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Minimisation of Power System Losses on the Nigerian 330 kV Transmission Network using Static Synchronous Compensator (STATCOM) and Interline Power Flow Controller (IPFC)

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ABSTRACT: This study outlines the use of an interline power flow controller (IPFC) and a static synchronous compensator (STATCOM) to minimise power losses in the Nigerian 330 kV transmission system. The case study utilised a seven-bus transmission network with seven transmission lines that were created from the 52-bus transmission network in Nigeria. Geregu, Ajaokuta, Benin, Omotosho, Ikeja West, Onitsha, and Okpai were the locations of the seven buses. Matrix Laboratory's power system analytical toolset (PSAT) was utilised to independently create the circuit models of the transmission network with and without IPFC and STATCOM. Based on the modelling results, it was shown that approximately 60% of power losses were optimised in the seven-bus transmission network between Geregu and Okpai after STATCOM was added. The voltages of the buses were optimised to roughly 70%, but power losses were reduced to up to 80% when IPFC was added to the seven bus transmission networks. The bus voltages have a 100% improvement. The bus voltages met the permitted operating range of V = 1.0 ± 6% per unit value. The findings suggest that the seven-bus network should employ IPFC to reduce power losses and optimise bus voltages. Therefore, to stabilise bus voltages and minimise power losses along transmission lines, it is advised that IPFC be used in Nigerian power transmission networks.

KEYWORDS: Transmission network, Power system losses, static synchronous compensator (STATCOM), interline power flow controller (IPFC), seven-bus network.

I. INTRODUCTION

The efficient transmission of electrical power from the generating stations to the load centres with minimal losses incurred is the Nigerian power transmission system's most significant problem [1]. According to [2], the Nigerian power system is persistently under strain due to the exponential demand for constant, dependable, and high-quality electrical power. Voltage instability and imbalances in reactive power result from system overload [3]. Voltage instability is a significant issue in Nigeria's electricity transmission network [4]. Recurrent voltage failures and blackouts are the outcomes [5].

Conventional power loss reduction devices installed at transmission injection stations in Nigeria, as reported by [6], only use fixed and rotating capacitors and inductors equipped with mechanical switching methods. Their effectiveness and reliability still pose challenges in the power industry [7]. However, the operations of static synchronous shun Compensator (STATCOM) and Interline Power Flow Controllers (IPFC) devices, which are types of flexible alternating current transmission systems (FACTS), are by electronic means enabling instantaneous control of reactive power, voltage magnitude, transient stability, and transmission line losses at the point of compensation [8].

This study uses a case study of a 7-bus transmission lines network to minimise power losses in the Nigerian power system. The 7-bus transmission network case study was developed from the 330 kV Nigerian transmission lines network. The seven buses are Geregu, Ajaokuta, Benin City, Omotosho, Ikeja West, Onitsha, and Okpai. Minimising technical power losses on these seven buses and their interconnected transmission lines aims to enhance electrical equipment's effective and efficient operation.

II. REVIEW OF SOME PAST LITERATURE

Several authors have worked on power loss minimisation using FACT devices. Selvi et al. [9] presented a comparative analysis of power loss optimisation by reactive power compensation using a unified power flow controller (UPFC) and static synchronous series compensator (SSSC) on transmission lines. Sepribo and Adebisi [10] implemented a unified power flow controller (UPFC) to improve power loss on the Nigerian 330 kV transmission lines network. Sambo [11] proposed using IPFC on a 5-bus transmission network developed from the Nigerian 330 kV transmission network to minimise power loss. Samuel et al. [12] proposed minimising voltage stability and power losses on Nigerian transmission lines network using Static Synchronous Shunt Compensator.

III. METHODOLOGY

Figure 1 illustrates the steps taken to realise the study's objectives using the materials obtained as data. The procedures on the flowchart in Figure 1 were carried out on Power System Analytical Toolbox (PSAT). The graphical illustration guided the implementation of the research methods using the materials obtained as data to achieve the research objectives.

3.1 Data Obtained for the Transmission Lines and Buses

The data used in this research were obtained from the Transmission Company of Nigeria (TCN) operational records. Tables 1 and 2 show the research's transmission lines and bus data.

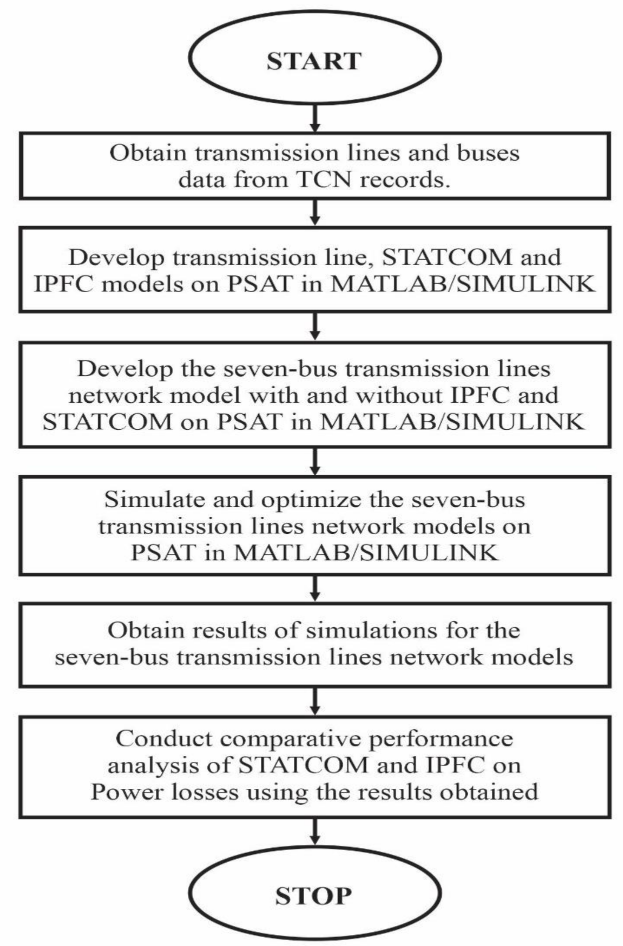

Figure 1: Research methodology

Table 1: Bus data for the transmission Lines

S/N	Buses	Bus voltages (p.u)	P Flow (p.u)	Q Flow (p.u)
1	Geregu (Gen)	1.00	0.9101	0.1100
2	Ajaokuta (Load)	0.94	0.7426	0.1481
3	Benin City (L)	0.95	0.5761	0.2147
4	Omotosho (Gen)	1.00	0.9416	0.0100
5	Ikeja West (Load)	0.96	0.3109	0.1300
6	Onitsha (Load)	0.95	0.8166	0.1210
7	Okpai (Gen)	1.03	0.6218	0.2031

