ABSTRACT
The present Nigerian 330kV grid system is predominantly known to be unstable, fragile, and ill-conditioned. This is due to rapid increase in the consumers demand for electricity and other technical factors. A network is said to be weak and ill-conditioned when it is deficit of reactive power, with low voltages below the nominal limit and has high R/X line ratios. To maintain a secure, efficient and economical operation of electrical power system and to meet the enormous demand by consumers, it becomes imperative to carry out real power flow control and its redirection. Presented in this paper is the application of phase shifting transformers to the Nigerian 330kV grid system for active power flow control. Newton Raphson Iterative algorithm was adopted for solving the power flow problems. Modified power flow algorithm was implemented by the application of phase shifter approach using Phase Shifting Transformers (PST). The phase shifting transformer was inserted one at a time on each of the four suitable transmission lines directly connected to the generator bus. These lines are between Benin to Osogbo (8-10), Alaoji to Onitsha (12-14), Benin to Onitsha (8-14), and Osogbo to Ikeja West (10-5). Results obtained show that, with the incorporation of PST, active power flow can be redirected between the two points in power system and hence, enhancing its operation in terms of efficiency and reduced system losses.

KEY WORDS
Power flow, Phase shifting transformer, Newton-Raphson, Power system, active power, phase angle.

1. Introduction
Electrical power production with respect to demand and consumption had often been the determinant factors of economic growth in this recent time all around the world [1]. In times past, the electric grid system has encountered various difficulties which distort stability in power flow (real and reactive power flow) and this call for an effective and efficient response. Hence, the need to obtain information on the nodal voltage magnitudes and system frequency which must be kept within narrow boundaries, the voltage angle, the active power flow and reactive power flow on the transmission lines which must be operated well below their thermal and stability limits [2].

Due to the difficulty faced in effectively and efficiently transmitting power to meet the demands of consumers and to favour the power suppliers, power flow analysis is usually carried out in determining the problem encountered and also to suggest solution and overall improvement of the entire grid system. Power flow analysis is usually employed with the sole aim of obtaining the best operating condition for existing power utility and how to plan for future expansion of power system [3].

The power flow equations are non-linear in nature and therefore numerical methods are usually employed in solving them within an acceptable tolerance [4]. Iterative techniques such as Newton-Raphson, Gauss-Seidel and Fast Decoupled had been extensively discussed and used to solve power flow problems [2],[5],[6],[7]. However, Newton-Raphson iterative technique is preferred to others because of its distinct features such as obtaining high accuracies of convergence in only little iteration. This method is therefore employed in this work.

Overloading of transmission lines is typically caused by many factors among which are generator outages, excessive wheeling, and transmission lines outages and to mention a few [8]. In any of the cases, line overloading can be alleviated by redirecting power flow from overloaded lines to less loaded lines. To maintain a secure, efficient and economical operation of the electrical power system for real power flow control and redirection, special transformers known as the Phase Shifting Transformers (PSTs) or simply phase shifters are usually employed nowadays for phase angle control between the primary (source) and secondary (load) side. Phase shifting transformer is a device that controls power flow through the network grid by means of varying the voltage angle between the primary side and the secondary side. The aim of the variation in phase angle is to control the active power flow over transmission network. Thus, it is possible to control both the magnitude and the direction of the power flow by varying the phase shift [9][14][15][16][17][18].

PSTs create a phase shift between the primary side and secondary side voltage. The purpose of this phase shift is usually the control of power flow over transmission lines. Both the magnitude and the direction

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of the power flow can be controlled by varying the phase shift [10]. Although, in an attempt to control the power flow on the lines, Flexible Alternating Current Transmission Systems (FACTS) devices such as STATCOM, SSSC, SVC and so on had been employed by many researchers, but the main disadvantage of FACTS devices identified is that it is expensive in term of cost to provide smooth and fast response to secure power system during normal and steady state operations[11] [12][19]. [5] carried out power flow analysis using Load Tap Changing Transformer with a case study of Nigerian 330kV grid system. The paper focused majorly on the application of LTCT to regulate voltage magnitude taking into consideration the set of binding limits. The paper however, did not take into account active power flow control. It concerned majorly on voltage magnitude control and system loss reductions. Although, [8] had worked on the power flow control using phase shift considering IEEE 5 standard bus system, yet emphasis was not placed on the details effects of the circulating current on the system losses that usually emanate from the use of PST. This paper however, is an extension of [8].

