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Application of Optimal Interline Power Flow Controller Placement for Voltage Improvement in the Lagos Regional 330 KV Transmission Network

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ABSTRACT
The increasing demand for reliable electric power and the growing complexity of transmission networks have intensified the need for advanced power flow control and voltage stability enhancement techniques. This study investigates the optimal placement of an Interline Power Flow Controller (IPFC) for voltage profile improvement and transmission loss minimization the Lagos Regional 330 kV transmission network as case studies. The networks were modeled in the Power System Analysis Toolbox (PSAT) environment within MATLAB/Simulink. Load flow analysis was initially performed to identify weak buses, evaluate voltage profiles, and determine active and reactive power losses under uncompensated operating conditions. For the Lagos Regional 330 kV network, a polynomial regression model relating transmission distance to active power loss was developed and utilized as an objective function for optimization. Particle Swarm Optimization (PSO) and a hybrid PSO–Multi-Verse Optimization (PSO-MVO) algorithm were employed to determine the optimal IPFC location. The optimization process identified the transmission line 5 between Olorunsogo and Ikeja West at an approximate distance of 600 km as the most suitable location for IPFC installation. Simulation results demonstrated significant improvements in voltage profiles, active and reactive power flow distributions, and reductions in transmission losses after IPFC implementation. The simulation results when the IPFC was placed within the ten (10) buses showed that the impact of the of the optimal placement of IPFC using PSO-MVO on the network obtained voltage improvement above 10% on bus 2, 5, 6 and 10 as a result of impact of IPFC placement on the network when compared to that without IPFC placement while the active and reactive power losses improved between 92% to 95% for all the buses when IPFC was placed on the test network. Finally, techno-economic evaluation using the profitability index confirmed the economic viability of the proposed approach.

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INTRODUCTION

Electricity has a major impact on every aspect of our socioeconomic life. It plays a vital role in the economic, social, and political development of any nation. Electricity is the most popular and commonly used source of energy in the world today. One significant pattern that has observed is that as the country's population grows, so does the demand of power. Poor transmission capacity, inadequate generation, and poor maintenance culture have also contributed greatly to the inadequate supply of electricity to the Nigerian people. This situation has no doubt impacted negatively both socially

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and economically. Technically speaking, one of the key causes of inadequate power supply and challenges faced in transmission network are such as voltage instability, line congestion and power losses and these contribute greatly to network instability, low voltage profile, and network insecurity [1].

Efficient operation of power transmission networks is crucial for ensuring reliable and stable electricity delivery to consumers anywhere in the world. In recent years, there has been increasing interest in deploying Flexible Alternating Current Transmission Systems (FACTS) devices to enhance network performance [2]. Among these devices, Interline Power Flow Controllers (IPFCs) helps mitigate these issues by providing dynamic control of power flow and improve voltage stability and reducing power losses in high-voltage transmission lines [3].

Several studies have investigated the optimal placement of FACTS devices, such as Unified Power Flow Controllers (UPFCs), Generalized Unified Power Flow Controllers (GUPFCs), and Static Synchronous Compensators (STATCOMs), to address various operational challenges in power transmission networks [4] [5] [6]. However, there remains a gap in the literature regarding a focused investigation into the optimal placement of IPFCs specifically for voltage improvement on a 330kV transmission lines.

The deployment of IPFCs presents a unique opportunity to address voltage stability concerns on high-voltage transmission lines, critical components of the power grid infrastructure [7]. By strategically placing IPFCs along Lagos Regional 330kV transmission lines, it may be possible to optimize voltage profiles, mitigate voltage deviations, and improve the overall reliability of the power transmission network.

In this context, this study aims to fill this gap by exploring the optimal placement of IPFCs for voltage improvement on the 330kV transmission lines. By leveraging insights from existing research on FACTS device optimization and voltage stability enhancement, this study seeks to develop a comprehensive methodology for determining the optimal placement of IPFCs to achieve optimal voltage improvement on high-voltage transmission lines.