Source: Operational data from Transmission Company of Nigeria (TCN) (2021)

Table 2: Transmission lines data

Line No.	Sending End Bus	Receiving End Bus	Length of Line (km)	Resistance (ohms/km)	Reactance (ohms/km)
1	Geregu	Ajaokuta	11	0.06	0.61
2	Ajaokuta	Benin	231	0.24	0.52
3	Benin City	Omotosho	136	0.18	0.26
4	Omotosho	Ikeja West	172	0.29	0.41
5	Ikeja West	Onitsha	226	0.35	0.18
6	Onitsha	Okpai	71	0.21	0.16
7	Okpai	Geregu	265	0.18	0.13

Source: Operational data from Transmission Company of Nigeria (TCN) (2021)

The case study transmission network analysed in the study was developed from the existing fifty-two (52)-bus Nigerian 330 kV transmission lines network.

3.2 Modelling Method

The computer-based modelling method was used to develop the required models on PSAT in MATLAB/SIMULINK environment. The transmission lines, STATCOM and IPFC models were developed on PSAT. The seven-bus case study transmission network was also created on PSAT.

3.3 Modelling of Transmission Line

Typical transmission lines have parameters such as Conductance (G), Inductance (L), Capacitance (C), resistance (R), and impedance (Z). A transmission line is lossless if the line is made of a material with very minimal resistance and its conductance is infinite ($\sigma\ C\ \approx\ \infty$). The dielectric medium separating the conductors in the transmission line is also lossless ($\sigma \cong 0$). Equation (1) is a necessary condition for a line to be lossless, which is desirable for power transmission

$$R = Z = 0 \quad (1)$$

$$\mathrm{Z} = (\mathrm{R} + \mathrm{j}\omega\mathrm{L}) \quad (2)$$

$$\mathrm{Y} = (\mathrm{G} + \mathrm{j}\omega\mathrm{C}) \quad (3)$$

Equation (2) depicts the total series impedance in Ohms, and Equation (3) shows the admittance between the lines to the ground in Siemens.

$$\gamma = (\mathrm{j}\omega\mathrm{L})(\mathrm{j}\omega\mathrm{C}) = \alpha + \mathrm{j}\beta \quad (4)$$

Equating the left-hand side of Equation (3) to the right-hand side gives the result shown in Equation (4).

$$\alpha = 0, \beta = \omega\mathrm{LC} \quad (5)$$

$$Xo = 0,\ Zo = Ro = \sqrt{\frac{L}{C}} \quad (6)$$

where L = Inductance per unit length, C= Capacitance per unit length, Z_0 = Characteristic Impedance, R = Resistance per unit length, G = Conductance of the dielectric per unit length, α = Attenuation Constant, β = Phase Constant, γ= Propagation Constant, j = Imaginary unit, and ω = angular frequency, R_0 = Resistive Impedance, X_0 = Inductive reactance.

Figure 2 shows a typical transmission line model from where bus $-i$ and bus $-j$ represent any two buses interconnected by a transmission line with series impedance Z_{ij} and shunt impedance $Y_c\ /2$. According to Kirchhoff's current law;

$$I_i = I_{ji} + I_i = \frac{Vi-Vj}{Z_{ij}} / Z_{ij} + V_i\frac{Yc}{2} \quad (7)$$

$$I_j = -I_{ji} + I_{jj} = \frac{Vi-Vj}{Z_{ij}} + V_j\frac{Yc}{2} \quad (8)$$

Equations (7) and (8) may be written in matrix form as follows:

$$\begin{bmatrix} \frac{1}{Zij} + \frac{Yc}{2} & \frac{-1}{Zij} \\ \frac{-1}{Zij} & \frac{1}{Zij} + \frac{Yc}{2} \end{bmatrix} \begin{bmatrix} Vi \\ Vj \end{bmatrix} = \begin{bmatrix} Ii \\ Ij \end{bmatrix} \quad (9)$$

Equation (9) is the bus voltage equation of a transmission line, which can be inputted into the network voltage equation for analysis of any n-bus transmission lines.

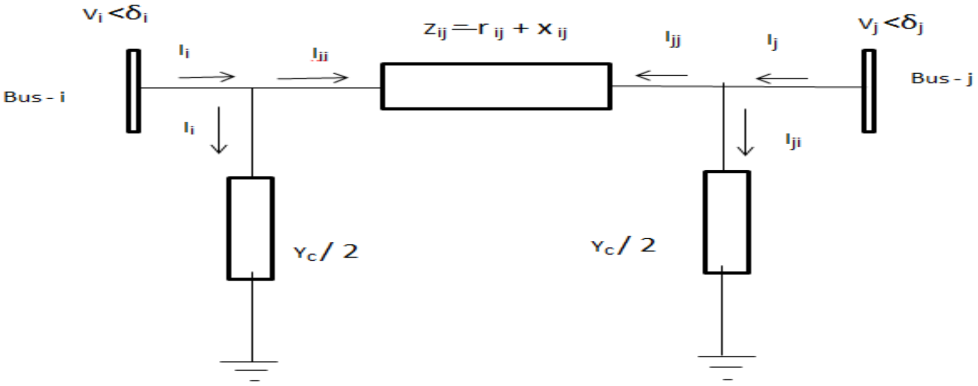

Figure 2: A typical transmission line model

Modelling an $n-$bus transmission lines network can be better understood by considering a $2-$bus separated by a single transmission line as presented in Figure 2 having V_s as the sending-end voltage, V_t as the receiving-end voltage and X_t as the transmission line reactance. P_r as the active power and Q_r as the reactive power transferred through the line. The current I_R is given as:

$$I_R = (Vs - Vr) / jX \tag{10}$$

On substituting $Vs = Vs\cos\delta + Vs\sin\delta$ into Equation (6), the Equation becomes;

$$I_R = \frac{Vs\,\mathrm{Cos}\,\delta + jVs\,Sin\,\delta - Vr}{jX} \tag{11}$$

Multiplying and dividing Equation (7) by $-j$,

$$I_R = \frac{Vs\,\mathrm{Cos}\,\delta + jVs\,Sin\,\delta - Vr}{jX} \text{ x } \frac{-j}{-j} \tag{12}$$

$$I_R = \frac{Vs\,\mathrm{Cos}\,\delta - j(Vs\,Cos\,\delta - Vr)}{X} \tag{13}$$

The complex current is

$$I_R^* = \frac{Vs\,Sin\delta}{X} + \frac{j(Vs\,Cos\delta - Vr)}{X} \tag{14}$$

The complex is

$$S_R = P_r + jP_r = V_r I_R^* \tag{15}$$

By controlling V_s and V_r in Equation (14), both the active and reactive power can be controlled by STATCOM and IPFC, and their performance can be evaluated using the results obtained.

