

Development of an Optimal Power Flow Control on Katampe 330KV Transmission System using Phase-Shift Transformer

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ABSTRACT

This research presents an optimal power flow control method for the Katampe 330kV Transmission System using a Phase Shift Transformer (PST). Power transmission systems often experience unequal power flow, affecting power quality in terms of reactive power, active power, and voltage profile. The study employs Newton-Raphson's power flow algorithm, PID control, and Particle Swarm Optimization (PSO) to optimize PST parameters and improve system performance. MATLAB R2021a simulations demonstrate significant improvements in real and reactive power losses across IEEE test networks (16, 33, and 69 Bus systems). The results show reductions in real power losses by 2.94%, 35.02%, and 53.88%, while reactive power losses improved by 1.99%, 24.28%, and 13.82%, respectively, after reconfiguration. These findings confirm the effectiveness of PST in enhancing power flow control and system efficiency.

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INTRODUCTION

The power system industry has evolved and transformed in recent years as the energy market and complex power generation is growing day by day hence, the capacity to control the power flow becomes very eminent. This evolution and transformation have brought changes in the way electrical transmission systems are operated. It is widely agreed upon that, nowadays, electrical power production with respect to demand and consumption had often been the determinant factors of economic growth all around the world (Energy for Economic Growth Summit, 2012). In times past, the electric grid system has encountered various difficulties which distort stability in power flow (real and reactive power flow) and this calls 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 (Acha *et al*, 2004). 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 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 (*Elements of power system analysis*, McGraw-Hill, 1982).

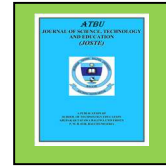
The present Nigerian 330kV grid system is predominantly known to be unstable, fragile, and ill-conditioned. This is due to rapid increase in the consumers demand for electricity and other technical factors. A network is said to be weak and ill-conditioned when it is deficit of reactive power, with low 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 (Isaiah *et al*, 2014). In previous years, the operation of transmission systems was not as complex

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because each transmission system was developed to supply electricity to its specific load within the country and nearby countries during emergency situations (Ogahara *et al.*, 2014). This arrangement had its own challenges in terms of directing the direction of power flow. In most cases, the arrangement of transmission lines has been used to transport electricity from generation A to consumer B. There is a legal contractual agreement between A and B in which it states that A will be responsible to supply a certain amount of energy/power which B will carry the financial implications (Verboomen *et al.*, 2005).

However, along the transmission line corridor could be other parallel lines near the existing line which can be interconnected to increase capacity. One major problem of this interconnection is the issue of power flow which arises from the unequal load demand of parallel transmission lines (Garcia-Guzman *et al.*, 2013). An issue that becomes increasingly important in meshed systems is power flow control, which is reflected in the fact that throughout Europe, phase shifting transformers (PSTs), which are examples of power flow controllers, are installed at numerous locations. There are basically three reasons why these devices are adopted (Ogahara *et al.*, 2014). The efficiency of grid management can be improved by solving bottlenecks in transmission systems. PSTs are able to shift flows from congested areas to other areas where transmission capacity is still available, offering the possibility to delay grid investments (Verboomen, 2008). The impedance of the transmission lines determines the power flow (IEEE Power Engineering Society, 2002). In order to control the direction of power flow and the amount of power flow magnitude, a phase shift transformer (PST) is employed. The power flow equations are non-linear in nature and therefore numerical methods are usually employed in solving them within an acceptable tolerance (Bewszko, 2011). Iterative techniques such as Newton-Raphson, Gauss-Seidel and Fast Decoupled had been extensively discussed and used to solve power flow problems (Acha *et al.*, 2004). 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.

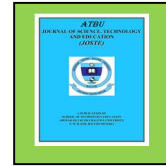
Overloading of transmission lines is typically caused by many factors among which are generator outages, excessive wheeling, and transmission lines outages and to mention a few (Al-Rawi *et al.*, 2010). In any of the cases, line overloading can be alleviated by redirecting power flow from overloaded 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. 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 of the power flow can be controlled by varying the phase shift (ABB Power Systems AB, 1999). 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 (Sule *et al.*, 2010). (Adebayo *et al.*, 2013) 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

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concerned majorly voltage magnitude control and system loss reductions.

