition) is determined as:

$$\mathbf{C = 2\pi k / \ln [(2\sqrt{3})\, D/r]} \qquad \mathbf{F/m} \qquad \mathbf{(2.24)}$$

2.2.4 Effect of Earth on the Capacitance :-

In order to ascertain the effect of earth on the phase-to-neutral capacitance, the "Method of Images" is applied to the calculation of capacitance (i.e. the voltage drop from "a" to "b" is determined by the total number of charged conductors and their images). It is evident that the phase-to-ground capacitances are different owing to the different heights of the phases above ground. These differences can be overcome by transposing the line cyclically; and the capacitance-to-neutral of the Twelve-Phase line can be obtained by:

$$\mathbf{C_n = (1/12) \sum_{i=1}^{12} C_{ni}} \qquad \mathbf{F/m} \qquad \mathbf{(2.25)}$$

Where, C_{ni} is the capacitance-to-neutral of any phase conductor at the i^{th} position of the transposition cycle. The capacitance expression for conductor 'a' at the first position of the transposition cycle (Fig.2.1) is found as follows:

$$\mathbf{C_{ni} = 1.035\, \pi k \,/\, \{[\,(0.134 \ln (161.68\, D/r)\, (K_1)^{3.73}\, (K_2)^{6.463}\;]^2 + [\,0.5 \ln (55.31\; 3D/r)\, (K_2)(K_4)^{1.732}\,]^2\}^{1/2}} \qquad \mathbf{F/m} \qquad \mathbf{(2.26)}$$

where,

$$K_1 = (4H_1^2 I_{27}^2 I_{13} I_{25} I_{29} I_{1,11}) / (I_{12}^2 I_{17}^2 I_{15} I_{19} I_{2,11})$$

$$K_2 = (I_{12} I_{26} I_{26} I_{28} I_{1,12}) / (2 H_2 I_{16} I_{18} I_{2,12})$$

$$K_3 = (2H_2 I_{24}^2 I_{1,10}^2 I_{26} I_{18} I_{1,12}) / (I_{14}^2 I_{2,10}^2 I_{12} I_{16} I_{28} I_{2,12})$$

$$K_4 = (I_{23} I_{25} I_{19} I_{1.11}) / (I_{13} I_{15} I_{29} I_{2.11})$$

The complete expression for C_n, with ground effect is quite lengthy and therefore, it is not shown here due to the paucity of space.

Similarly, the capacitance-to-neutral of Six-Phase line is given by:

$$C_n = 2\pi k / \ln[((2\sqrt{3})D/r) - \ln \tfrac{1}{2}\{(I_{14}^4 I_{13}^2 I_{15}^2 I_{24}^2 I_{25}^2)/(H_1^2 H_2^2 H_3 I_{12}^2 I_{23}^2 I_{16} I_{34})\}^{1/6}] \text{ F/m} \quad (2.27)$$

The comparison of the above equation with (2.24) reveals that the effect of ground is to increase the capacitance C_n (similar to that in Three-Phase line).

2.2.5 Potential Coefficients and capacitance Matrices:-

For a multi-phase line with multi-conductors above ground, the potential of the conductors can be expressed [15] as:

$$[V] = [P]\,[Q/2\pi k] \qquad \text{V} \qquad (2.28)$$

In terms of conductor charges and potential coefficients, the (NxN) elements of the matrix [P] can be obtained by using equation 2.13 (a) & (b) except that " r " is to be used in place of " r' ". The capacitance is then obtained as:

$$[C] = 2\pi k\,[P]^{-1} \qquad \text{F} \qquad (2.29)$$

LINE PARAMETERS FOR MODES OF PROPAGATION:

The inductance, capacitance and other parameter matrices which have been presented in the previous sections, can be diagonalised with the help of a transformation matrix using a standard set of rules [15]. From these diagonal matrices the sequence parameters can be obtained. These diagonal matrices also govern the propagation characteristics of the line. For this purpose the Eigen-vectors and the transformation matrices for Six-Phase lines are developed.

Sequence Inductance and Capacitance:

In order to develop an insight into the propagation characteristic of a multi-phase system, the line is assumed to be completely transposed, implying that all off-diagonal terms in (2.12) for Twelve-Phase line; and in (2.15) for Six-Phase line are equal to Lm.
By solving the determinantal equation,

$$\left| \lambda [u] - [L] \right| = 0 \tag{2.30}$$

we can obtain Eigen-values for the inductance matrix [L] of N-phase order system are as under:

$$\lambda_1 = Ls + (N-1) L_m \tag{2.31a}$$
$$\lambda_2 = \lambda_3 = \ldots\ldots = \lambda_N = Ls\text{-}Lm \tag{2.31b}$$

Each of the above Eigenvalues, the Eigenvectors which are column vectors, can be evaluated by solving the matrix equation:

$$[[u] \lambda_N - [L] [x]] = 0 \tag{2.32}$$

By choosing suitable values for x in each case according to the N-Eigenvalues, the resulting normalized Eigenvectors are obtained, and from these Eigenvectors, the transformation matrix is obtained. For the Six-Phase line the Eigenvectors are obtained as:

$1/\sqrt{6}\ [1,\ 1,\ 1,\ 1,\ 1,\ 1]^t$ for λ_1

$1/\sqrt{30}\ [5,\ -1,\ -1,\ -1,\ -1,\ -1]^t$ for λ_2

$1/\sqrt{20}\ [0,\ 4,\ -1,\ -1,\ -1,\ -1]^t$ for λ_3

$1/\sqrt{12}\ [0,\ 0,\ 1,\ -1,\ -1,\ -1]^t$ for λ_4

$1/\sqrt{6}\ [0,\ 0,\ 0,\ 2,\ -1,\ -1]^t$ for λ_5

$1/\sqrt{2}\ [0,\ 0,\ 0,\ 0,\ 1,\ -1]^t$ for λ_6 (2.33)

And the transformation matrix T6 is given by:

$$=1/\sqrt{60}\begin{bmatrix} \sqrt{10} & 5\sqrt{2} & 0 & 0 & 0 & 0 \\ \sqrt{10} & -\sqrt{2} & 4\sqrt{3} & 0 & 0 & 0 \\ \sqrt{10} & -\sqrt{2} & -\sqrt{3} & 3\sqrt{5} & 0 & 0 \\ \sqrt{10} & -\sqrt{2} & -\sqrt{3} & -\sqrt{5} & 2\sqrt{10} & 0 \\ \sqrt{10} & -\sqrt{2} & -\sqrt{3} & -\sqrt{5} & -\sqrt{10} & 0 \\ \sqrt{10} & -\sqrt{2} & -\sqrt{3} & -\sqrt{5} & -\sqrt{10} & \sqrt{30} \\ \sqrt{10} & -\sqrt{2} & -\sqrt{3} & -\sqrt{5} & -\sqrt{10} & -\sqrt{30} \end{bmatrix} \quad (2.34)$$

This is identically the same as obtained by Peeran et al. [23].

The inductance matrix of the Twelve-Phase line is diagonalised by the relation $[T_{12}]^{-1}[L][T_{12}]$, the diagonal elements of which are :

$$L_0 = L_S + 11\,L_m \quad (2.35a)$$

$$L_1 = L_2 = \ldots = L_S - L_m \quad (2.35b)$$

Similar diagonalisation on the capacitance matrix produces,

$$C_0 = C_S + 11\,C_m \quad (2.36a)$$

$$C_1 = C_2 = \ldots\ldots = C_S - C_m \quad (2.36b)$$

In the case of cyclic transposition, the inductance matrix of the cyclically transposed Twelve-Phase line can be transformed into its sequence form employing the symmetrical component transformation given in Ref. [11]. This yields in seven different inductances as given below:

$$L_0 = L_S + 2(L_{m1} + L_{m2} + L_{m3} + L_{m4} + L_{m5}) + L_{m6} \quad (2.37a)$$

$L_1 = L_{11} = L_S + 1.732(L_{m1} - L_{m5}) + L_{m2} - L_{m4} - L_{m6}$ (2.37b)

$L_2 = L_{10} = L_S + L_{m1} - L_{m2} - 2L_{m3} - L_{m4} + L_{m5} + L_{m6}$ (2.37c)

$L_3 = L_9 = L_S - 2L_{m2} + 2L_{m4} - L_{m6}$ (2.37d)

$L_4 = L_8 = L_S - (L_{m1} + L_{m2} + L_{m4} + L_{m5}) + 2L_{m3} + L_{m6}$ (2.37e)

$L_5 = L_7 = L_S - 1.732(L_{m1} - L_{m5}) + L_{m2} - L_{m4}\ L_{m6}$ (2.37f)

$L_6 = Z_S - 2(L_{m1} - L_{m2} + L_{m3} - L_{m4} + L_{m5}) + L_{m6}$ (2.37g)

2.3 C0MPLETE LINE PARAMETERS:-

In order to ascertain the effect of ground return, the series parameters of multi-phase line as described in Sections 2.2, and 2.3, may be modified as follows:

$Z_{ii} = R_{ii} + \Delta r_{ii} + j\,(X_{ii} + \Delta X_{ii})$

= self impedance in Ω /m (2.38a)

$Z_{ij} = \Delta r_{ij} + j\,(\Delta X_{ij} - X_{ij})$

= mutual impedance in Ω /m (2.38b)

Where, Δr_{ii}, Δr_{ij}, ΔX_{ii} and ΔX_{ij}, are Carson's earth return corrections which can be computed by employing the relations given in reference [87]. After having ascertained the effect of ground return, the complete line parameters of multi-phase (12-phase and 6-phase) lines with the assumption of full transposition, can be represented as in [15]

$[R_{comp}] = [R_c] + [R_g]$

$= R_c\,[U] + R_g\,[D]$ (2.39a)