3.4 Modelling of Static Synchronous Shunt Compensator (STATCOM)

Modelling the STATCOM involves understanding its operational principles as a static synchronous generator operated in the shunt-connected static var compensator mode as a voltage source converter (VSC) whose capacitive and inductive output currents can be coupled to the transmission line to regulate the reactive power of the transmission network. The mathematical model of the STATCOM has a basic voltage source converter (VSC). Figure 3 shows the STATCOM model with impedance Z_{sh} amplitude of converter voltage U_{st}, phase angle δ_{st}, injection voltage of the converter U_i, injection phase angle δ_i and coupling coefficient g_{sh}.

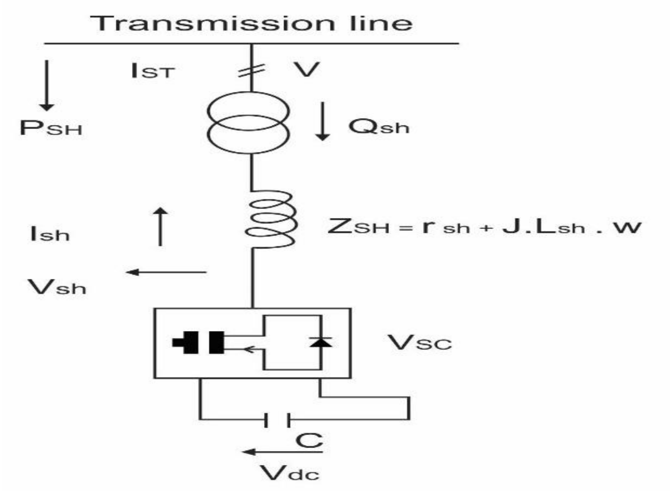

Figure 3: The STATCOM model

Therefore, the interchange of active and reactive power by the STATCOM with the transmission line can be expressed as in Equations (16) and (17). These models help understand the impact of STATCOM on minimising power losses on the case study transmission network.

$$P_{st} = U_i g_{sh} - U_i U_{st}[g_{sh}\, Cos\,(\delta_i - \delta_{st}) + B_{sh}\, Sin\,(\delta_i - \delta_{st})] \qquad (16)$$

$$Q_{st} = U_i b_{sh} - U_i U_{st}[g_{sh}\, Sin\,(\delta_i - \delta_{st})] \qquad (17)$$

where $Y_{sh} = \frac{1}{Z_{sh}} = g_{sh} + jb_{sh}$

Equations (16) and (17) are the power flow equations of power flow of the STATCOM that can be incorporated into PSAT.

3.5 Modelling of the Interline Power Flow Controller (IPFC)

The IPFC model was created through the use of mathematical models of the IPFC in Figures 4 and 5. Figure 4 is the injection model showing the intrinsic characteristics, and Figure 5 shows the equivalent circuit of the IPFC coupled to the transmission line.

The IPFC power injection model was incorporated into the PSAT power flow model for power losses minimisation analysis. The IPFC injection model equations for regulation of active and reactive power at the terminal of coupling to the transmission lines are as presented in Equations (18) to (21), from where V_{s1}, V_{s2} and V_{s3} are equal to V_i.

$$P_{in,n} = \sum_{n=j,k.l} V_i\, V_{sen}\, b_n\, \text{Sin}\,(\theta_i - \theta_{sen}) \qquad (18)$$

$$Q_{in,n} = -\sum_{n=j,k.l} V_i V_{sen}\, b_n\, \text{Cos}\,(\theta_i - \theta_{sen}) \qquad (19)$$

$$P_{in,n} = -\sum_{n=j,k.} V_i V_{sen}\, b_n\, \text{Sin}\,(\theta_i - \theta_{sen}) \qquad (20)$$

$$Q_{in,n} = \sum_{n=j,k} V_i V_{sen}\, b_n\, \text{Sin}\,(\theta_i - \theta_{sen}) \qquad (21)$$

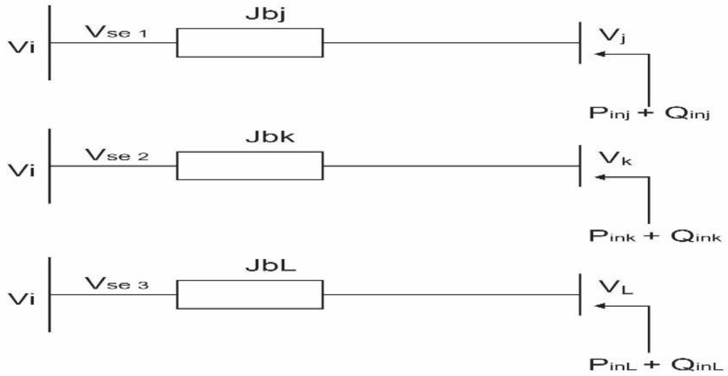

Figure 4: The Interline Power Flow Controller Power injection model

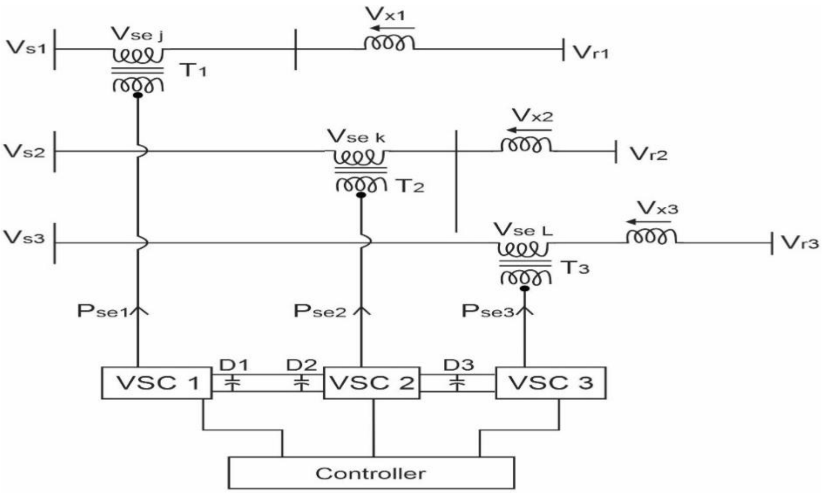

Figure 5: The Interline Power Flow Controller equivalent circuit model

3.6 Modelling of the Case Study 7-Bus Transmission Lines Network

The 7-bus transmission lines network developed from the Nigerian 330 kV power transmission lines network was modelled on PSAT in MATLAB/SIMULINK, as presented in Figures 6, 7, and 8. The data on the buses and transmission lines used are shown in Tables 1 and 2.