In the research area, several papers have been published recently in a related field, to mention but few among others, Li *et al*, 2022, Yuan *et al*, 2023, Santos & Steinke 2023, Shao *et al*, 2023, Jin *et al*, 2024, Odion & Ekpa 2024 and many more.

PROPOSED METHOD

This section presents step by step detailed procedures (materials and methods) used in achieving the research work and are discussed below.

Simulation Platform

All simulations analyses were carried out in MATLAB R2021a software using HP 635 PC with the following specifications:

- Processor: Intel(R) Pentium (R) CPU B950 @ 2.10GHz Dual Core
- Installed Memory (RAM): 8.00GB
- System type: 64-bit Operating system, x64-based processor
- Operating System: Windows 8 pro single language.

Standard IEEE 16-Bus Test System

The IEEE 16-bus network is a standard power system test case used for the analysis and simulation of power flow and stability in electrical networks. In this work, twelve (12) load buses, four (4) generators, and twenty (20) transmission lines were used with bus one (1) taken as slack bus. The IEEE 16-Bus network is used to evaluate the performance and test power system control devices in which the work uses PSTs.

IEEE 33-Bus Test System

The IEEE 33-bus system is a radial distribution system consisting of 33 buses and 32 branches (lines). The IEEE 33-bus system is a medium voltage distribution network employed to model standard distribution network problems, including voltage control, loss minimisation, and the effects of distributed generation or load fluctuations.

IEEE 69-Bus Test System

The topology of the IEEE 69-bus system is usually tree-like. Apart from the slack bus, every bus is connected to a single parent bus, forming a radial distribution system. There are buses that branch off from the main trunk, forming a hierarchical network structure. The IEEE 69-bus system was used for power flow studies, where the goal is to find the voltage magnitude and angle at each bus in the network given the load and generation data, as well as the line impedances. The power flow equations are typically derived using the Newton-Raphson method.

Modelling of the PST on 330kV Gwagwalada/KATAMPE Transmission line

The PST was modelled as a reactance in series with a phase shift. The power flow through the line was then increased by adding an angle to the existing angle. This means that the phase shift is controlled within certain limits. The PSTs leakage reactance was varied with the tap position. Thereafter, a PST was inserted in the line as it does not pick up sufficient load, this provides an advance phase shift, meaning that the load side voltage phasor leads the source side voltage. Alternatively, a PST with retard phase angle could be inserted in the line that tends to overload, meaning that the load side voltage phasor should lag the source side voltage. Fig 1 present a Single Line Diagram of Nigeria 330kV line, Katampe transmission station as a case study.

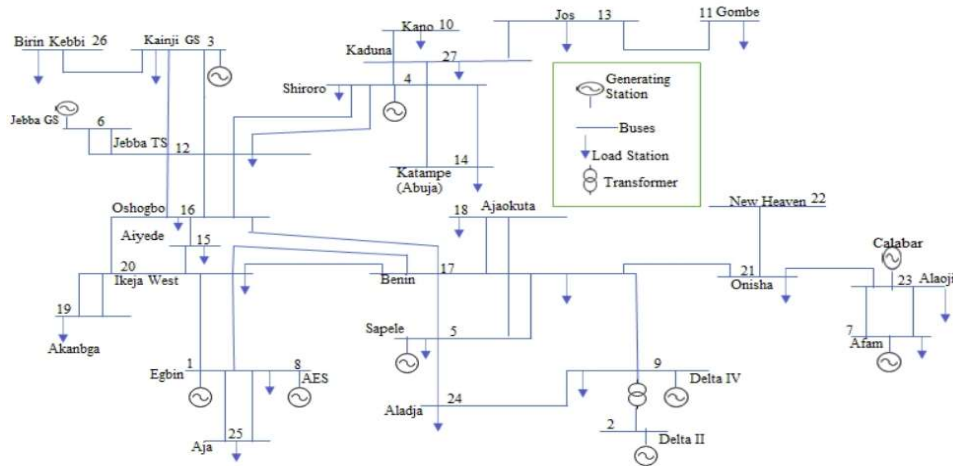


Fig 1: Single line diagram of Nigeria 330kV line (Joseph and Madueme 20213)

The PST is assumed to the following form in the transmission line as equation (1)
Minimize $v = \sum_{(i,j)} c_{ij} n_{ij} \sum d_{ij} * (n_{ij}^0 + n_{ij}) * \delta_{ij} + \alpha \sum r_k$ (1)