$[L_{comp}] = [L] + [L_g] = (L_s - L_m)\,[U] + (L_g + L_m)\,[D]$ (2.39b)

$[C] = (C_s - C_m)\,[U] + C_m\,[D]$ (2.39c)

Where,

$[R_{comp}]$ = Complete line resistance matrix

$[L_{comp}]$ = Complete line inductance matrix

[Rc] = [R1] the conductor resistance matrix

[Rg] = the ground return resistance matrix

[Lg] = the ground return inductance matrix

[D] = is a square matrix with elements

d ii = d ij = 1, $i \neq j$,. I,j = 1,2,.......N

The diagonalisation of matrix-C is given in (2.36). However, the diagonalisation of matrices [R_{comp}] and [L_{comp}], obtained by means of the transformation matrix (2.34) yields:

Diag, $[R_{comp}] = R_l \; [U] + R_g [Q]$ (2.40a)

Diag, $[L_{comp}] = (L_s - L_m) [U] + (L_g + L_m) [Q]$ (2.40b)

Where Q is a square matrix with

$Q_{ii} = N.\; Q_{ii}$, for $i = 2,3 \ldots\ldots N$

and $Q_{ij}=0$, for $i \neq j$, $i,j = 1,2,\ldots\ldots N$

The sequence parameters are thereby as under:

$R_0 = R_l + NR_g$ H /m (2.41a)

$L_0 = L_s + (N - 1) L_m + NL_g$ H/m (2.41b)

$L_l = L_s - L_m$ H/m (2.41c)

From equations, (2.41 a, b and c) it is observed that the ground contributes a resistance of (NR_g) and an inductance of (NL_g). This is due to the fact that in this mode the ground return current is equal to the sum of currents in all phase conductors above the ground. Therefore, Equations (2.41) can be rewritten as follows.

.

$R_g = (R_0 - R_l) / N$ Ω /m (2.42)

$(L_g + L_m) = (L_0 - L_l) / N$ H/m (2.43)

Similarly, the expression for the neutral to ground capacitance can be evaluated as:

$C_g = N\, C_l\, C_0 / (C_l - C_0)$ F/m (2.44)

2.4 LINE PARAMETERS INCLUDING THE EFFECT OF LIGHTNING SHIELD WIRES:-

For evaluation of series and shunt parameters of N-phase transmission line with the presence of (N_s) number of lightning shield wires for any conductor configurations, the impedance matrix of N-phase order is obtained by,

$$[Z]_{MxM} = \begin{bmatrix} Z_{ph} & Z_{ps} \\ Z^t_{ps} & Z_{ss} \end{bmatrix} \qquad \textbf{(2.45)}$$

Where,

$$M = N + N_s \qquad (2.45a)$$

Z_{ph} = Matrix of the self and mutual phase impedances of the N-phase line.

Z_{ss} = Matrix of the self and mutual phase impedances of the shield wire circuit

Z_{ps} = Matrix of the mutual coupling between the N-phase line and the shield wire circuits with due consideration of ground effect which can be computed from equations (2.45) and (2.45a), whereas the self and the mutual impedances of the line and shield wire circuits with due consideration of ground effect can be computed from (2.38).

Since the potential of the shield wires is assumed to be zero, the axes of the shield wires are eliminated and thereby series impedance matrix in (2.45) is reduced to [NxN] matrix as,

$$[Z]_{NXN} = [Z_{ph}] - [Z_{ps}]\,[Z_{ss}]^{-1}\,[Z^t_{ps}] \qquad (2.46)$$

Similarly, the effect of lightening shield wires on shunt admittance can be taken into account by finding first elements of (MxM) potential coefficient matrix, and thereafter, by eliminating the axes of shield wires, (NxN) potential coefficient matrix is obtained. The resulting (NxN) potential coefficient matrix is then inverted to obtain the shunt admittance matrix.

2.5 ILLUSTRATIVE CALCULATIONS AND DISCUSSIONS :

The expressions derived in earlier sections are applied to evaluate the parameters of some representative conductor configurations and line geometries for multi-phase lines. The corresponding values of the Three-Phase line parameters are also listed for a quantitative comparison. The geometric mean radius and the radius of bundle conductors as well as the bundle distance used in the calculations are based on the procedure outlined in Ref. [88].

2.5.1 Validation of Analytical Expressions :

The validity of the expressions derived for multi-phase line parameters is examined with the values available in the literature. The relevant details and the circuit configurations employed for the purpose, are given in figures (Fig.2.2).