Figure 6 is the 7-Bus transmission lines network model without STATCOM and IPFC, while Figure 7 is the 7-bus transmission lines network with STATCOM, and Figure 8 is the 7-bus transmission lines network with IPFC.

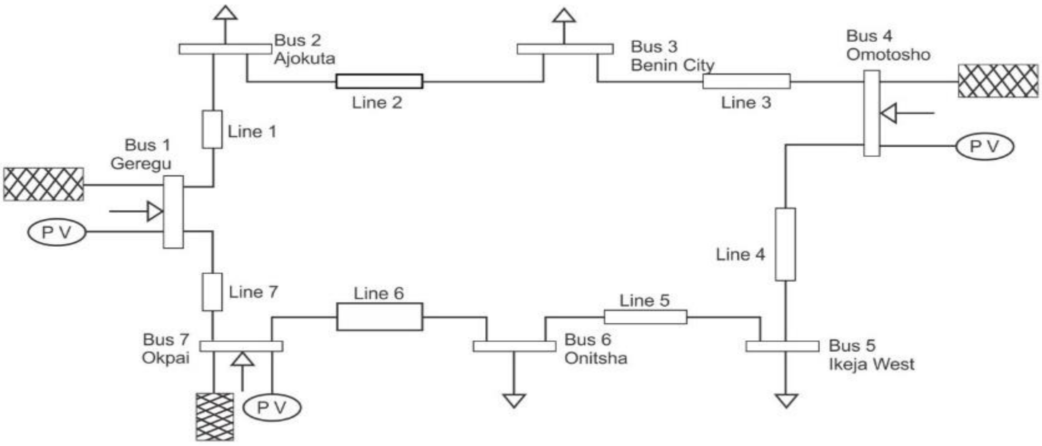

Figure 6: The 7-Bus transmission lines Network without STATCOM and IPFC

Figure 6 shows the 7-bus transmission lines model having the following buses in the network: Geregu (Bus 1), Ajaokuta (Bus 2), Benin (Bus 3), Omotosho (Bus 4), Ikeja West (Bus5), Onitsha (Bus 6) and Okpai (Bus 7).

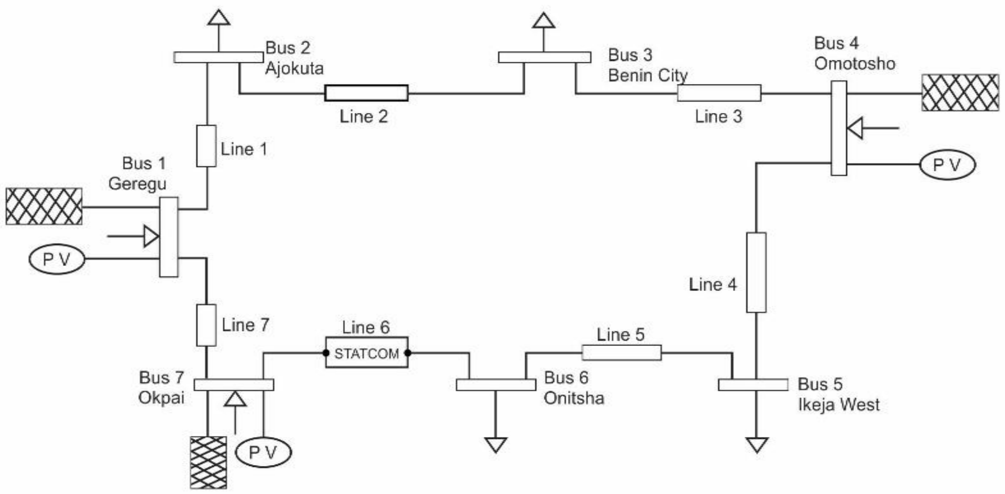

Figure 7: The 7-Bus transmission lines Network with STATCOM

Figure 7 shows that STATCOM was incorporated in the 7-bus transmission lines network between bus Okpai and Onitsha.

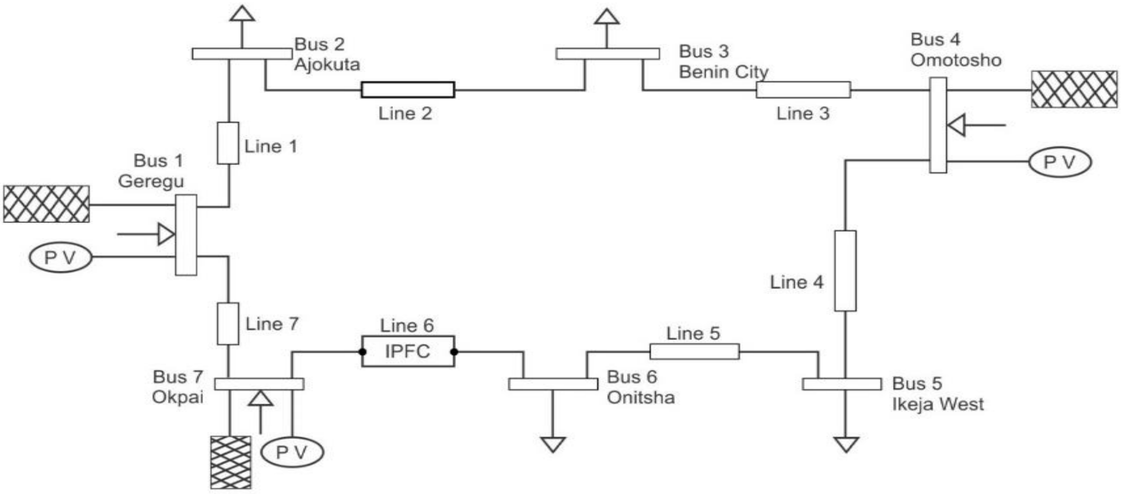

Figure 8: The 7-Bus transmission lines Network with IPFC

Figure 8 shows that the IPFC was also incorporated in the 7-bus transmission lines network between bus Okpai and bus Onitsha.