Through a systematic analysis of existing literature, this study will identify key factors influencing the placement of IPFCs, such as network topology, load distribution, and operational constraints [8]. Building upon insights gained from previous research, the proposed methodology will aim to maximize the voltage improvement potential of IPFCs while ensuring cost-effective and efficient deployment of these devices in real-world transmission networks [9].

Ultimately, the findings of this study are expected to contribute valuable insights into the optimal deployment of IPFCs for voltage improvement on the regional 330kV transmission lines, thereby enhancing the reliability and performance of power transmission networks and supporting the transition towards a more resilient and sustainable energy infrastructure [10].

LITERATURE REVIEW

Some research relevant to the study are reviewed and presented in this section. These literatures include the previous works on optimal placement on grid network[4].Author in reference [11] utilized PSAT and the Newton-Raphson load flow algorithm to model the Nigeria 330kV transmission network and evaluate the impact of UPFC integration, resulting in improved voltage stability and reduced power losses. These studies collectively illustrate the effectiveness of various FACTS devices and optimization techniques in enhancing voltage stability and reducing power loss across different transmission networks in Nigeria, contributing to the overall improvement of the country's power infrastructure.

The study in reference [13] aimed at the importance of optimal IPFC placement using Transmission Line Performance Index (TLPI) and Newton-Raphson Load Flow (NRLF) algorithm, giving rise to a reduction of transmission line utilization levels (TLUL) on an IEEE-30 test-bed network. Similarly, [17] carried out power flow analysis using GUPFC in the Nigerian power system, showing improved active power flow

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control, reduced losses, and improved voltage profile. [18] utilized Grey Wolf Optimization (GWO) to optimally size and site GUPFCs, realizing significant reduction in power loss and adherence to voltage tolerance limits on a 28-bus, 330kV transmission network in Nigeria.

In [15], GUPFC for maintaining security margin and performance improvement under (N-1) contingencies was proposed, utilizing Particle Swarm Optimization (PSO) and Improved Particle Swarm Optimization (IPSO) for optimal device placement on IEEE 14-bus and 30-bus systems, indicating effectiveness even under contingency situations. [12s] solved real power losses in the Nigerian 47-bus transmission network using an Artificial Neural Network (ANN)-based IPFC, accomplishing significant cutbacks in losses and normalized voltage profiles. Together, these studies show the range of approaches used to optimize the placement of FACTS devices, leading to higher voltage stability and lower power loss in different power transmission networks, including those in Nigeria.

Reference [9] investigated the performance of IPFCs for voltage enhancement and power loss reduction, using a modified Newton-Raphson load flow algorithm to evaluate the impact of IPFC integration on a Nigerian 41-bus transmission network. [6] focused on voltage profile enhancement in the Nigerian 330kV transmission power network using a Static Synchronous Compensator (STATCOM), which substantially improved voltage stability and reduced power losses. [18] explored the use of FACTS devices, including Static Synchronous Series Compensator (SSSC) and STATCOM, to enhance voltage stability and reduce power losses in a Nigerian 330kV 10-bus transmission power system

MATERIALS AND METHODS

The materials and methods used to determine the optimal place interline power flow controller for voltage improvement on Lagos Regional 330 KV transmission line are presented in this section.

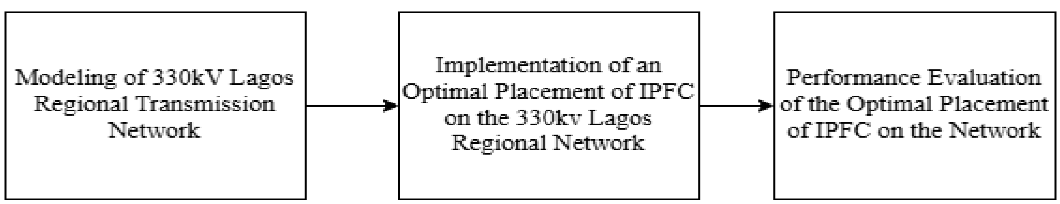

Fig.1: Framework for the Implementation of optimal place interline power flow controller for voltage improvement on Lagos Regional 330 KV.

Modeling of the power system network of the in PSAT.