Effects of PST on the system losses were presented here as applied to Nigerian 330kV grid system being weak and ill-conditioned networks. Presented in section 2 is the formulation of power flow equation without PST, power flow formulation with the incorporation of PST is presented in section 3. Section 4 shows the results and discussion of the work. The results of the power flow obtained with PST are presented in section 5. Section 6 concludes the work.

2. Formulation of Power Flow Equations

In power flow analysis, the power injected by the generator at any bus k and the power delivered to the load at bus k are both known because they are both directly controlled by the power suppliers and consumers respectively. This is illustrated with the equivalent impedance of transmission line shown in Fig. 1. The difference between the two is a known value called the scheduled or specified power. At any bus k, the scheduled power is given by equation (1) and (2) [2].

![Fig 1: Equivalent impedance of a transmission line](image)

The transmitted active and reactive power between the generator and the load are functions of both the bus voltage and the line admittances and they are often calculated. They are denoted by $P_k^{calc}$ and $Q_k^{calc}$, $P_m^{calc}$ and $Q_m^{calc}$ for active and reactive power respectively [2].

$$P_k = P_{Gk} - P_{Lk}$$

$$Q_k = Q_{Gk} - Q_{Lk}$$

The complex power between buses k and m and between m and k are given by equations (9) and equations (10).

$$P_{km}^{calc} = V_k^* G_{km} + V_m^* V_m (G_{mm} \cos (\delta_k - \delta_m) + B_{mm} \sin (\delta_k - \delta_m))$$

$$Q_{km}^{calc} = -V_k^* B_{km} + V_m^* V_m (G_{mm} \cos (\delta_k - \delta_m) - B_{mm} \sin (\delta_k - \delta_m))$$

where $J_1$, $J_2$, $J_3$, and $J_4$ represent the Jacobian elements, where the active power and reactive power mismatches at any bus k are given by equations (9) and equations (10).

The net active and reactive power at any bus k is as presented in [2].

The equations obtained are solved iteratively from initial estimates until a mismatch is obtained. The linearized Newton-Raphson solution to the power flow equation is given by equation (7).

$$\begin{bmatrix}
\Delta P_k \\
\Delta Q_k \\
\Delta P_m \\
\Delta Q_m
\end{bmatrix} = \begin{bmatrix}
\frac{\partial P_k}{\partial V_k} & \frac{\partial P_k}{\partial V_m} \\
\frac{\partial Q_k}{\partial V_k} & \frac{\partial Q_k}{\partial V_m} \\
\frac{\partial P_m}{\partial V_k} & \frac{\partial P_m}{\partial V_m} \\
\frac{\partial Q_m}{\partial V_k} & \frac{\partial Q_m}{\partial V_m}
\end{bmatrix} \begin{bmatrix}
\Delta V_k \\
\Delta V_m
\end{bmatrix}$$

where $J_{11}$, $J_{12}$, $J_{21}$, and $J_{22}$ are the correction values to be added to the initial estimates of state variables for each iteration. To obtain the updated value of the calculated power, the updated voltage magnitude and phase angle values are required and were substituted into the equations (3) and (4). The updated voltage magnitude $V_k$ and $\delta_k$ at bus k is given by the equations (11) and (12).

$$V_k^{(i+1)} = V_k^{(i-1)} + 2 \Delta V_k^{(i)}$$

$$\delta_k^{(i+1)} = \delta_k^{(i-1)} + 2 \Delta \delta_k^{(i)}$$

where $i$ is the number of iteration.