3.7 Simulation and Optimisation of the Case Study 7-bus Transmission Lines Network

The 7-bus transmission lines network shown in Figures 6 to 8 were modelled and simulated on PSAT in MATLAB/ SIMULINK. Newton-Raphson algorithm optimised the transmission network without STATCOM and IPFC and with STATCOM and IPFC. The results were obtained and recorded for comparative analysis.

The transmission lines started from Geregu generation station to Ajaokuta, then to Benin City, Omotosho, Ikeja West, Onitsha and finally to Okpai injection station.

3.8 Optimisation using Newton-Raphson Algorithm

The optimisation of the 7-bus transmission lines network under study was done using the Newton-Raphson algorithm on PSAT in MATLAB/ SIMULINK environment. The Jacobian matrix J of Equation (22) was used to apply the Newton-Raphson algorithm.

$$\mathrm{J} = \begin{bmatrix} \frac{\partial fP}{\partial V} & \frac{\partial fP}{\partial \theta} \\ \frac{\partial fQ}{\partial V} & \frac{\partial fP}{\partial \theta} \end{bmatrix} \qquad (22)$$

For an N–bus transmission lines network that contains M-VSCs, the load flow equation of Equation (22) must be expanded by 2M equations to derive Equation (23).

$$\begin{bmatrix} fP\ (v) = P \\ fQ\ (v) = Q \\ fVSC\ (v) = R \end{bmatrix} \qquad (23)$$

Where $v = [V^T \theta^T V_M{}^T\ \alpha^T]^T = [V_1 \dots V_N, \theta_1, \dots \theta_N, V_{m1} \dots V_{mM}, \alpha 1 \dots \alpha_M\ ]^T$ is a $2[N+M] - N_g - 1$ vector variable of bus voltage magnitude and angles and the 3rd-row function in Equation in (23) is determined by the VSCs operating modes, where R is a vector of the VSC-based controller set points or reference values.

To apply the Newton-Raphson algorithm to Equation (22), the Jacobian matrix will be modified to become:

$$^{*}\mathrm{J} = \begin{bmatrix} \frac{\partial f_p}{\partial V} & \frac{\partial f_p}{\partial \theta} & \frac{\partial f_p}{\partial V_m} & \frac{\partial f_p}{\partial \alpha} \\ \frac{\partial f_Q}{\partial V} & \frac{\partial f_Q}{\partial Q} & \frac{\partial f_Q}{\partial V_m} & \frac{\partial f_Q}{\partial \alpha} \\ \frac{\partial f_{VSC}}{\partial V} & \frac{\partial f_{VSC}}{\partial \theta} & \frac{\partial f_{VSC}}{\partial V_m} & \frac{\partial f_{VSC}}{\partial \alpha} \end{bmatrix} \qquad (24)$$

The first 2×2 terms in matrix *j are identical to the Jacobian matrix J in Equation (22), but the additional terms are due to the shunt and series VSCs transformer reactance and injection terms. Only the factors constituting the 3rd term of Equation (24) need to be modified to implement different control modes of an IPFC and STATCOM, which means that only the last row of the Jacobian matrix *J was modified before incorporation into the PSAT model for simulation and optimisation of the 7-bus transmission network case study.

3.9 Case Studies

This research used three case study scenarios on the 7-bus transmission lines network shown in Figures 6 to 8 to implement its objectives without STATCOM, IPFC, and with STATCOM and IPFC. The data used in this research are expressed per unit and are presented in Tables 1 and 2. The seven-bus network is comprised of three generation buses and four load buses, supplying seven transmission lines (L1, L2, L3, L4, L5, L6, and L7). The base power used was 1000MVA base power and a 330 kV base voltage.

Case A: In this first case, the 7-bus transmission lines network was simulated without inserting the STATCOM and IPFC devices, as indicated in Figure 6. The results obtained were recorded.

Case B: In this second case, the 7-bus transmission lines network was simulated after STATCOM was inserted between Onitsha and Okpai buses, as shown in Figure 7. The results obtained in this case were recorded. The voltage of bus 1 (Geregu) was set to 1.00 p.u. at 0^o phase angle.

Case C: In this third case, the 7-bus transmission lines network was simulated after IPFC was inserted between Onitsha and Okpai buses, as shown in Figure 8. The results obtained were recorded.

3.10 Identification of the 7-Bus Transmission Lines Network Case Study

The following are identification of the seven buses used in this research:

Bus 1 = (generation (Slack) bus) - Geregu
Bus 2 = (Load bus) - Ajaokuta
Bus 3 = (Load bus) - Benin City
Bus 4 = (generation bus) - Omotosho
Bus 5 = (Load bus) - Ikeja West
Bus 6 = (Load) - Onitsha
Bus 7 = (Gen) - Okpai

4.0 Discussion of Result

The results obtained from the simulation and optimisation of the three case study scenarios of this research are as follows:

4.1 Case A: Without STATCOM and IPFC

The optimised simulation results for the 7-bus transmission lines network without insertion of STATCOM and IPFC FACTS devices are shown in Tables 3 and 4.

Table 3: Power flow analysis of transmission lines without STATCOM and IPFC

Sending End Bus	Receiving End Bus	Line No.	P Flow (pu)	Q Flow (pu)	P Loss (pu)	Q Loss (pu)
Geregu	Ajaokuta	1	0.9106	0.1100	0.0350	0.6510
Ajaokuta	Benin	2	0.7420	0.1481	0.0438	0.4216
Benin City	Omotosho	3	0.5760	0.2140	0.0301	0.2900
Omotosho	Ikeja West	4	0.9414	0.0110	0.0460	0.5010
Ikeja West	Onitsha	5	0.3107	0.1300	0.0640	0.3317
Onitsha	Okpai	6	0.8161	0.1219	0.0810	0.8200
Okpai	Geregu	7	06221	0.2034	0.0186	0.1505

Table 4: Power flow analysis of buses without STATCOM and IPFC

Buses	Bus Voltage (pu)	Bus No.	P Flow (pu)	Q Flow (pu)	P Loss (pu)	Q Loss (pu)
Geregu (Gen)	1.0000	1	0.9106	0.1100	0.0350	0.6617
Ajaokuta (Load)	0.9400	2	0.7420	0.1481	0.0438	0.4236
Benin City (Load)	0.9500	3	0.5760	0.2140	0.0301	0.2903
Omotosho (Gen)	1.0000	4	0.9414	0.0110	0.0461	0.5023
Ikeja West (Load)	0.9600	5	0.3107	0.1300	0.0642	0.3217
Onitsha (Load)	0.9500	6	0.8161	0.1219	0.0806	0.8208
Okpai (Gen)	1.0300	7	0.6221	0.2034	0.0184	0.1506