The power system line diagram was first obtained from the research of the TCN regional centre. The following sections discussed the details of the modeling

Data Acquisition and analysis

The data used in this work were collected from the public utility service provider known as Transmission Company of Nigeria (TCN) Lagos regional centre, during visitation to the station. The Company provides Power to Lagos and other states within the Southwest part of Nigeria. The bus information, line information and information of network were shown in Table 1 and Table 2

Table 1: Bus data

Bus number	Bus location	Voltage (pu)
1	Oshogbo	1
2	Ayede	1
3	Omotosho	1
4	Olorunsogo	1
5	Ikeja West	1
6	Akangba	1
7	Benin	1
8	Egbin	1
9	Oke-Aro	1
10	Ajah	1

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Table 2: Line data

Line number	From bus	To bus	Resistance	Reactance	Susceptance	Distance (km)
1	Oshogbo	Ayede	0.369389	1.175946	0.028681	214
2	Ayede	Olorunsogbo	0.369389	1.175946	0.028681	142
3	Omotosho	Ikeja West	0.369389	1.175946	0.028681	131
4	Omotosho	Benin	0.553561	1.764006	0.041835	102
5	Olorunsogbo	Ikeja West	1.0209	3.253601	0.077276	88
6	Ikeja West	Akangba	1.0209	3.253601	0.077276	104
7	Ikeja West	Egbin	0.5535	1.764006	0.041835	122
8	Ikeja West	Oke-Aro	0.5535	1.764006	0.041835	172
9	Benin	Egbin	2.460007	7.839998	0.185973	93
10	Egbin	Oke-Aro	2.460007	7.839998	0.185973	56
11	Egbin	Ajah	3.940926	12.55967	0.297959	74

Modeling of the Power system Network in PSAT using MATLAB

The datasets obtained from section 3.2 were used to model the power system network in PSAT using MATLAB. The procedure for the modeling of the power system network in PSAT was shown in the flow diagram in Fig. 2.

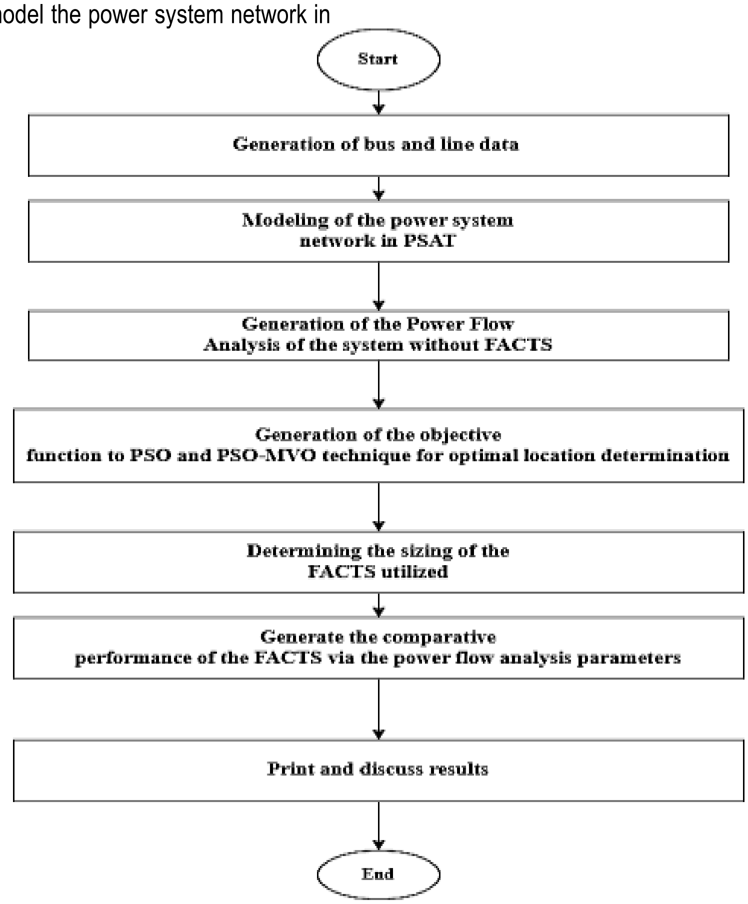

Fig.2: Flow diagram of the procedure of PSAT modeling of the power system network.

