Voltage Stability Analysis in Conversion of Double Three-Phase to Six-Phase Transmission Line

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***Abstract*—In recent years, problems regarding the voltage stability have been of vital importance at EHV and UHV level because of its sensitivity to active and reactive power changes. Beside, conversion of three-Phase Double-Circuit (3PDC) to six-Phase Single-Circuit (6PSC) line is known as a well method to increase the power transfer capability. The voltage stability problem has received little attention in case of 6PSC systems. In this paper, an investigation of voltage stability has been carried out in conversion of an existing 3PDC to a 6PSC transmission line considering conversion transformers reactance. The results show that by this conversion, improvement in power transfer capacity is gained for long 6PSC lines, but a 3PDC line has the better performs from reactive power view for voltage stability and the minimum line length at which the power transfer capability is limited by voltage stability concern is dramatically decreased in 6PSC line. Moreover, the reactance increase of conversion transformers worsens the aforementioned problems. A comparison of 3PDC and 6PSC systems presented in the paper and other economical and practical factors can be studied for planning, development and design of future transmission network.**

***Keywords*— Power Transfer Capability; Static Analysis; Voltage Stability; 3PDC; 6PSC**

I. Introduction

Electricity is considered as the driving force for a country, which is undergoing rapid industrialization. Traditionally, the need for increasing power transmission capability and more efficient use of right of way (ROW) space has been accomplished by the use of successively higher system voltages. Constrains on the availability of land and planning permission for overhead transmission lines have renewed interest in techniques to increase the power carrying capacity of existing ROWs. High phase order (HPO) transmission, using more than three phases (6, 12 and more phases), was conceived as a means for increasing the power transfer capability of existing ROW space [1].

Among the HPO, six-phase transmission is appeared to be the most promising solution to the need to increase the capability of existing transmission lines [2-7] and at the same time, it responds to the concerns related to electromagnetic fields [6-9].

Three-phase line can be easily converted to a six-phase line using conversion transformers, which make the required 60° phase shift at six-phase operation side [10].

NYSEG (New York State Energy Electric and Gas Corporation) HPO demonstration project is a major step forward in promoting this technology and in demonstrating the technical and environmental benefits of HPO transmission [11]. Some of these potential benefits over three-phase system are as well: smaller structure [11], lower insulation requirement [2], better stability margin [7], better voltage regulation [10, 11] and increased power transfer under faulted conditins [12].

In [13], it was found out that the use of six-phase transmission can be a cost effective solution. In other words, the cost penalty is not excessive, particularly if physical constraints exist.

However, several drawbacks of 6PSC lines have been implied in some papers. Based on their relatively recent consideration, algorithms for analysis and protection are not well established. Because, the additional phases obviously complicate line analysis especially in the case of faults. HPO structures tend to include higher electric field strength beneath the line [14], which could also be a political drawback in light of the recent public interest in fields near power transmission lines.

Voltage Stability is a relatively recent and challenging problem in Power Systems. It is gaining in importance as the trend of operating power systems closer to their limits continues to increase [15]. Therefore, it is important to include the voltage stability limit in the line loadability curve [16].

Line loadability curves have been a valuable planning tool for the three-phase systems since their publication by St. Clair [17]. In this study, influence of voltage stability limit on line loadability is illustrated. Reactive power requirement to have the stable voltage is discussed and typical static analysis as P-V curves (a common method to study the voltage stability) is investigated.

A review of the literature reveals that no work has so far been reported regarding the effect of conversion transformers reactance on converted lines. Results of such study are reported in the present paper. Moreover, 6PSC line was often considered as a compact line shown in Fig. 1. But the most applicable and simple scheme can be conversion of an existing 3PDC transmission line to 6PSC line at the same structure and configuration.

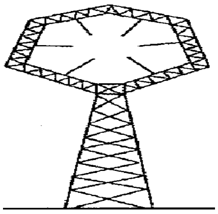

Figure 1. Six-phase compact structure [4]

In the present paper, a comparison of power transmission capability, voltage stability and shunt compensator in conversion of a 3PDC transmission line to a 6PSC line, considering the reactance of conversion transformers, are studied.