The complex power between buses k and m and between buses m and k are given by equations (13) and (14).

$$S_{km} = E_k I_{km}$$

$$S_{mk} = E_m I_{km}$$

The power loss on the line k-m is the algebraic sum of the complex power flow as given by equation (15).

$$SL_k = S_{km} + S_{mk}$$

where $SL$ is the net power loss on the line k-m.

3. Power Flow Formulation with the Incorporation of PST

Incorporating the phase shifting transformer into the network, the nodal current injection equation is given by equation (16) [2].
We assumed that the primary and secondary sides of the transformer are connected to bus k and bus m respectively. Where φ is the phase angle of the PST and is allowed to vary within the range of design values (φ_{min} < φ < φ_{max}) [2]. The power injected is given by equations (3), (4), (5) and (6).

For phase shifting transformer, the admittances are given by equation (17) [2].

\[
\begin{bmatrix}
I_k \\
I_m
\end{bmatrix} =
\begin{bmatrix}
Y & -Y(\cos\phi + j\sin\phi) \\
Y & -Y(\cos\phi - j\sin\phi)
\end{bmatrix}
\begin{bmatrix}
V_k \\
V_m
\end{bmatrix}
\] (16)

We assumed that the primary and secondary sides of the transformer are connected to bus k and bus m respectively. Where φ is the phase angle of the PST and is allowed to vary within the range of design values (φ_{min} < φ < φ_{max}) [2]. The power injected is given by equations (3), (4), (5) and (6).

For phase shifting transformer, the admittances are given by equation (17) [2].

\[
Y_{kk} = G_{kk} + jB_{kk} = Y
\]
\[
Y_{mm} = G_{mm} + jB_{mm} = Y
\]
\[
Y_{km} = G_{km} + jB_{km} = -Y(\cos\phi + j\sin\phi)
\]
\[
Y_{mk} = G_{km} + jB_{km} = -Y(\cos\phi - j\sin\phi)
\]

Substituting equation (17) into the power injection equations (3), (4), (5) and (6). Assuming the PST controls the power flow from bus k at a specified value, then, the equations (18), (19), (20) and (21) are obtained [2].

\[
P_{k_{cal}} = V_k^2 G + V_k V_m [G \cos(\delta_k - \delta_m - \phi) + B \sin(\delta_k - \delta_m - \phi)]
\] (18)

\[
Q_{k_{cal}} = -V_k^2 B + V_k V_m [G \sin(\delta_k - \delta_m - \phi) - B \cos(\delta_k - \delta_m - \phi)]
\] (19)

\[
P_{m_{cal}} = V_m^2 G + V_k V_m [G \cos(\delta_m - \delta_k + \phi) + B \sin(\delta_m - \delta_k + \phi)]
\] (20)

\[
Q_{m_{cal}} = -V_m^2 B + V_k V_m [G \sin(\delta_m - \delta_k + \phi) - B \cos(\delta_m - \delta_k + \phi)]
\] (21)

The power mismatch equation can be expressed by the matrix form as in equation (22)

\[
\begin{bmatrix}
\Delta P_{km} \\
\Delta Q_{km}
\end{bmatrix} =
\begin{bmatrix}
P_{k_{reg}} - P_{km} \\
Q_{k_{reg}} - Q_{km}
\end{bmatrix}
\] (22)

\[
\Delta P_{km} = P_{km}^{reg} - P_{km}^{ps}
\] (23)

\[
\Delta Q_{km} = Q_{km}^{reg} - Q_{km}^{ps}
\] (24)

\[
\Delta P_{km} = \Delta P_{km}^{ps} + \Delta P_{km}^{reg}
\] (25)

\[
\Delta Q_{km} = \Delta Q_{km}^{ps} + \Delta Q_{km}^{reg}
\] (26)

\[
\Delta P_{km}^{ps} = V_k^2 G + V_k V_m [G \cos(\delta_k - \delta_m - \phi) + B \sin(\delta_k - \delta_m - \phi)]
\] (27)