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Fig. 3 represents one-line diagram of Lagos Regional 330Kv transmission network using PSAT software

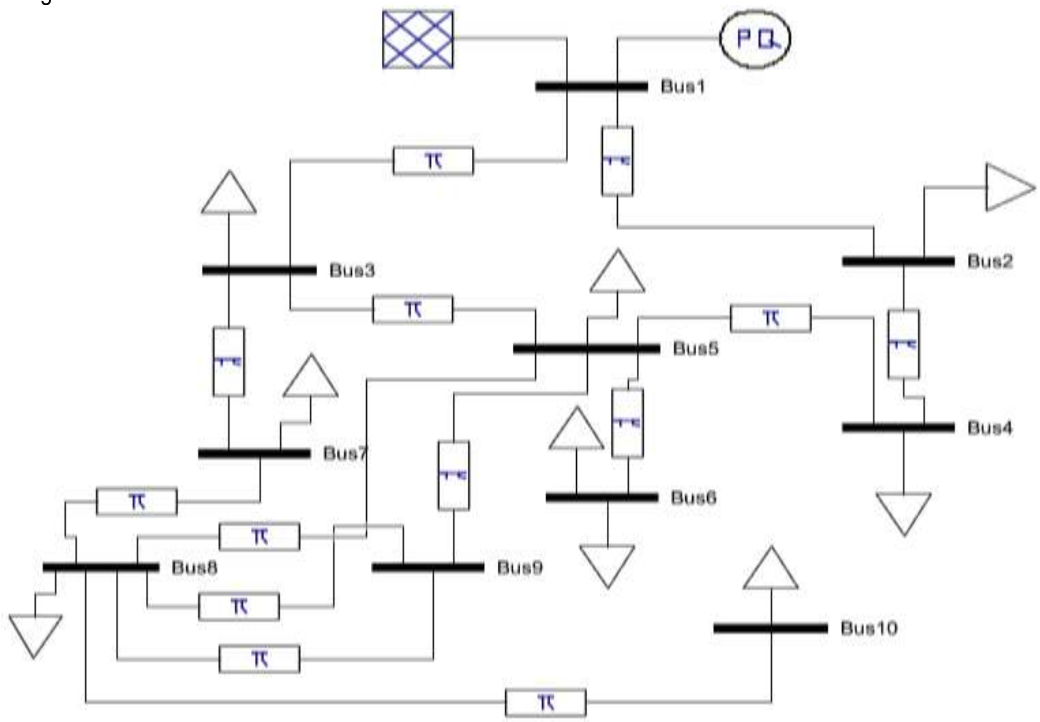

Fig.3: PSAT model of the power system network without FACTS devices

The model in Figure 3 was simulated and the data exported to MATLAB environment for the generation of tables, plots and charts for the power system network static and dynamic parameters for with and without IPFC . The outcome was presented in the result section.

Determination of the optimal placement of the IPFC based on the Polynomial using Particle Swarm Optimization (PSO) and Hybrid PSO-MVO

In this research, PSO and PSO-MVO were utilized for the determination of the optimal location for the implementation of the IPFC FACTS device. The procedures utilized were outlined in the specific steps. The active power flow outcome and the cumulative distance were presented in Table 3.

Table 3: Cumulative Distance Data

Line number	Line distance	Cumulative line distance
1	214	214
2	142	356
3	131	487
4	102	589
5	88	677
6	104	781
7	122	903
8	172	1075
9	93	1168
10	56	1224
11	74	1298

The polynomial model order and the R-square value was shown in Table 4.