II. DETERMINING THE SELECTED LINE INDUCTANCE & CAPACITANCE

To compare the electrical parameters between 3PDC and 6PSC line, the typical transmission line of 345kV shown in Fig. 2 was studied. Conductor diameter and bundle spacing are 3.623 cm and 45.72 cm, respectively.

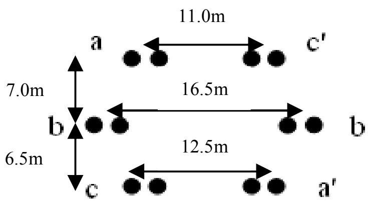

Figure 2. Typical configuration of 345kV line conductors

Equations of the inductance and capacitance for transposed 3PDC line are available in [18]:

$$L = 2\times 10^{-7}\, Ln \frac{GMD}{GMR_L} \quad \left(H/m\right) \tag{1}$$

$$C = \frac{2\pi\varepsilon_0}{Ln \dfrac{GMD}{GMR_C}} \quad \left(F/m\right) \tag{2}$$

Where, *GMD* and *GMR* are Geometric Mean Distance and Geometric Mean Radius in configuration, respectively.

The inductance and capacitance of aforementioned 3PDC line were calculated using (1) and (2):

$L=0.44909\ mH/km$ and $C=0.02543\ \mu F/km$

Similarly, selected 3PDC line conversion to 6PSC line was studied. The most common 6PSC line transposition is roll transposition [10], shown in Fig. 3. In this transposition type, each phase locates in each position up to one sixth of total line length.

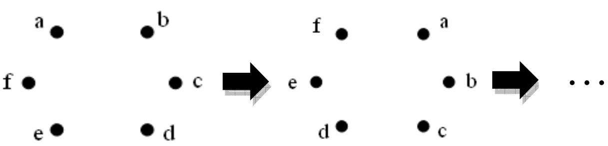

Figure 3. Six-phase line configuration with roll-type transposition

Equations needed in order to calculate the inductance and capacitance of a 6PSC line are established in appendix. By using the mentioned equations, inductance and capacitance of 3PDC line converted to 6PSC line is:

$L=1.16481\ mH/km$ and $C=0.00955\ \mu F/km$

As a result, in conversion of a 3PDC line to 6PSC line, the line inductance would be increased while the line capacitance would be decreased.

III. VOLTAGE STABILITY

Voltage stability is becoming an increasing source of concern in secure operation of present-day power systems. A power system at a given operating state and subject to a given disturbance is "voltage stable" if voltages near loads approach post-disturbance equilibrium values. Voltage instability is the absence of voltage stability, and results in progressive voltage decrease (or increase) [19].

Note, the rotor angle stability is seldom a reason for the restriction of power transfers due to stronger power systems and development of equipment technology compared to past decades, while the power system blackouts occurring all over the world have in the past years mainly been voltage collapses. Voltage collapse is the catastrophic result of a sequence of events leading to a low-voltage profile suddenly in a major part of the power system [20].

The changes of system configuration, such as loss of generation and line tripping, may cause instability of system voltage owing to the inability of the network to meet the demand for reactive power [21].

A. Basic Circuit Model for Study

The basic circuit model for considered analysis is represented on single phase basis by positive sequence parameters as shown in Fig. 4. In the system to simplify calculations, the voltage phase angle at the receiving end was seen as reference, and voltage magnitude at the sending end (V_S) is constant.

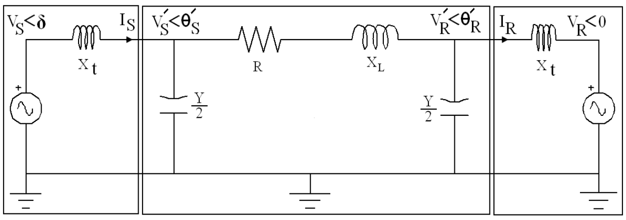

Figure 4. The circuit model for voltage stability study

Equations of sending end voltage and current are [18]:

$$V'_S = V'_R Cos\theta + jZ_0 I_R Sin\theta \tag{3}$$

$$I_S = j\frac{V'_R}{Z_0} Sin\theta + I_R Cos\theta \tag{4}$$

Where, I_S and I_R represent the current at sending and receiving end, respectively. Also, Z_0 and θ are surge impedance and line electrical length, respectively.