Table 3 presents the power flow analysis of the transmission lines without STATCOM and IPFC, whereas Table 4 shows the power flow analysis of the buses without STATCOM and IPFC. The power flow analysis showed that Bus 6, located at Onitsha, had the highest power losses with a value of 0.00806 p.u, whereas bus 7 located at Okpai, had the least active power losses of 0.00154 p.u. These results indicated that the STATCOM and IPFC devices be inserted between bus 6 at Onitsha and bus 7 at Okpai. Likewise, the highest and lowest reactive power losses also occurred on the same buses. Figures 9 and 10 show the active and reactive power loss plots without STATCOM and IPFC devices.

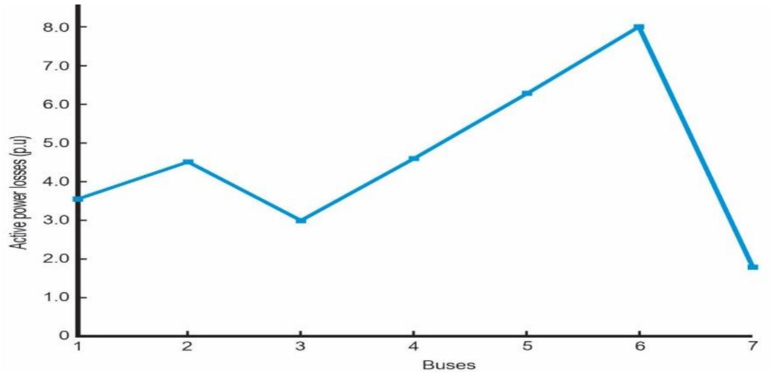

Figure 9: Plot of Active power losses without STATCOM and IPFC

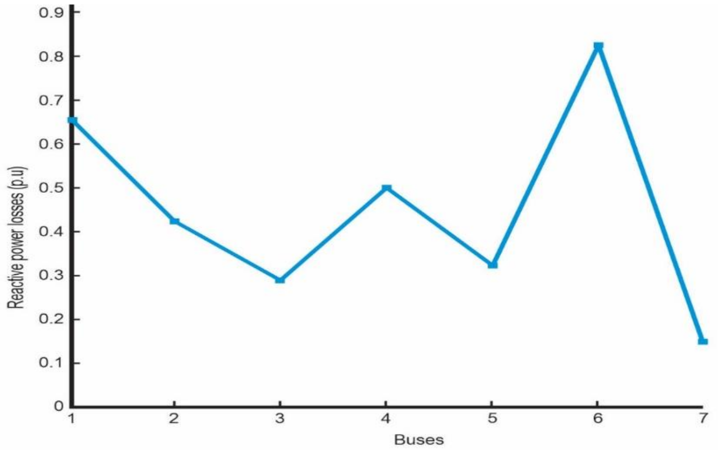

Figure 10: Plot of reactive power losses without STATCOM and IPFC

Figure 9 shows the plots of active power losses against the seven buses. Bus 6 located at Onitsha, had the highest power losses with a value of 0.0806 p.u, whereas bus 7 located at Okpai, had the least active power losses of 0.0154 p.u. These results indicated why STATCOM and IPFC FACTS devices were inserted between bus 6 at Onitsha and bus 7 at Okpai. Figure 4.2 shows the plot of the reactive power losses against the buses. Bus 6 at Onitsha had the highest reactive power loss of 0.8208 p.u, whereas bus 7 at Okpai had the least reactive power loss value of 0.1506 p.u. The total power losses without STATCOM and IPFC were Active Power Losses (P Losses) = 0.2935 p.u and Reactive Power Losses (Q Losses) = 3.1710 p.u.

4.2 Case B: With STATCOM

With the insertion of STATCOM FACTS device into the 7-bus transmission lines network modelled in PSAT, the simulation results obtained are presented in Table 5.

Table 5: Power flow analysis of buses with Static Synchronous Shunt Controllers (STATCOM)

Buses	Bus Voltage (pu)	Bus No.	P Flow (pu)	Q Flow (pu)	P Loss (pu)	Q Loss (pu)
Geregu (Gen)	1.0000	1	0.5189	0.1000	0.0300	0.4019
Ajaokuta (Load)	0.9800	2	0.4123	0.1098	0.0351	0.3096
Benin City (Load)	0.9850	3	0.5560	0.0067	0.0200	0.2001
Omotosho (Gen)	1.0000	4	0.6980	0.0563	0.0400	0.3017
Ikeja West (Load)	1.0000	5	0.4450	0.1100	0.0261	0.1506
Onitsha (Load)	1.0200	6	0.9231	0.1200	0.0264	0.2510
Okpai (Gen)	1.0100	7	0.7541	0.2012	0.0100	0.0847

Table 5 shows the simulation results after STATCOM was inserted in the power transmission lines network at bus 6 at Onitsha and bus 7 at Okpai. The results indicate that STATCOM affected the power losses of the transmission lines and buses. The total power losses reduced from 0.2935 + j 3.1710 p.u. to 0.1906 + j 1.6896 p.u. STATCOM also improved the bus voltages to 56 %. The bus voltages operated within the 1.0 ±6% p.u acceptable deviation range.

Figures 11 and 12 show the plots of active and reactive power losses with the STATCOM device inserted into the transmission lines network used in this research, respectively. The STATCOM FACTS device was inserted between bus 6, located at Onitsha, and Bus 7, situated at Okpai.