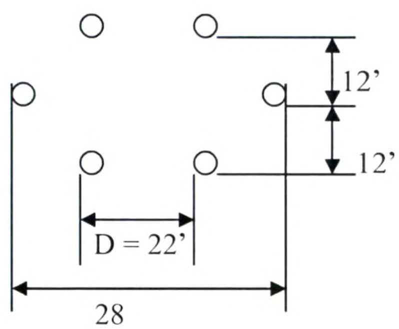


Fig. 2.2 954 Kcmil (RAIL) ACSR Conductor

Multi-phase Line (cyclically transposed)	L(mH/mi)	C_n (μf/mi) (with effect of earth)
138 KV 6-ph line (Fig. 2.2)		
calculated values	2.151	0.0163
values given in [65]	2.053	0.0148

Table : 2.1 Line parameters of Six-Phase line for validation of expressions

An examination of Table 2.1 reveals that the values of parameters in the present work are in close agreement with the values given in Ref. [65] which support the validity of the expressions derived for the Six-Phase system. Similar comparison for the Twelve-Phase system could not be carried out owing to the unavailability of values in the literature.

2.5.2 Computations of phase and Sequence Parameter Matrices.

Computations of the phase impedance and the shunt admittance matrices and sequence parameters which lead to reveal the mutual coupling between phases; sequence components; and effect of transposition of lines (with due consideration of earth and lightning shield wires) have been carried out. For purpose of investigation, a test system of 400 KV double-hung vertical-offset Three-Phase transmission line is assumed to be operated as a Six-Phase line, as shown in Fig. 2.3 with the following details:

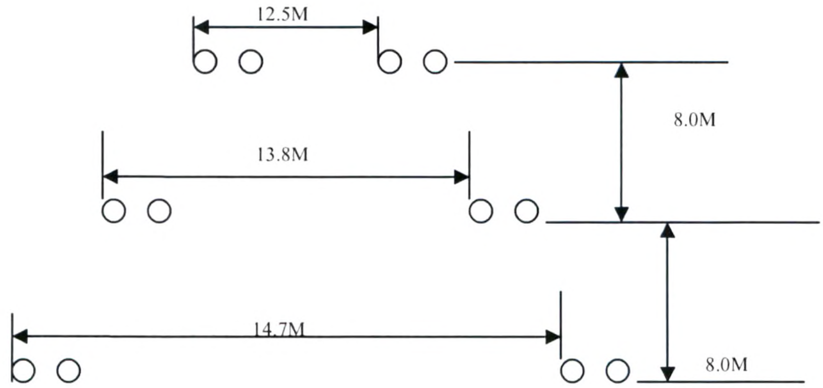


Fig 2.3 **GETCO'S Existing 400 KV 3-ph Double Circuit ,10 in. Bundle Spacing**

Twin Mouse Conductor Used, Dia. 31.77 MM, 900A C.C./Conductor

LINE CONSTANTS AND ASSUMPTIONS:-

Line length : 400 to 1000 Kms. Operating Voltage : 400 KV

Type of conductor: Twin mouse Bundle spacing : 25 Cms.

Phase spacing :As shown in Fig.2.3 Height of the lowest Conductor from ground: 21.9 M.

Shield wires : Two 0.548 Aluminium-clad steel (r_c = 0.7538 **Ω** /Km at 20^0c)

Earth conductivity: 0.01 mho/m

Computed line parameters per Km. for Three-phase Double Circuit System:

L= 0.0005014 C= 2.43 E -8

Computed line parameters per Km. for Six-phase conversion of the same configuration:

L= 0.001268 C= 9.01 E -9

Wherein,

- Terminal equipments and machine variants are not considered.
- Shunt compensation is specified as susceptance.

The computed values of line parameter matrices, using the first term from Carson's earth corrections, are given in Table 2.2. The computed (8x8) series impedance matrix of the Six-Phase untransposed line (as given in matrix (a)) shows that its terms are equal to their corresponding terms of the Double Circuit Three-phase impedance matrix [86], except for the terms in the 4^{th} and 6^{th} columns wherein the inductive parts differ by a small percent. This is because of the fact that the circuits of the 3-phase line are operated with (1-6), (2-5) and (3-4) in parallel. The matrix (b) shows the reduced (6x6) series impedance matrices for the untransposed Six-Phase line, while the matrix (c) shows the same for the cyclically transposed line wherein the diagonal terms are almost the same as compared those of their counterparts of 2x3-phase transposed line [86].

The matrix shown in (c) has three different mutual impedances (Z_{m1} =Z_{m5}, Z_{m2}=Z_{m4}, Z_{m3}) with Z_{m1} and Z_{m3} having the largest and the lowest values respectively, whereas the mutual impedances of 2x3-phase line has equal mutual impedances (Z_{m1} = Z_{m2}) between any two phases in the same circuit. The other three impedances (Z_{m3}, Z_{m4} =Z_5) emerge from the mutual coupling between the two circuits with Z_{m1} having the largest and Z_{m4} the lowest one. The shunt admittance matrix for Six-Phase cyclically transposed line is given in matrix (d). The elements of this matrix are completely different but with somewhat higher diagonal terms as compared to their 2x3-phase line counterparts.