Using Kirchhoff voltage law:

$$V'_S = V_S - jX_t I_S \tag{5}$$

$$V_R' = V_R + jX_t I_R \tag{6}$$

Where, X_t is conversion transformer reactance.
At the receiving end:

$$I_R = \frac{P - jQ}{V_R} \tag{7}$$

Where, P and Q are active and reactive power of load.
Using above equations and then simplifying them:

$$V_S = V_S e^{j\delta} = V_S\left(Cos\delta + jSin\delta\right) = V_R\left(Cos\theta - \frac{X_t}{Z_0}Sin\theta\right)$$
$$+\frac{Q}{V_R}\left(2X_t Cos\theta - \frac{X_t^{\,2}}{Z_0}Sin\theta + Z_0 Sin\theta\right)$$
$$+j\frac{P}{V_R}\left(2X_t Cos\theta - \frac{X_t^{\,2}}{Z_0}Sin\theta + Z_0 Sin\theta\right) \tag{8}$$

Equalising real and imaginary parts of (8) separately, power flow equations are stablished:

$$P = \frac{V_S V_R}{\left(Z_0 - \frac{X_t^{\,2}}{Z_0}\right)Sin\theta + 2X_t Cos\theta} Sin\delta \tag{9}$$

$$Q = \frac{V_R\left(V_S Cos\delta - V_R\left(Cos\theta - \frac{X_t}{Z_0}Sin\theta\right)\right)}{\left(Z_0 - \frac{X_t^{\,2}}{Z_0}\right)Sin\theta + 2X_t Cos\theta} \tag{10}$$

There are five common combinations that can be used to form a three to six-phase conversion transformer which are Y-Y & Y-Y inverted, Δ-Y & Δ-Y inverted, diametrical, double-Δ and double-Y [10]. In this paper, the Δ-Y & Δ-Y inverted connection was selected. One of each pair of transformers has reverse polarity to obtain the required 60° phase shift. Parameters of conversion transformers are the same and available in Table I.

TABLE I.
PHASE CONVERSION TRANSFORMERS DATA

Three-phase rated power (MVA)	*X* (p.u.)
600	0.06

B. *Static Analysis*

Voltage stability studies are frequently undertaken through the use of static analysis. Generally, voltage stability is a dynamic phenomenon not a static one. However, static analysis may be used as done in this paper. A common use of this is the development of *P-V* curves. Static analysis (also referred to as load-flow or steady-state analysis) reveals equilibrium points of a system under study. The power flow equations employed in static analysis assume constant system frequency; in other words, generated power is equal to load demand plus losses [19].

Assuming constant sending end voltage, P-V curves for transmission line with 300km length, Fig. 4, and 345kV are shown in Figs. 5-7, on the basis of rated voltage and 1000MVA power for unity, 0.85 lag and 0.95 lead power factors.

From Figs. 5-7, it is observed that for each load power factor the maximum power at the receiving end is found out higher for 6PSC system.

Thus it can be concluded that at long 6PSC line (here 300km), maximum power at the receiving end will be progressively enhanced maintaining the voltage stability at various power factors of the load.

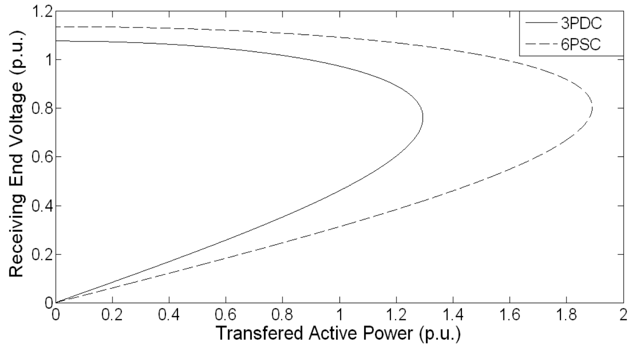

Figure 5. Receiving end voltage profile for varying active power at unity power factor for a 300km line