Subject to

$$S * f + g + r = d \quad (2)$$

$$f_{ij} - \gamma_{ij} * (n_{ij}^0 + n_{ij}) * (\theta_i - \theta_j + \varphi_{ij} * \delta_{ij}) = 0 \quad (3)$$

$$|f_{ij}| \leq (n_{ij}^0 + n_{ij}) * \overline{f_{ij}} \quad (4)$$

$$0 \leq g_i \leq \overline{g_{ij}} \quad (5)$$

$$0 \leq n_{ij} \leq \overline{n_{ij}} \quad (6)$$

$$0 \leq r_{kj} \leq d_k \quad (7)$$

The objective function in equation (1) corresponds to the investment cost. First two

terms refer to the costs due to the insertion of transmission lines and PST, respectively. Last term refers to a penalty for the configuration under analysis, due to the presence of artificial generation. The penalty parameter α was properly weighted to turn those configurations less attractive with artificial generation.

In constraint given as equation (2), corresponds to KCL, vectors g and r indicate existent and artificial generations, respectively. Also, the angular difference of the PST was taken as an unbounded variable although, a limit was set without modifying the mathematical model significantly. The Set of constraints (4) – (7) were refers to the transmission capacity of the circuits, limits of generation buses, limits of circuits added in each candidate path i - j , and limits of artificial generation buses, respectively.



Fig 2: Transmission line

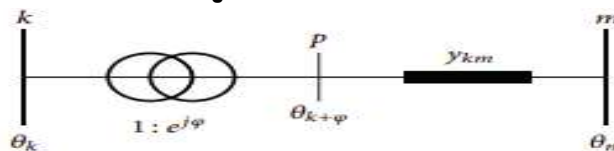


Fig 3: Transmission line with phase shift transformer

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Adopt the Newton-Raphson power flow technique

The power flow analysis using Newton Raphson method was carried out through the following outlined steps to obtain the unspecified parameters:

- i. Load the network parameters.
- ii. Classify the buses into slack bus, load bus and generator bus
- iii. Identify slack bus and set voltage magnitude and phase angle data to be equal to the slackbus value.
- iv. Active $P_i^{(k)}$ and Reactive power $Q_i^{(k)}$ of load buses are computed.
- v. Real $\Delta P_i^{(k)}$ and Reactive power $\Delta Q_i^{(k)}$ mismatch is calculated.
- vi. Compute Jacobian matrix elements

- vii. Calculate new bus voltage magnitude and its angle on all buses (except slack bus) and updatesolution
- viii. Continue until $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are within the specified tolerance.

RESULTS AND DISCUSSION

In this section, the performance of the developed optimal power flow control on KATAMPE 330kV transmission system using phase-shift transformer was discussed with relevant results shown. The simulation was carried out in MATLAB/Simulink environment

Standard IEEE 16-Bus Test System

Power flow analysis was performed to determine the condition of the network using Newton-Raphson method. Thereafter, the PSO was used to get the best position to insert the PST

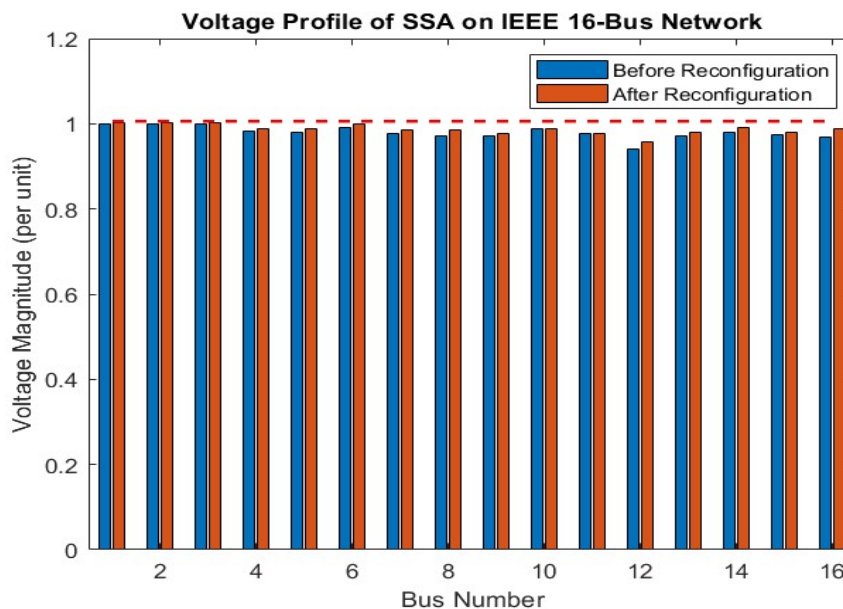


Fig. 4: Voltage Profile on IEEE 16-Bus Test System using PSO

Figure 4 present the voltage profile of IEEE 16 bus test system using the PSO before the reconfiguration and after the reconfiguration. It could be observed that there was improvement

across all the buses when the PST was placed. The result also presents a maximum of 1pu and minimum of 0.92pu on bus 12.