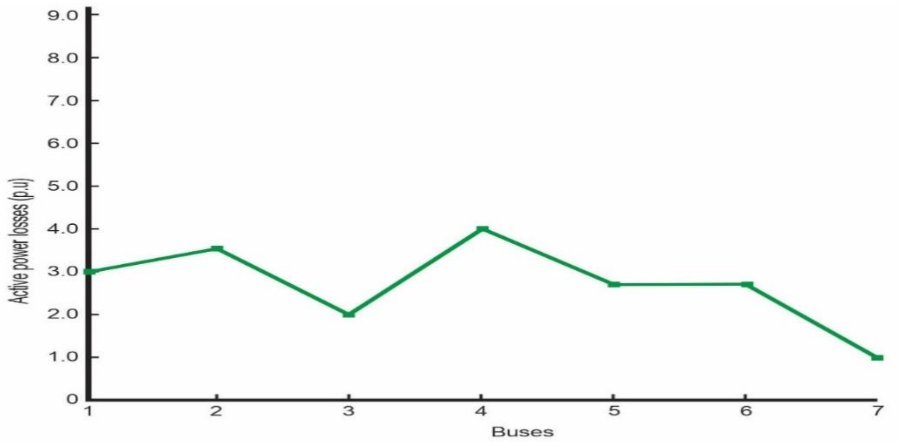

Figure 11: Plot of active power losses with STATCOM FACTS device

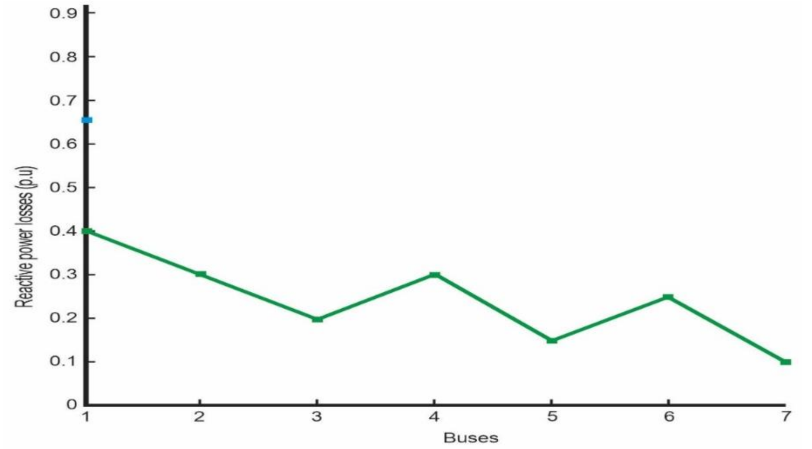

Figure 12: Plot of reactive power losses with STATCOM FACTS device

4.3 Case C: With IPFC

The simulation results obtained from the 7-bus transmission lines network modelled in PSAT after the insertion of IPFC between bus 6 located at Onitsha, and bus 7 located at Okpai, are tabulated in Table 6.

Table 6: Power flow analysis of buses with Interline Power Flow Controllers (IPFC)

Buses	Bus Voltage (pu)	Bus No.	P Flow (pu)	Q Flow (pu)	P Loss (pu)	Q Loss (pu)
Geregu (Gen)	1.0000	1	0.1009	0.2100	0.0101	0.2043
Ajaokuta (Load)	1.0000	2	0.4310	0.1001	0.0158	0.1503
Benin City (Load)	1.0000	3	0.2309	0.0100	0.0134	0.1017
Omotosho (Gen)	1.0000	4	0.1000	0.0547	0.0203	0.1042
Ikeja West (Load)	1.0000	5	0.1098	0.1230	0.0183	0.0501
Onitsha (Load)	1.0000	6	0.1001	0.0091	0.0180	0.0101
Okpai (Gen)	1.0000	7	0.2007	0.0176	0.0083	0.0096

Table 6 shows the bus voltages and the power losses of the seven buses. The active and reactive power losses were minimised from (0.2935 p.u + j3.1710 p.u) to (0.1137 p.u + j 1.6896 p.u.) This indicated that when the IPFC was inserted into the transmission lines network, the total power losses were minimised to about 90%, and the bus voltages improved by 100%. The bus voltages were improved to 1.00p.u.

Figures 13 and 14 show the plots of active and reactive power losses with the IPFC FACTS device inserted into the 7-bus transmission lines network used in this research, respectively. The IPFC FACTS device was inserted between bus 6 at Onitsha and bus 7 at Okpai.

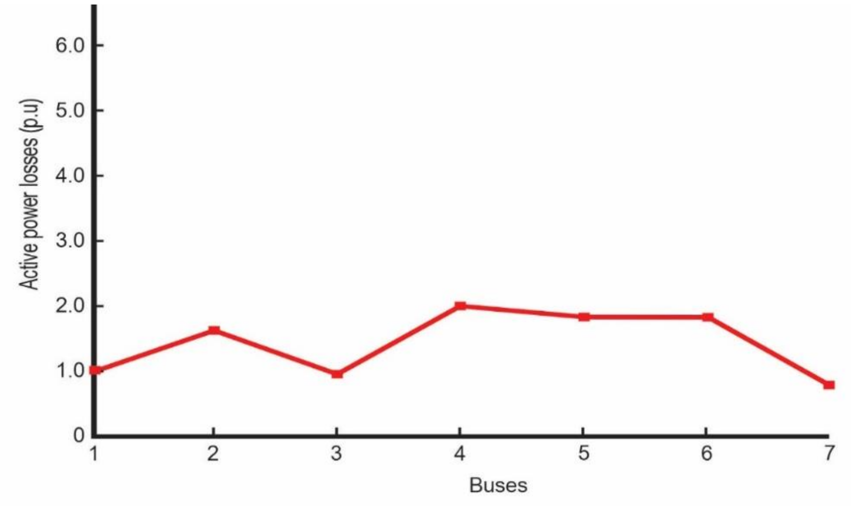

Figure 13: Plot of active power losses with IPFC FACTS device.

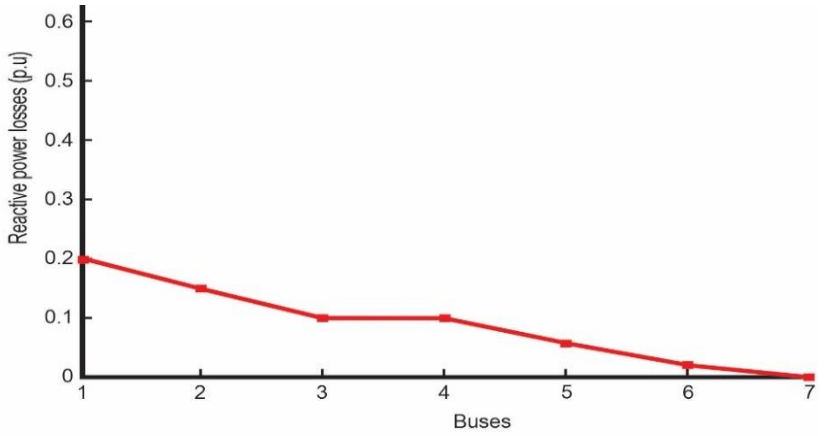

Figure 14: Plot of reactive power losses with IPFC FACTS device

4.4 The Combined Simulation Results of Power Losses without and with STATCOM and IPFC FACTS Devices

The combined results obtained for the 7-bus transmission lines network without and with STATCOM and IPFC FACTS devices are shown in Tables 7 and 8. Table 7 shows the total power losses of the 7-bus transmission lines network. Table 8 shows the bus voltages without and with the incorporation of STATCOM and IPFC FACTS devices in the 7-bus transmission network. Figures 15 and 16 show the combined plots of active and reactive power losses without and with STATCOM and IPFC FACTS devices, respectively.