The updated value of the phase shifter angle is given by equation (29);

\[
\phi_{(t)} = \phi_{(t-1)} + \Delta \phi_{ps}
\] (29)

where,

- δ_k = Voltage angle at bus k
- δ_m = Voltage angle at bus m
- φ = Phase shifting transformer angle
- V_k = Voltage at bus k
- V_m = Voltage at bus m
- P_k = Active power at bus k
- P_m = Active power at bus m
- P_k^{reg} = Scheduled active power at bus k
- P_m^{reg} = Scheduled active power at bus k
- P_k^{error} = Generator active power at bus k
- P_L = Load active power at bus k
- P_k^{calc} = Calculated active power at bus k
- P_k^{prev} = Phase shifter active power flow
- Q_k = Reactive power at bus k
- Q_m = Reactive power at bus m
- Q_k^{error} = Scheduled reactive power at bus k
- Q_k^{prev} = Phase shifter regulated active power flow
- Q_k^{calc} = Calculated reactive power at bus k
- ΔP_k = Active power mismatch at bus k
- ΔP_k^{prev} = Phase shifter active power mismatch
- ΔQ_k = Reactive power mismatch
- ΔQ_k^{prev} = Phase angle correction factor at bus k
- ΔV_k = Voltage correction factor at bus k
- ΔV_m = Voltage correction factor at bus m

4. Results and Discussion

4.1 The Nigerian National Grid

The one line diagram of the Nigerian 330KV grid system is shown in Fig.2. The grid system comprises of the generating stations which are connected in radial form with only one control centre which is the National Control Centre (NCC). This has posed a serious challenge to the amiable control of power in the network grid thus having a low reliability index [6] [13]. The installed power capacity on the Nigerian grid system is about 5500MW and the transmission network consists of 5000Km of 330KV lines and 6000Km of 132KV line. The power system is characterized by low voltage profile in most parts especially in the northern part of the country, inadequate dispatch, radial and fragile network grid, system collapse and an apical profile of transmission losses [11].
4.2 Power Flow Solutions without Phase Shifting Transformer (PST)

Presented in Table 1 is the power flow solutions obtained for the Nigerian 330kV grid system without the incorporation of PST. A tolerance of 1.000e-12 was used and the maximum power mismatch obtained from the power flow solution was 9.76996e-14. Convergence was attained after 7 iterations. These results were obtained using equations (3) to (6), and equations (11) to (12).

Table 1

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Name</th>
<th>Voltage Mag (p.u)</th>
<th>Voltage Angle (degree)</th>
<th>Load Power MW</th>
<th>Generated Power MW</th>
<th>Total Active Power MW</th>
<th>Total Reactive Power MVAR</th>
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<td>10.3</td>
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<td>0</td>
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<td>Aladja</td>
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<td>96.5</td>
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<td>150.9</td>
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<td>0</td>
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<td>Onitsha</td>
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Total | 4152.5       | 3024.9             | 4245.797               | 800.519       |

4.3 Line Flow and Losses without Phase Shifting Transformer

To calculate the line flow and total active and reactive power losses, equations (13) – (15) were used. Table 2 presents the result of the line flows and losses obtained without the incorporation of PST. The total active and reactive power losses of all the lines are found to be 93.3MW and -2224.4MVar respectively.
5. Power Flow Results with Phase Shifting Transformers

The power flow solutions obtained after the insertion of Phase shifting transformer using the Newton-Raphson iterative technique converged after 4 iterations. Also, a tolerance of 1.000e-12 was used. The phase shifting transformer was inserted one at a time on each of the four suitable transmission lines which are directly connected to the generator bus. This fact is well reported in [8]. The lines are between Benin to Osogbo (8-10), Alaoji to Onitsha (12-14), Benin to Onitsha (8-14), and Osogbo to Ikeja West (10-5). Out of these four cases, only case 1, that is, insertion of PST on line between Benin and Osogbo (8-10) is presented in the subsequent section of

<table>
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<th>line</th>
<th>PQsend MW</th>
<th>Mvar</th>
<th>MVA</th>
<th>PQrec MW</th>
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Table 2 Line flow and losses without phase shifting transformer

Total 93.3 2224.4
this paper. The results for the rest of the cases considered are presented in Table 4 in a summarized form.