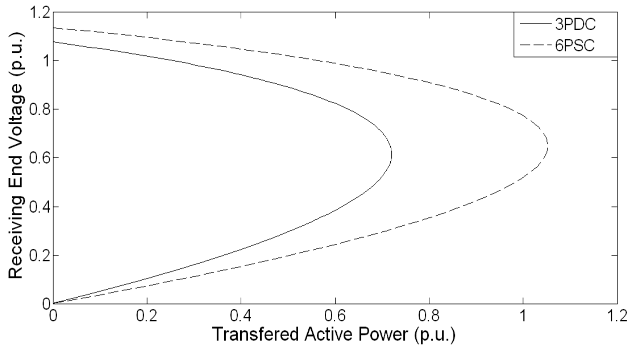

Figure 6. Receiving end voltage profile for varying active power at 0.85 lag power factor for a 300km line

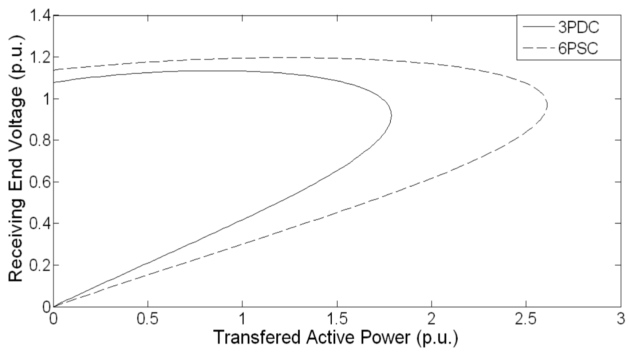

Figure 7. Receiving end voltage profile for varying active power at 0.95 lead power factor for a 300km line

C. *Loadability Curve Included Voltage Stability Constrains*

Using (8), when *Q=0*:

$$V_S{}^2 = V_R{}^2 \cdot \left(Cos\theta - \frac{X_t}{Z_0} Sin\theta \right)^2 + \frac{P^2}{V_R{}^2} \cdot \left(2X_t Cos\theta - \frac{X_t{}^2}{Z_0} Sin\theta + Z_0 Sin\theta \right)^2 \quad (11)$$

The power delivered to the load as a function of receiving end voltage can be solved using (11) as:

$$P = \frac{\sqrt{|V_S|^2 - m^2 V_R{}^2}}{n} \cdot V_R \quad (12)$$

Where:

$$m = Cos\theta - \frac{X_t}{Z_0} Sin\theta \quad (13)$$

$$n = 2X_t Cos\theta - \frac{X_t{}^2}{Z_0} Sin\theta + Z_0 Sin\theta \quad (14)$$

Since V_S is constant, and m and n can not change, V_R is the only variable that can vary.

Using *P-V* curves, the maximum power that can be transmitted is reached when $dP/dV_R=0$, which can be determined as:

$$P_{max\_Vstab} = \frac{V_S{}^2}{2mn} \quad (15)$$

The above limit is called voltage stability limit of power transmission. The voltage corresponding to (15) is:

$$V_{nose} = \frac{V_S}{m\sqrt{2}} \quad (16)$$

Note, when the line length increases, the open circuit voltage increases accordingly because of the line charge. This is the well-known Ferranti effect. This effect leads to the increase of nose point voltage V_{nose}. When this happens, it becomes impossible to operate the system as any operating point with acceptable voltage level will be below the nose point, which is an unstable case. The line length at which the nose point will move above the sending end voltage can be determined using the following condition:

$$V_{nose} = V_S \quad (17)$$

Substituting (16) in (17) and solving it, it is obtained:

$$Cos\theta - \frac{X_t}{Z_0} Sin\theta = \frac{\sqrt{2}}{2} \quad (18)$$

The minimum line length at which power transfer capability is limited by voltage stability concern using (18) was calculated for:

3PDC line: 624.639km

6PSC line neglecting conversion transformers reactance: 616.479km

6PSC line considering conversion transformers reactance: 524.138km

The above values reveal that increasing reactance of conversion transformers impairs the line loadability and voltage stability.