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Table 4: Polynomial model order

Polynomial order (n)	R-square values
1	0.3317
2	0.5598
3	0.7813
4	0.8817
5	0.9592

The best model utilized as the objective function to the PSO and PSO-MVO was the 5th polynomial shown in equation 1.

$$f(x) = 1.2217 + 1.0531D - 0.9813D^2 + 0.5514D^3 - 0.0164D^4 + 0.0114D^5 \quad (1)$$

The flowchart for the implementation is shown in Fig.4

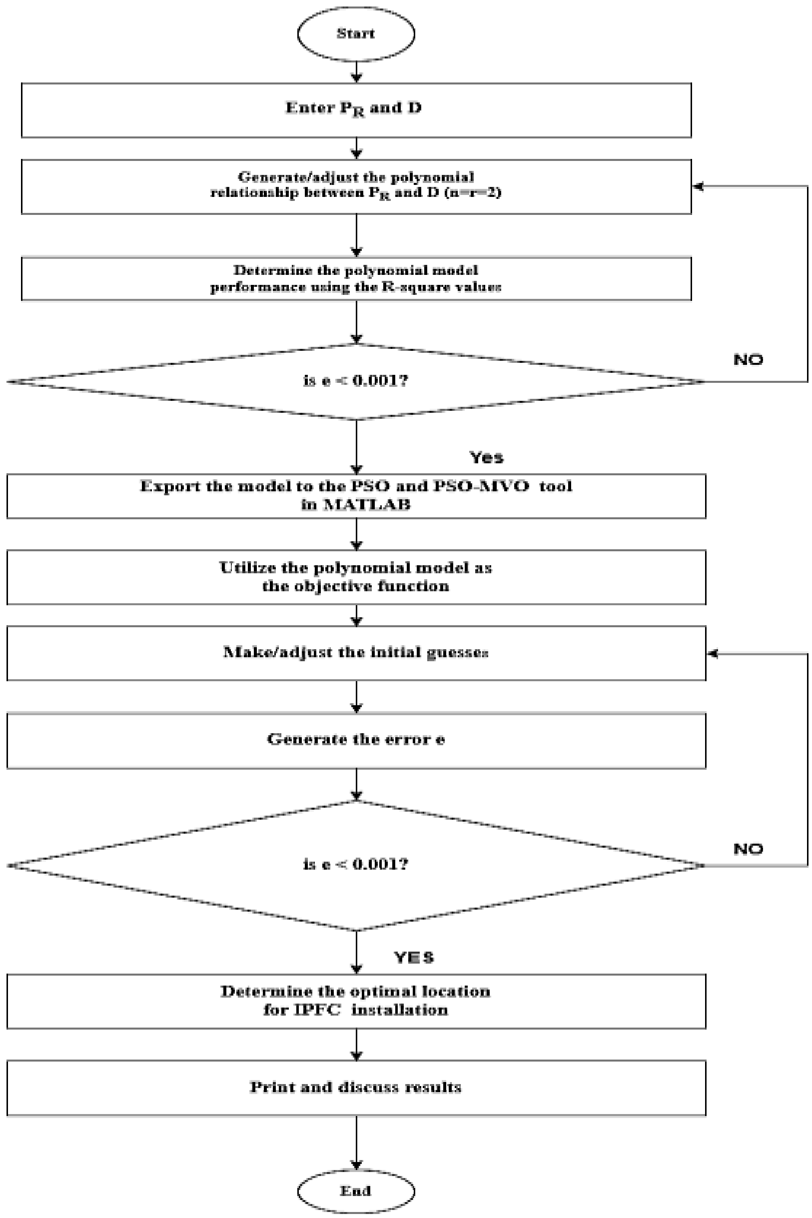

Fig. 4: Flowchart of the Optimal Location using PSO-MVO

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Determination of the Economic Impact

The cost parameter that suites the research utilized was the profitability index (PI) which on FACTS implementation which was given as;

$$PI = \frac{\sum_{t=1}^{T} \frac{B_t}{(1+r)^t}}{C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}} \qquad (2)$$

Determination of the system impact without and with the implementation of the IPFC on the Lagos 330 KV regional network

The equation for the determination of the improvement for each voltage profile (%Vimp) was shown in equation 4.

$$\%V_{imp_i} = \frac{V_{IPFC} - V}{V_{IPFC}} \, 100 \qquad (3)$$

Then

$$\%V_{imp} = \frac{sum(V_{imp_i})}{n} \qquad (4)$$

Where $\%V_{imp_i}$ represents the voltage improvement for each bus, V_{DG} represents the voltage with DG, V represents the voltage without DG and n represents the number of stations.
The percentage real power improvement was shown in equation 6.

$$\%P_{imp} = \frac{sum(P_{IPFC} - P)}{sum(IPFC)} \, 100 \qquad (5)$$

Where $\%P_{imp}$ represents the real power improvement achieved, P_{DG} represents the real power flow with

RESULTS AND DISCUSSION

The results obtained based on the methodologies presented in chapter three that addressed the research objectives are discussed and presented in this section. Fig.6 below shows the convergence curve of optimal placement of IPFC on Lagos regional 330kV network obtained using PSO and PSO-MVO algorithms.