The sequence parameters are listed in matrix (e) to (g). The results in matrix (e) show that the coupling is present between the zero, second and fourth sequences; whereas in the case of untransposed 2x3-phase sequences matrix, the coupling is present between all the sequences. The matrix (f) shows that the sequence component matrix offers no coupling between the sequences, while the identical matrix of the transposed 2x3–phase line offers mutual coupling between the zero sequences and the positive sequences of the two circuits.

For 400 KV Six-Phase line:

(a) (8x8) series impedance matrix of Six-Phase untransposed line (phase comps. Ω /Km)

0.076 +j0.695	0.059 +j0.333	0.059 +j0.288	0.059 +0.267	0.059 +j0.276	0.059 +j0.301	0.059 +j0.338	0.059 +j0.290
	0.076 +j0.695	0.059 +j0.338	0.059 +j0.276	0.059 +0.271	0.059 +j0.277	0.059 +j0.285	0.059 +j0.259
		0.076 +j0.695	0.059 +j0.296	0.059 +j0.276	0.059 +j0.278	0.059 +j0.276	0.059 +j0.246
symmetry			0.076 +j0.695	0.059 +j0.338	0.059 +j0.288	0.059 +j0.246	0.059 +j0.276
				0.076 +j0.695	0.059 +j0.333	0.059 +j0.277	0.059 +j0.285
					0.076 +j0.695	0.059 +j0.290	0.059 +j0.339
						0.810 +j1.10	0.059 +j0.302
							0.810 +j1.10

(b) (6x6) Se. impedance matrix of 6-phase untransposed line (phase comps. Ω /Km)

0.1029 +j0.5688	0.0789 +j0.2497	0.0756 +j0.1864	0.0841 +j0.1428	0.0781 +j0.1676	0.0753 +j0.2003
	0.0908 +j0.5988	0.0711 +j0.2497	0.0781 +j0.1666	0.0731 +j0.1756	0.0708 +j0.1878
		0.0859 +j0.6118	0.0753 +j0.1945	0.0709 +j0.1867	0.0686 +j0.1843
	Symmetry		0.1029 +j0.5688	0.079 +j0.2291	0.075 +j0.1864
				0.0913 +j0.5978	0.0711 +j0.2438
					0.0853 +j0.6123

(c) (6x6) series impedance matrix of 6-ph. transposed line (phase comps. in Ω /Km)

0.0923 +j0.5941	0.0751 +j0.2231	0.0751 +j0.1799	0.0751 +j0.1680	0.0751 +j0.1804	0.0751 +j0.2231
	0.0923 +j0.5941	0.0751 +j0.2231	0.0751 +j0.1799	0.0751 +j0.1680	0.0751 +j0.1804
		0.0923 +j0.5941	0.0751 +j0.2231	0.0751 +j0.1799	0.0751 +j0.1680
	symmetry		0.0923 +j0.5941	0.0751 +j0.2231	0.0751 +j0.1799
				0.0923 +j0.5941	0.0751 +j0.2231
					0.0923 +j0.5941

(d) (6x6) Shunt admittance matrix of 6-ph. transposed line (phase comps, in μs/Km)

10.0129	-1.5683	-0.4825	-0.3016	-0.4836	-1.5683
	10.0129	-1.5683	-0.4825	-0.3016	-0.4836
		10.0129	-1.5683	-0.4825	-0.3016
			10.0129	-1.5683	-0.4825
				10.0129	-1.5683
	symmetry				10.0129

(e) (6x6) Series impedance matrix of 6-ph. untransposed line (symm. comps.Ω /Km)

0.4684 +j1.5680	0.0001 +j0.0002	0.0097 -j0.0442	0.0005 +j0.000	0.0168 -j0.0352	0.0001 +j0.0002
	0.0181 +j0.4686	0.0003 -j0.0005	-0.0146 +j0.0086	0.0050 +j0.0000	-0.0259 -j0.0154
		0.0186 +j0.9141	-0.0001 +j0.0003	-0.0105 +j0.0169	0.0050 +j0.0000
			0.0174 +j0.3394	-0.0001 +j0.0003	-0.0146 +j0.0086
Symmetry				0.01862 +j0.3570	0.0003 +j0.0005
					0.01858 +j0.4686

(f) (6x6) series impedance matrix of Six-Ph transposed line (seq. comps. In Ω /Km)

$Z_0 = 0.4683 + j1.5681$ $Z_1 = Z_5 = 0.0468 + j0.4694$

$Z_2 = Z_4 = 0.0171 + j0.3591$ $Z_3 = 0.0171 + j0.3396$

(g) (6x6) shunt admittance matrix of Six-Ph. transposed line (seq. comps. in μ s/Km)

$Y_0 = j5.6096$ $Y_1 = Y_5 = j9.2288$

$Y_2 = Y_4 = j11.7620$ $Y_3 = j12.4859$

Similar inferences can be drawn for the sequence admittance matrix of Table [2.2g].