Fig. 8 shows the power transfer capability as a function of line length considering voltage stability limit for 345kV transmission line, on the basis of 1000MVA power. The load angle 44° (the corresponding stability margin is 30%) and voltage drop of 5% were selected in this study.

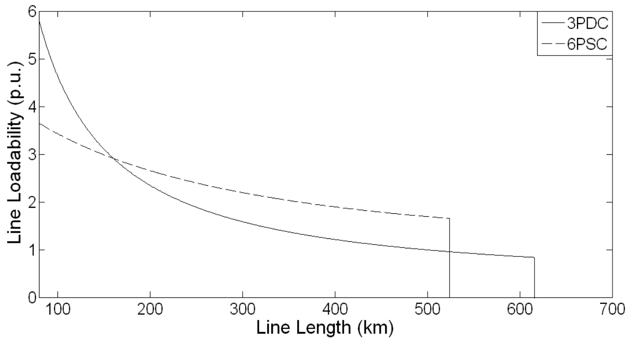

Figure 8. Loadability curve of 345kV 3PDC and 6PSC line considering voltage stability

It is evident from Fig. 8 that power transfer capability, for the length higher than 160km, is greater for 6PSC line compared to its 3PDC counterpart.

Compensation of line charging by shunt compensator can mitigate Ferranti effect, and as a result it can enhance the minimum line length at which power transfer capability is limited by voltage stability concern.

D. Optimal Reactive Power for Voltage Stability

The determinant of the Jacobian [18] for load flow equations (*P* and *Q*) in a lossless network, when V_S is constant, is given by:

$$\Delta[J] = \frac{1}{n^2}\left(V_S{}^2 V_R - 2m V_S V_R{}^2 Cos\delta \right) \quad (19)$$

With $\Delta J=0$ at voltage stability limit, the receiving end voltage can be written as:

$$V_S = 2m V_R Cos\delta \quad (20)$$

Substituting (20) in (10), the value of reactive power at the limiting stage of voltage stability is given by:

$$Q_{lim} = \frac{m}{n} V_R{}^2 Cos(2\delta) \quad (21)$$

Where, Q_{lim} represents the limiting value of reactive power transfer in a transmission system and it is critical value for voltage collapse.

A study of Q_{lim} with respect to V_R has been carried out employing (21) and it is illustrated in Fig. 9 for a 345kV transmission line with 300Km length, on the basis of rated voltage and 1000MVA power.

It is observed that the reactive power limit at 6PSC line is higher than 3PDC line at each point of receiving end voltage. Thereby, with conversion of a 3PDC to 6PSC line with 300km length, the rating of the devices required from the view point of compensation is gradually increased. This also implies that the even in uncompensated mode, 3PDC line performs well from the voltage stability view point since its requirement of reactive power is gradually reduced.

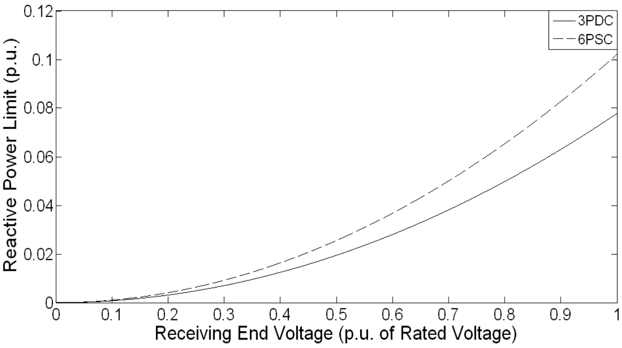

Figure 9. Reactive power limit profile for 3PDC & 6PSC lines (300km length) to have the voltage stability

E. Shunt Compensation

Shunt capacity support at voltage stability limit using (9) and (10) was obtained and it is illustrated by the following equation:

$$Y_{SH} = \frac{\sqrt{V_S^{\,2} - \left(\frac{nP}{V_R}\right)} - \left(mV_R + \frac{nQ}{V_R}\right)}{nV_R} \tag{22}$$

Equation (22) provides a relationship for the magnitude of Y_{SH} at the receiving end for getting a stable voltage state under set of specified operating conditions.