CASE 1 (INSERTION OF PST ON LINE (8-10))
The result of the line flow and losses obtained with the insertion of PST on line Between Benin and Osogbo (8-10) is as presented in Tables 3. The phase shift (PST angle) is set to -0.134° and the controlled bus is bus 10. It could be deduced from Table 2 (base case) that there is a redistribution of power flow on the lines connected to bus 8 and 10 compared with Table 3 when PST is connected between bus 8 and 10. The values of the active power flow through the lines 5-8 and 8-10 before inserting PST are 152Mw and 31.2Mw respectively, whereas the active power flow through the same lines when PST was inserted are 151Mw and 33.1Mw respectively. The overall active power line loss is 93.2Mw with PST compared with 93.3Mw without PST. The implication of this result is that, for the active power flow, the percentage increase in line 8-10 loadability is 5.74% while there is a percentage decrease in line 5-8 loadability by 0.7%. Hence, the power flow direction is changed and exchanged from one direction to a new direction. The summary of all the results obtained for cases 1, 2, 3 and 4 is as presented in Table 4. The bar chart representation of the active power flow results obtained for the four (4) cases considered is shown in Figure 3.

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Table 3: Line flow and losses With PST (Case 1)
With the insertion of phase shifting transformer in the four cases, it is shown that power redistribution occurred in the system. It could be observed in cases 1, 2, 3 and 4 that the total active power loss reduced to 93.2, 93.0, 93.2 and 93.1 MW respectively compared with 93.3 MW obtained for the base case. As the difference in phase angle between two buses increased, the active power flow on the line connecting them also increased and as the phase angle difference of two buses decreases, the active power flow on the line connecting them also decrease. Therefore, the active power flow is directly proportional to change in phase angle difference between two buses.

![Fig. 3: Bar-Chart representation of the active power flow between lines](image)

**Table 4**

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With the insertion of phase shifting transformer in the four cases, it is shown that power redistribution occurred in the system. It could be observed in cases 1, 2, 3 and 4 that the total active power loss reduced to 93.2, 93.0, 93.2 and 93.1 MW respectively compared with 93.3 MW obtained for the base case. As the difference in phase angle between two buses increased, the active power flow on the line connecting them also increased and as the phase angle difference of two buses decreases, the active power flow on the line connecting them also decrease. Therefore, the active power flow is directly proportional to change in phase angle difference between two buses.
6. Conclusion

In this research work, power flow analysis was carried out using the Newton Raphson iterative technique with the MATLAB toolbox. Power flow and line losses at the steady state condition was obtained. This showed the lines and buses with abhorrent power flow. To enhance the active power flow, phase shifting transformer was inserted one at a time on each of the four suitable transmission lines directly connected to the generator bus. These lines are between Benin to Osogbo (8-10), Alajo to Onitsha (12-14), Benin to Onitsha (8-14), and Osogbo to Ikeja West (10-5). The insertion of phase shifting transformer between these buses improved the active power flow on the lines and also reduced the system’s total power losses, which is as a result of a little variations in the voltage angle of each of the cases considered. This proves the efficiency of the phase shifting transformer when applied as a means of solution to the power flow problem on weak and ill-conditioned power system like Nigerian 330KV grid, the results of which can still be applied to any power system network with similar condition.

Acknowledgement

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References

[16] Z.X. Han, Phase Shifter and Power Flow Control IEEE transaction on power Apparatus and system; 101 (10), 1982.