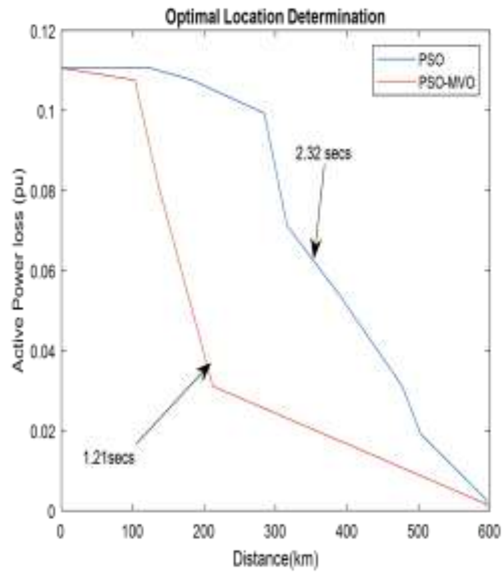

Fig.5: Outcome of the PSO and PSO-MVO optimization

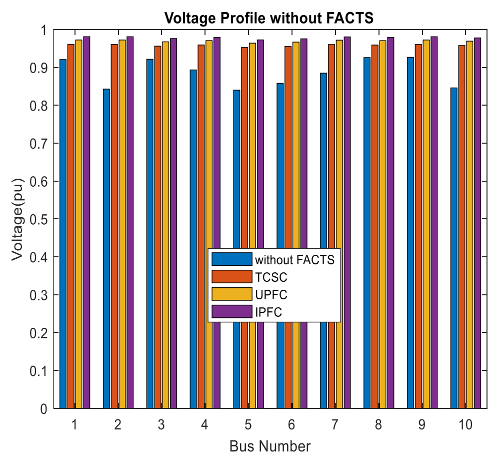

Fig.6: The voltage profile for with and without FACTS device

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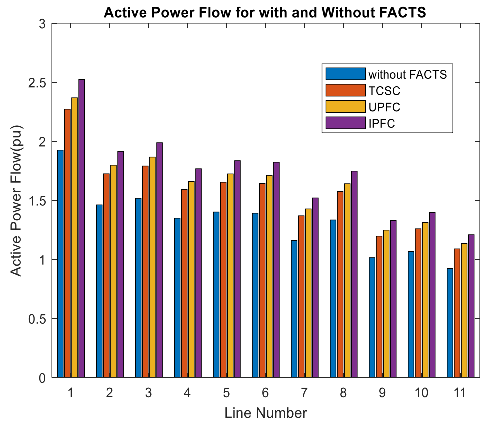