The modeling of loads is essential in voltage stability analysis. The voltage dependence and dynamics of loads require consideration in these studies. The voltage dependence of loads is usually modeled with an exponent or a polynomial model. The exponent load model is presented [15, 22] as:

$$P = P_a\left(\frac{V}{V_o}\right)^{\alpha}, Q = Q_a\left(\frac{V}{V_o}\right)^{\beta} \tag{23}$$

Where P is active load, Q is reactive load, V is load voltage, V_o is nominal voltage of load, α is exponent of active load, β is exponent of reactive load and P_a and Q_a represent the active and reactive load at nominal voltage of load. Here, load was assumed as a mixed type load. The typical value for the exponents for this load type is [22]: α=2.16 and β=0.76.

Fig. 10 exhibits the shunt compensator capacity at different load voltages for different power factors (0.85 lag, 0.95 lead and unity) in both configurations. Line length is assumed equal to 300km and load is 100MVA.

From Fig. 10, it is observed that the shunt compensator rating for voltage dependent load is increased at 6PSC line to fix the load voltage at nominal value, but in much lower voltages, the rating is decreased at 6PSC line compared to 3PDC line for different power factors.

The same analysis has been carried for variation of length of transmission line shown in Fig. 11, for different power factors (0.85 lag, 0.95 lead and unity) in both configurations. Here, it was assumed that compensation is done to fix the load voltage at nominal value, i.e. $P=P_a$ and $Q=Q_a$. Also, Load was assumed equal to 100MVA.

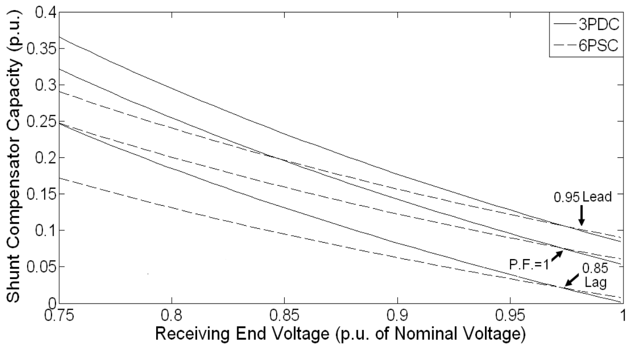

Figure 10. Shunt compensator capacity for different voltages and power factors at voltage stable states for a 300km line

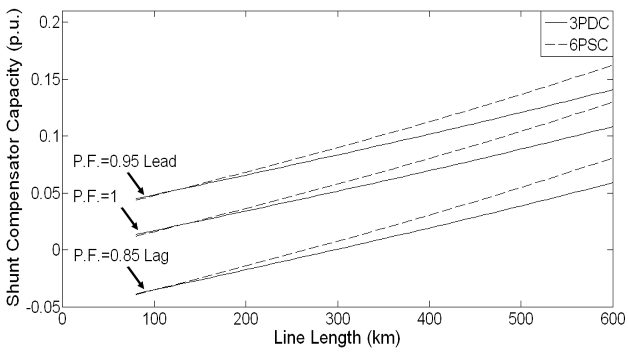

Figure 11. Shunt compensator capacity for varying line length with different power factors at nominal voltage of receiving end

From Fig. 11, it is concluded that in long lines, shunt compensator rating is increased at 6PSC line as compared to 3PDC line for different power factors.

It should be note that the capacitance of 6PSC line is decreased and inductance is increased. Furthermore, the phase voltage of 6PSC line is increased upto √3 times than to 3PDC line while line current is decreased; so charging the line is increased and the loss of line is decreased. This results less decreased voltage drop and more compensation capacity in 6PSC transmission line.