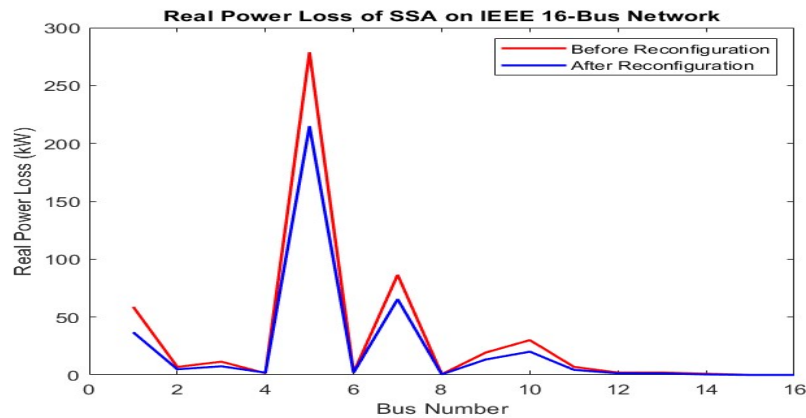


Fig. 5: Power loss on IEEE 16-Bus Test System using PSO

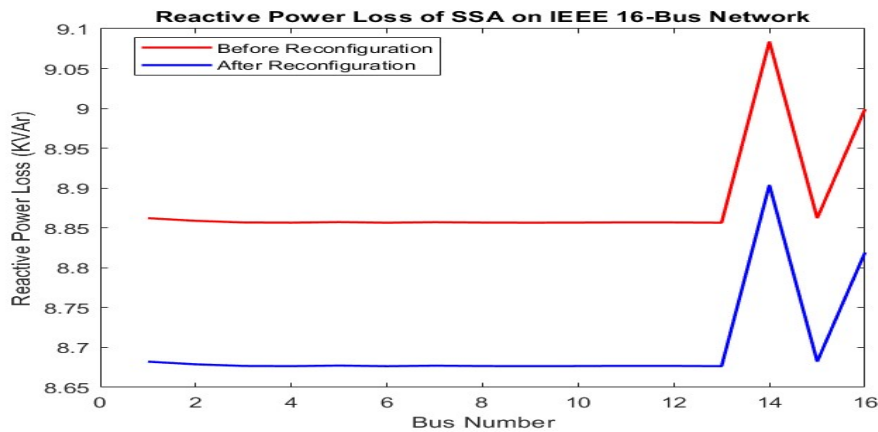


Fig. 6: Reactive Power loss on IEEE 16-Bus Test System using PSO

Figure 5 and Figure 6 present the real power loss and reactive power loss on the IEEE 16 bus test system before and after reconfiguration respectively. It could be observed that the power loss before the reconfiguration was 37.4789kW as compared with 36.3769kW after reconfiguration, representing 2.94%

improvement. The reactive power loss on the same test system was observed to be 8.3383kVar before reconfiguration and 8.1727kVar after reconfiguration, representing 1.99% improvement. Table 1 gave the summary of the result obtained on IEEE 16 bus network

Table 1: Summary of the Simulation Result of IEEE 16 Bus Test System

	Before Reconfiguration	After Reconfiguration	Reduction In%
Real power loss (kW)	37.4789	36.3769	2.94
Reactive power loss (kVar)	8.3383	8.1727	1.99

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Standard IEEE 33-Bus Test Network

Power flow analysis was performed on IEEE 33 bus network to determine the condition of the network. The Newton-Raphson method together with PSO were used to get the best position to insert the PST.

Figure 7 shows the voltage profile of IEEE 33 bus test system before and after reconfiguration. After properly inserting the PST, it could be observed that there was a significant improvement across all the buses. The highest improvement was 1pu and the least improvement was recorded to be 0.98pu.