Fig.7: The Active Power flow for with and without FACTS device

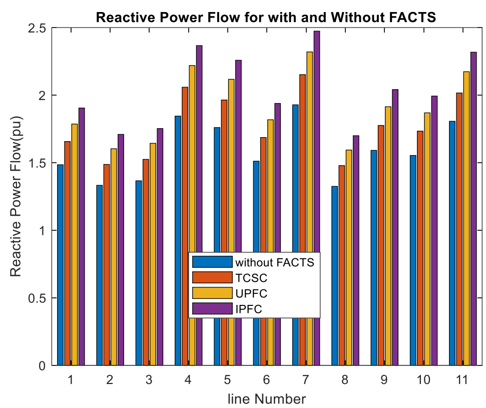

Fig.8: The reactive power flow for with and without FACTS devices

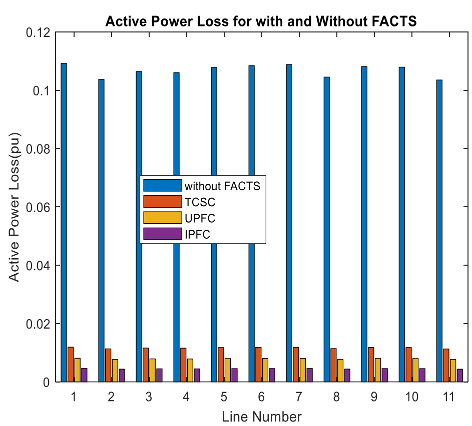

Fig.10: The active power loss for with and without FACTS devices

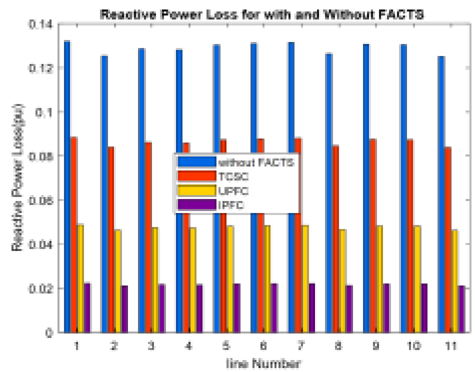

Fig.9: The Reactive Power Loss for with and without FACTS devices

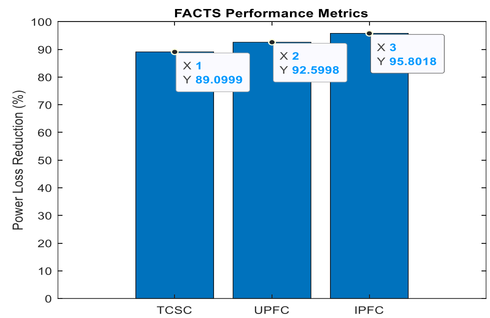

Fig.11: Percentage power loss reduction of FACTS devices

The parameters utilized to study the FACTS impact on the transmission system was profitability index. The profitability of the system before and after FACTS allocation was shown in the bar chart presented in Fig.12.

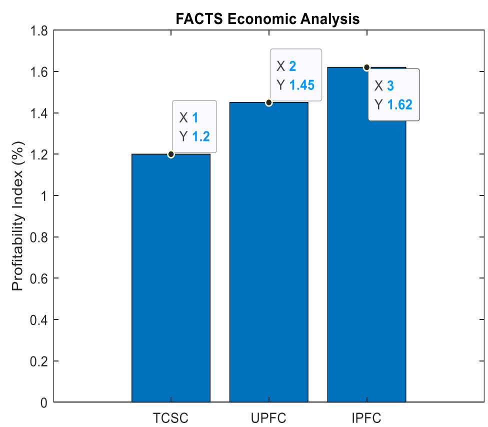

Fig.12: Profitability Analysis

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CONCLUSION

The research presents an optimal placement interline power flow controller for voltage improvement on Lagos Regional 330 KV transmission line in order to improve the voltage profile and minimize power loss, a scientific solution is highly required. Thus, this thesis introduces an optimal placement of IPFC for voltage improvement on Lagos Regional 330 KV transmission line to achieve this purpose. The data used in this work were collected from the public utility service provider known as Transmission Company of Nigeria (TCN) Lagos Regional centre. Subsequently, modeling of the Power system network using PSAT in MATLAB. The Simulation of the developed system was carried out by considering active and reactive response improvement.

The performance evaluation of the results was carried out and compared to the system PSO and hybrid PSO-MVO optimal placement in terms of voltage profile improvement, active and reactive power loss minimization. The simulation results reveal that an optimal placement on interline power flow controller for voltage improvement on Lagos Regional 330 KV transmission line has the overall improvement of voltage profile improvement when considering the buses the load flow analysis after IPFC placement to assess power quality improvements on the network. For active and reactive power loss minimization improvement, the implementation of optimal location for IPFC placement within Lagos Regional 330kV transmission network in order to minimize transmission losses, improve voltage stability, enhance power flow control, and increase the overall reliability and efficiency of the network.

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