IV. CONCLUSIONS

Six-phase transmission is conceived as a technique to increase the power transfer capability of existing ROW space. In this paper, it was found out that conversion of an existing 3PDC to a 6PSC transmission line results in line inductance increment and capacitance decrement. Also, in this study, voltage stability as a recent challenging subject was analyzed. It was shown that in 6PSC line conversion, for the lengths about higher than 160km, maximum power at the receiving end will progressively enhance maintaining the voltage stability at various power factors of the load. However, the minimum line length at which power transfer capability is limited by voltage stability concern is dramatically decreased in 6PSC line compared to 3PDC line due to conversion transformers reactance effect. Moreover, reactive power limit in 6PSC line is increased at each point of receiving end voltage. Thereby, even in uncompensated mode, a 3PDC line performs well from reactive power view for voltage stability compared to a 6PSC line; and also rating of the shunt compensators required at long 6PSC lines is gradually increased to fix the load voltage at nominal value.

However, other economical and practical factors can be studied for planning, development and design of future transmission network.

APPENDIX

Using linkage flux relations and Fig. 3, line inductance for each position is achieved as below: (24)

$$L_a = 2\times10^{-7}\left[Ln\frac{1}{D_S^b} + aLn\frac{1}{D_{ab}} + a^2Ln\frac{1}{D_{ac}} + a^3Ln\frac{1}{D_{ad}} + a^4Ln\frac{1}{D_{ae}} + a^5Ln\frac{1}{D_{af}}\right]$$

$$L_b = 2\times10^{-7}\left[a^5Ln\frac{1}{D_{ab}} + Ln\frac{1}{D_S^b} + aLn\frac{1}{D_{af}} + a^2Ln\frac{1}{D_{ae}} + a^3Ln\frac{1}{D_{ad}} + a^4Ln\frac{1}{D_{ac}}\right]$$

$$L_c = 2\times10^{-7}\left[a^4Ln\frac{1}{D_{ac}} + a^5Ln\frac{1}{D_{af}} + Ln\frac{1}{D_S^b} + aLn\frac{1}{D_{cd}} + a^2Ln\frac{1}{D_{ce}} + a^3Ln\frac{1}{D_{fc}}\right]$$

$$L_d = 2\times10^{-7}\left[a^3Ln\frac{1}{D_{ad}} + a^4Ln\frac{1}{D_{ae}} + a^5Ln\frac{1}{D_{cd}} + Ln\frac{1}{D_S^b} + aLn\frac{1}{D_{de}} + a^2Ln\frac{1}{D_{ce}}\right]$$

$$L_e = 2\times10^{-7}\left[a^2Ln\frac{1}{D_{ae}} + a^3Ln\frac{1}{D_{ad}} + a^4Ln\frac{1}{D_{ce}} + a^5Ln\frac{1}{D_{de}} + Ln\frac{1}{D_S^b} + aLn\frac{1}{D_{cd}}\right]$$

$$L_f = 2\times10^{-7}\left[aLn\frac{1}{D_{cf}} + a^2Ln\frac{1}{D_{ac}} + a^3Ln\frac{1}{D_{fc}} + a^4Ln\frac{1}{D_{ce}} + a^5Ln\frac{1}{D_{cd}} + Ln\frac{1}{D_S^b}\right]$$

Where, $a = 1\angle 60°$ (25)

Since in roll-type transposition each phase locates in each position up to one sixth of total line length, thus by averaging above equations, inductance is:

$$L = \frac{L_a + L_b + L_c + L_d + L_e + L_f}{6} \quad (26)$$

Finally, after substituting (24) in (26) and simplifying, inductance of 6PSC line is:

$$L = 2\times 10^{-7}\, Ln\frac{\sqrt[6]{D_{ac}^2 D_{ad}^4 D_{ae}^2 D_{fc}^2 D_{ce}^2}}{D_s^b \sqrt[6]{D_{ab} D_{af}^2 D_{cd}^2 D_{de}}} \quad \left(H/_m\right) \quad (27)$$

Where, $D_s^{\,b}$ is GMR magnitude of each single-phase circuit. And similarly, line capacitance was obtained as:

$$C = \frac{2\pi\varepsilon_o}{Ln\dfrac{\sqrt[6]{D_{ac}^2 D_{ad}^4 D_{ae}^2 D_{fc}^2 D_{ce}^2}}{D_s^b \sqrt[6]{D_{ab} D_{af}^2 D_{cd}^2 D_{de}}}} \quad \left(F/_m\right) \quad (28)$$

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