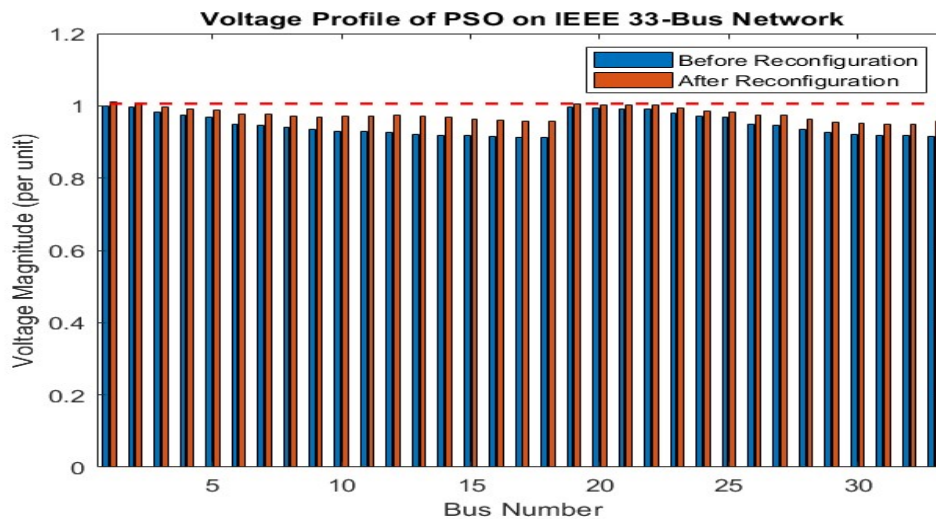


Fig. 7: Voltage Profile on IEEE 33-Bus Test System using PSO

Figure 8 and Figure 9 present the real power loss and reactive power loss on the IEEE 33 bus test system before and after reconfiguration respectively. The result shows a power loss before and after the system reconfiguration of 178.2516kW and 115.8297kW, which represents 35.02% improvement when

compared with based case. Also, the reactive power loss both before and after the reconfiguration were observed to be 135.2393kVar and 102.3976kVar, representing 24.28% improvement. Table 2 gave the summary of the result obtained on IEEE 33 bus network.