2.5.3 Comparative values of line parameters of multiphase systems:

In this section, the numerical calculations have been carried out on two cases of the alternative transmission lines to bring out the comparative observations of the Six-Phase system with its lower phase-order counterparts as follows:

Fig. 2.3 Conductor configuration for a 400 KV phase-to-phase line:

(A) 3-phase line

(B) 6- phase line

Table: 2.2

Comparative values of line parameters and certain characteristics of 400 KV phase-phase Double Circuit Transmission System and Six-Phase transmission systems			
Sr	**Quantity**	**Three-Phase**	**Six-Phase**
1	Phase-phase (adjacent) Voltage (KV)	400 KV	400 KV
2	Conductors per phase	2	2
3	Conductor diameter (mm)	31.77 mm	31.77 mm
4	Adjacent phase-phase Spacing (ft)	As per Configuration	As per Configuration
5	Bundle distance (in)	0.25 m (25 cm)	0.25 m (25 cm)
6	Inductance per phase (mH / Km)	L= 0.0005014	L= 0.001268
7	Capacitance to neutral (µf / k m)	C= 2.43 E -8	C= 9.01 E -9
8	Increase in capacitance due to effect of ground	2.14 %	1.22 %
9	Effect of transposition on Phase impedance matrix		
	(1) No transposition	Zph unbalanced	Zph unbalanced but loss than Three-Phase system
	(ii) full transposition	Transposition has considerable effect Zph become fully symmetric	Transposition has considerable effect Zph become fully symmetric
	(iii) Cyclic transposition	--------	Transposition has only a slight effect Zph become cyclic symmetric
10	Sequence inductive Reactances (Ω/Km)	X_0 =1.205 X_1 =X_2 =0.248	x_0=2.299 x_1=x_5=0.362 X_2=x_4=0.275 X_3=0.236
11	Sequence capacitive Reactances (mΩ/Km)	X_{C0}=1.456 X_{C1}=X_{C2} =0.150	X_{C0}=0.572 X_{01}=X_{05}=0.218 X_{02}=X_{04}=0.1568 X_{C3}=0.144
12	X_0/X_1 ratio	4.858	6.350
13	SIL(MW)	1112.71	2558.74
14	Increase in SIL		2.29 times

2.6 Comparative Study and Design Out-put Results of Existing (Gujarat Energy Transmission Company) GETCO's TPDCS with the Six-phase Conversion of the same:

Table: 2.3 Comparative Design Output of TPDCS and Six-phase System

COMPARATIVE STATEMENT									
3-PH DOUBLE CIRCUIT WITH VARIOUS CONFIGURATIONS									
TYPE	VOLT	IL	REG	EFFI	L	C	SIL	PF	PS IN MW
400 KV GEB'S CONFIG DOUBLE	400	1800	7.38	95.88	0.0005014	2.43E-08	1112.71	0.9992	2601.16
	400	900	2.98	97.81	0.0005014	2.43E-08	1112.71	0.9673	1274.88
400 KV DOUBLE CKT REG HEX	400	1800	7.67	95.89	0.0005274	2.16E-08	1024.42	0.9974	2600.98
	400	900	3.05	97.83	0.0005274	2.16E-08	1024.42	0.9775	1274.62
400 KV DOUBLE CKT HEX 12.5M	400	1800	7.08	95.88	0.0004761	2.43E-08	1141.90	0.9996	2601.25
	400	900	2.9	97.81	0.0004761	2.43E-08	1141.90	0.9658	1274.91
400 KV DOUBLE CKT REG HEX	400	1800	7.16	95.88	0.0004831	2.36E-08	1119.01	0.9993	2601.19
	400	900	2.92	97.82	0.0004831	2.36E-08	1119.01	0.9684	1274.83
6-PH CIRCUIT WITH VARIOUS CONFIGURATIONS									
6-PH GEB'S CONFIG	400	1800	8.83	97.60	0.001268	9.01E-09	2558.74	0.9771	4426.39
	400	900	2.90	98.76	0.001268	9.01E-09	2558.74	0.9974	2187.06
6-PH GEB'S CONFIG	231	1800	22.01	95.92	0.001268	9.01E-09	853.36	0.8917	2600.15
	231	900	6.97	97.91	0.001268	9.01E-09	853.36	0.9883	1273.73
6-PH REG HEX 12.5M SPACING	400	1800	9.42	97.60	0.001329	8.52E-09	2431.03	0.9723	4426.35
	400	900	3.06	98.77	0.001329	8.52E-09	2431.03	0.9987	2187.00
6-PH REG HEX 12.5M SPACING	231	1800	23.58	95.92	0.001329	8.52E-09	810.76	0.8802	2600.15
	231	900	7.42	97.91	0.001329	8.52E-09	810.76	0.9849	1273.71
6-PH HEX 12.5M SPACING, VERTI. HT 8M,	400	1800	9.21	97.60	0.001308	8.50E-09	2447.70	0.9734	4426.38
	400	900	3.00	98.77	0.001308	8.50E-09	2447.70	0.9985	2187.00
6-PH HEX 12.5M SPACING VERTI. HT 8M	231	1800	23.01	95.92	0.001308	8.50E-09	816.32	0.8836	2600.18
	231	900	7.26	97.91	0.001308	8.50E-09	816.32	0.9856	1273.72
6-PH REG HEX 8.026M SPACING	400	1800	8.59	97.60	0.001243	9.13E-09	2601.36	0.9788	4426.42
	400	900	2.84	98.76	0.001243	9.13E-09	2601.36	0.9968	2187.07
6-PH REG HEX 8.026M SPACING	231	1800	21.35	95.92	0.001243	9.13E-09	867.57	0.8962	2600.16
	231	900	6.79	97.91	0.001243	9.13E-09	867.57	0.9894	1273.73