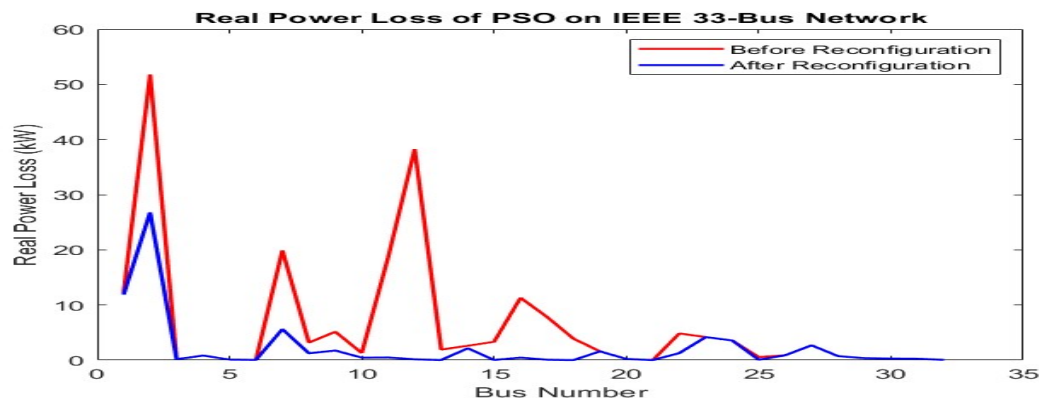


Fig. 8: Power loss on IEEE 33-Bus Test System using PSO

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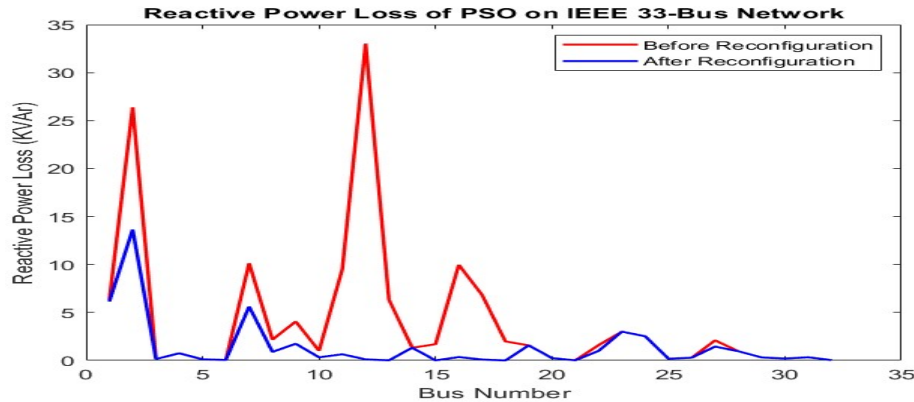


Fig. 9: Reactive Power loss on IEEE 33-Bus Test System using PSO

Table 2: Summary of the Simulation Result of IEEE 33 Bus Test System

	Before Reconfiguration	After Reconfiguration	Reduction In %
Real power loss (kW)	178.2516	115.8297	35.02
Reactive power loss (kVar)	135.2393	102.3976	24.28

Standard IEEE 69 Bus Test System

The voltage profiles of the IEEE 69 bus test system at all the buses for the power flow and the optimum power flow are presented below. Figure 10 presents the voltage profile of IEEE 69 bus test system before and after reconfiguration.

The results show that a significant improvement was achieved across all the buses after the reconfiguration. The highest improvement was 1pu and the least improvement was recorded to be 0.97pu with respect to voltage magnitude.

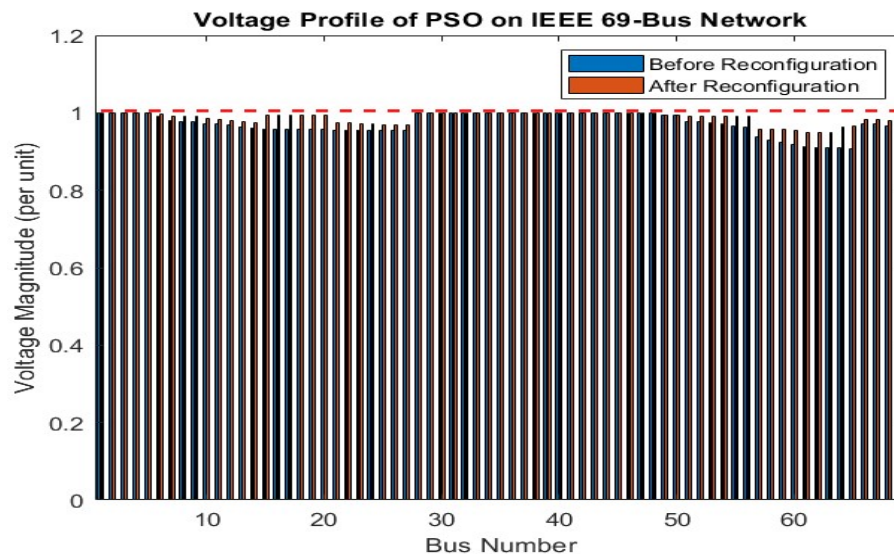


Fig. 10: Voltage Profile on IEEE 69-Bus Test System using PSO

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Figure 11 and Figure 12 shows the real power loss and reactive power loss on the IEEE 69 bus test system before and after reconfiguration respectively. The result shows a power loss before and after the system reconfiguration of 222.0918kW and 102.4310kW, which represents 53.88% improvement when

compared with based case. Also, the reactive power loss both before and after the reconfiguration were observed to be 107.1246kVar and 92.3230kVar which represents a 13.82% improvement when compared with the based case. Table 3 gave the summary of the result obtained on IEEE 69 bus network

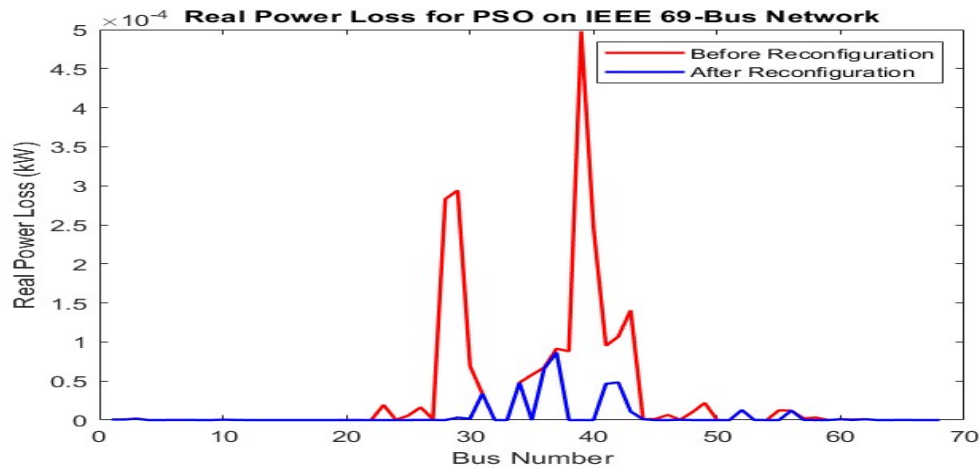


Fig. 11: Power loss on IEEE 69-Bus Test System using PSO

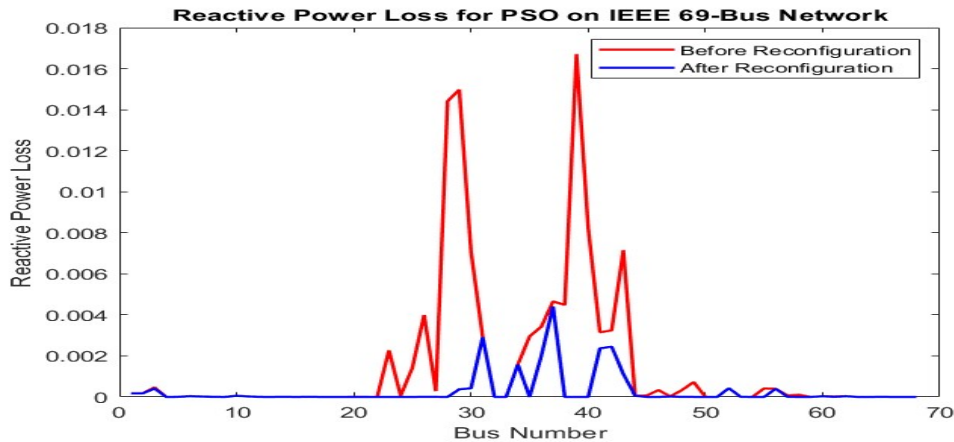


Fig. 12: Reactive Power loss on IEEE 69-Bus Test System using PSO

Table 3: Summary of the Simulation Result of IEEE 69 Bus Test System

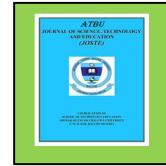
	Before Reconfiguration	After Reconfiguration	Reduction In %
Real power loss (kW)	222.0918	102.4310	53.88
Reactive power loss (kVar)	107.1246	92.3230	13.82

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CONCLUSION

The work presents the development of an optimal power flow control on KATAMPE 330kV transmission system using phase shift transformer for the power flow control. A PSO technique-based method for placement of PST on transmission line has been developed, in order to enhance efficiency and improve voltage profile. Newton-Raphson load flow method was used for all power flow analysis. Thus, the load flow problem consists of finding the power flows (real and reactive) and voltages of a network for given bus conditions. At each bus, there are four quantities of interest to be known: the real and reactive power, the voltage magnitude and its phase angle. The buses are classified into specified and the unspecified variables at a given bus, they are Slack bus, Generator bus and the Load bus. The slack bus does not carry any load. At this bus, the magnitude and phase angle of the voltage are specified. The phase angle of the voltage is usually set equal to zero. The active and reactive power of this bus is usually determined through the solution of equation.

A multi-objective function comprising of active power loss and network voltage deviation has been formulated and all system constraints were satisfied. The effectiveness of the approach was tested on the IEEE 16-bus network, IEEE 33-bus and IEEE 69-bus, 330kV Nigeria transmission systems. The result obtained demonstrates a 2.94% and 1.99% improvement on real and reactive power losses of IEEE 16 bus network, 34.02% and 24.28% improvement on IEEE33 bus network, 53.88% and 13.82% improvement on IEEE69 bus network respectively. In conclusion, it can be said that the ever-growing demand can be met by transmitting more power at operating condition without having to compromise the voltage stability by using the inexpensive methodology proposed and developed here.

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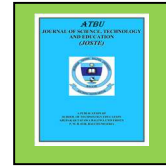
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