2.7 Discussions:

A careful examination of Tables 2.1, 2.2 and 2.3, reveals that the multi-phase lines are characterized by higher inductances and lower capacitances as compared to their lower phase-order counterparts, employing the same phase-ground voltage, transmission corridor and air space. This means higher inductive and capacitive reactances and surge impedances for the multi-phase lines. As a consequence, multi-phase lines have higher surge impedance loadings (37.2% in the present case) as compared to those of Three-Phase lines, which is a desirable feature for stability of multi-phase lines.

An examination of the phase impedance matrices of the lines for untransposed, Cyclically transposed and fully transposed situations, indicate that the Three-Phase line is the less balanced (inspite of employing equilateral spacing of the phase conductors) as compared to the Six-Phase line in an untransposed situation. A cyclic transposition (which also means a full transposition for a Three-Phase line) has a considerable effect on the mutual impedances of the Three-Phase lines, but only a slight effect on Six-Phase lines. However, a full transposition on Six-Phase lines has an appreciable effect, but such a transposition can not be carried out as it spoils the phase relationship between adjacent conductors. It is, therefore, deduced that the transposition is ruled out for multi-phase lines on account of its low effectiveness as well as the complexity involved in its implementation. The multi-phase lines are inherently better balanced circuits than their Three-Phase counterparts.

However, for simplicity; a cyclic transposition is assumed for the multi-phase lines in computing the sequence parameters. Under these conditions, the Six-Phase lines may be completely specified by four (zero to third) sequence parameters' values, whereas only two (zero and positive) sequence parameters need to be specified in the case of a Three-Phase line (see Table 2.2).

In addition, the multi-phase lines are characterized by higher sequence parameters (inductive reactance and capacitive reactance). The multi-phase lines similar to Three-Phase lines are associated with higher value of zero-sequence inductive and capacitive reactances as compared to the other sequences' values. The lines are also characterized by strong positive-sequence parameters with progressively lower values of other sequence parameters.

The X_0/X_1 ratio of the transmission line influences the earth fault characteristics, protective requirements and over voltage build-ups at sound phases of the line. The multi-phase lines are characterized by higher X_0/X_1 ratios and thus it is expected that the performance of multi-phase lines will be slightly inferior to that of their thee-phase counterparts

Table 2.2 shows that the effect of ground on capacitance parameters is considerably lower for multi-phase lines than that of their Three-Phase alternative. This is due to the fact that small tower dimensions are used in multi-phase systems.

The Table: 2.3 is prepared assuming 200 Kms line length and designs of transmission line with various feasible configurations. A careful examination of the table reveals that the multi-phase lines are characterized by higher inductances and lower capacitances as compared to their lower phase-order counterparts, employing the same phase-ground voltage, transmission corridor and air space. This means higher inductive and capacitive reactances and surge impedances for the multi-phase lines. As a consequence, multi-phase lines have higher surge impedance loadings as compared to those of Three-Phase lines, which is a desirable feature for stability of multi-phase lines.

From the table 2.3, we can also see that the SIL capacities of the order of several thousand MW are obtained with multi-phase lines of only 231 KV (Six-Phase), while a voltage as high as 400 KV is required to realize the same order of transmission capacity with a Three-Phase Double Circuit line. It is also evident that the multi-phase lines employ lower line sizes and tower dimensions [11]. This aspect of compact line structure makes a multi-phase system an attractive & potential alternative in planning as well as in embarking upon entirely new ventures for bulk power transmission, both at EHV and UHV levels.

The illustrative calculations have been carried out for the different conductor configurations and line geometries to provide quantitative and comparative values of parameters as well as certain characteristics of multi-phase lines as against those of conventional Three-Phase Double Circuit lines assuming 200 Kms. line lengths. Based on the computations and the findings of the case studies, the following conclusions may be drawn:

- The comparison of all configurations reveals that with the Six-Phase newly erected line, there will be a smaller size of tower for an equal amount of power transfer. If we employ the Six-Phase mode of power transmission on an existing Three-Phase Double Circuit line then the SIL is more, and the amount of power that can be transferred, is substantially higher than that of Three-Phase double circuit configuration.

- A comparative study has been made for the existing tower of TPDC 400 KV line employed for the Six-Phase mode of transmission, keeping the phase-to-neutral voltage (i.e. 231 KV) as well as the phase-to-phase voltage (i.e. 400 KV) intact. An attempt has been made to study and compare the effects of the regular hexagonal as well as the uneven-sided hexagonal configurations for Six-Phase mode of transmission on the existing Three-Phase double circuit line, requiring only minimum alterations in the basic tower design.

- The terminal expenses are higher than those of the TPDCS, as HPOTS would require specially built phase shifting transformers at both ends, but the increased cost of these transformers is offset by several factors; viz. the reduced tower size; tower foundation cost; and the right of way cost.

- From the table given above, it can be seen that because of the increased phase-to-ground voltage the power density for HPOS is higher, which enables greater power transfer capabilities. The Six-phase 231 KV, single conductor per phase, 4.65M sided regular hexagonal configuration with the same tower height, can transfer almost 86.6% power as compared to GETCO'S 400KV-TPDCS configuration having twin mouse conductor, as shown in fig. 2.3.

- Six-Phase regular hexagonal configuration with the same tower height and 8.026 M phase-to-phase spacing has lower inductance as compared to that of GETCO'S configuration up-rated by Six-Phase, and as such it results in more efficient power transfer, facilitating at the same time an inherently balanced line configuration.

2.8 CONCLUSIONS:

In this chapter, analytical expressions have been derived to evaluate the line parameters of multi-phase (6-phase and 12-phase) transmission systems considering both the transposed and the untransposed line conditions with the effect of ground. Also a method to obtain multi-phase line parameters with due consideration of the presence of earth and lightning shield wires, has been presented. The Transformation matrices have been developed to diagonalize the Six-Phase and Twelve-Phase line parameters matrices by using eigenvectors. The Maxwell and potential coefficients; sequence inductances; and capacitances for Six-Phase and Twelve-Phase lines have been discussed.

The illustrative calculations carried out for the different conductor configurations and line geometries, confirm the validity of expressions derived. Based on the computations and the findings of the two case studies, the following conclusions can be drawn:

- Multi-phase systems are found to possess higher inductive and capacitive reactances leading to higher SIL than that of the corresponding conventional TPDCS.

- The effectiveness of transposition (cyclic) on multi-phase lines is only meager since multi phase lines are inherently better balanced circuits than those of their Three-Phase counterparts.

- Multi-phase lines are also characterized by higher and stronger positive sequence parameters with progressively lower values of other sequence parameters.

- The X_0/X_1 ratios for multi-phase lines are higher than those of their lower phase-order alternatives, implying relatively an inferior performance during ground faults in terms of over voltages [12].

- The study of parameters of a 400 KV vertically double-hung, Three-Phase transmission line and its conversion into Six-Phase line reveals that the series impedance matrices (6x6) of both (after eliminating the shield wires of the 2x3-phase and Six-Phase lines) are similar, while; the shunt admittance matrices of both the lines are completely different from each other.

- The symmetrical component transformation of the untransposed lines yields coupling between Zero, Second and Fourth sequences in the Six-Phase system; whereas in the case of TPDCS, coupling between all sequences is present. With the cyclic transposition on Six-Phase line, the impedance matrix is completely diagonalised after transformation; but in the case of TPDC line, a strong coupling exists between zero sequence components of the two circuits, even after transposition.

- The comparison of all configurations reveals that with the Six-Phase newly erected line, there will be a smaller size of tower for an equal amount of power transfer. If we employ the Six-Phase mode of power transmission on an existing Three-Phase Double Circuit line then the SIL is more, and the amount of power that can be transferred, is substantially higher than that of Three-Phase double circuit configuration.

- A comparative study has been made for the existing tower of TPDC 400 KV line employed for the Six-Phase mode of transmission, keeping the phase-to-neutral voltage (i.e. 231 KV) as well as the phase-to-phase voltage (i.e. 400 KV) intact. An attempt has been made to study and compare the effects of the regular hexagonal as well as the uneven-sided hexagonal configurations for Six-Phase mode of transmission on the existing Three-Phase double circuit line, requiring only minimum alterations in the basic tower design.

- The terminal expenses are higher than those of the TPDCS, as HPOTS would require specially built phase shifting transformers at both ends, but the increased cost of these transformers is offset by several factors; viz. the reduced tower size; tower foundation cost; and the right of way cost.

- The comparison of all configurations reveals that with the Six-Phase newly erected line, there will be a smaller size of tower for an equal amount of power transfer. If we employ the Six-Phase mode of power transmission on an existing Three-Phase Double Circuit line then the SIL is more, and the amount of power that can be transferred, is substantially higher than that of Three-Phase double circuit configuration. These features of Six-phase mode of power transmission are eventually eye-catching, in view of the fact that with the same amount of Right of Way, we can transmit more power and alleviate the problem of adverse biological effects.