Table 7: Bus Power Losses without and with STATCOM and IPFC Devices

Bus Name	Bus No.	Power Losses (P loss + Q loss) in pu		
		Without STATCOM / IPFC	**With STATCOM**	**With IPFC**
Geregu (Gen)	1	0.0310 + j 0.6617	0.0300 + j 0.4219	0.0101 + j 0.2443
Ajaokuta (Load)	2	0.0418 + j 0.4236	0.0351 + j 0.3096	0.0158 + j 0.1503
Benin City (Load)	3	0.0204 + j 0.2903	0.0241 + j 0.1701	0.0134 + j 0.1017
Omotosho (Gen)	4	0.0411 + j 0.5023	0.0400 + j 0.3017	0.0183 + j 0.1042
Ikeja West (Load)	5	0.0632 + j 0.3217	0.0201 + j 0.1506	0.0257 + j 0.0501
Onitsha (Load)	6	0.0806 + j 0.8208	0.0264 + j 0.2510	0.0221 + j 0.0101
Okpai (Gen)	7	0.0154 + j 0.1506	0.0138 + j 0.0847	0.0083 + j 0.1566
Total Power Losses		**0.2935 + j 3.1710**	**0.1906 + j 1.6896**	**0.1137 + j 0.7713**

Table 8: Bus voltages of the transmission network without and with STATCOM and IPFC FACTS devices

Bus Name	Bus No.	Voltage Magnitude in pu		
		Without STATCOM/IPFC	**With STATCOM**	**With IPFC**
Geregu (Gen)	1	1.0000	1.0000	1.0000
Ajaokuta (Load)	2	0.9400	0.9800	1.0000
Benin City (Load)	3	0.9500	0.9850	1.0000
Omotosho (Gen)	4	1.0000	1.0000	1.0000
Ikeja West (Load)	5	0.9600	1.0000	1.0000
Onitsha (Load)	6	0.9500	1.0200	1.0000
Okpai (Gen)	7	1.0300	1.0100	1.0000

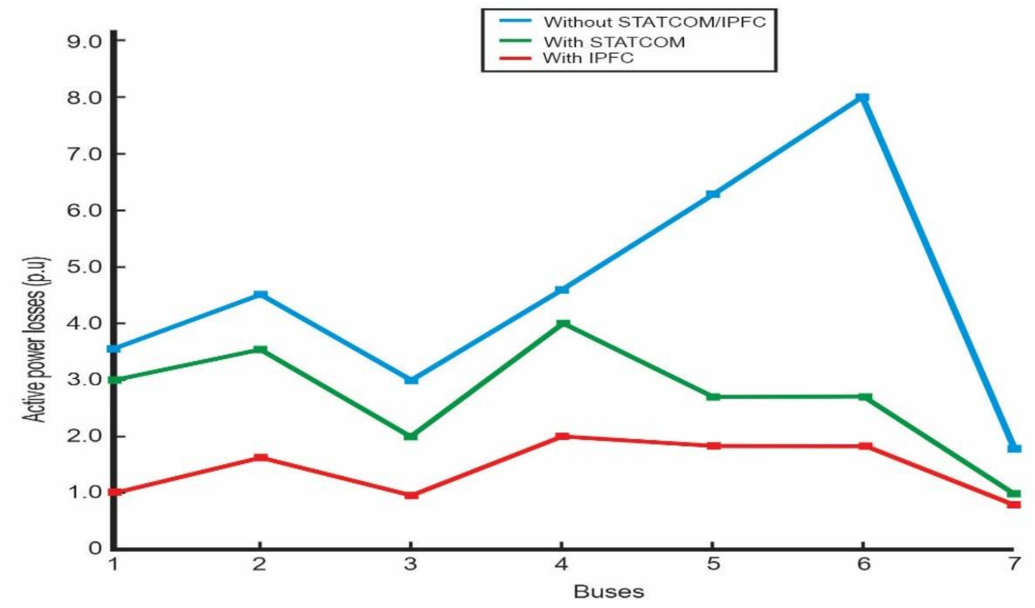

Figure 15: Combined plot of active power losses without and with FACTS devices

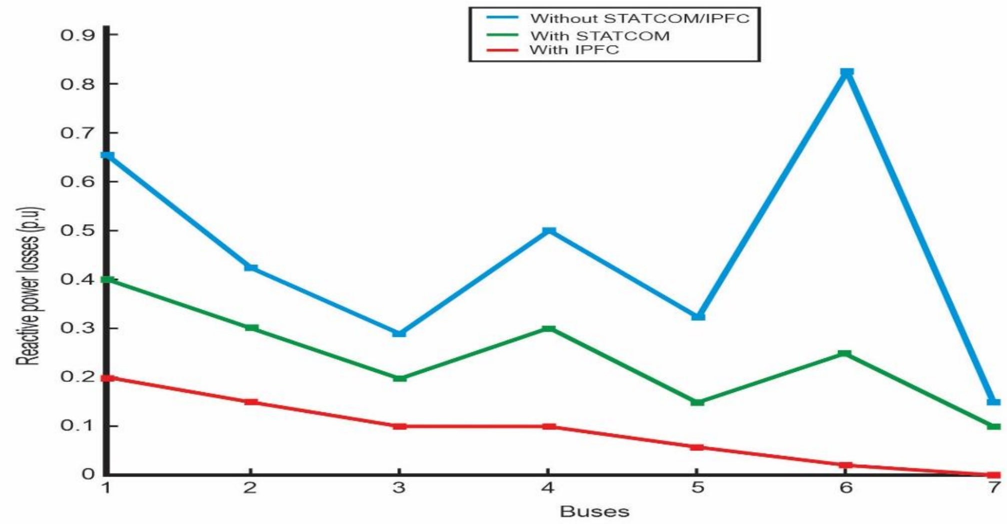

Figure 16: Combined plot of reactive power losses without and with FACTS devices

The results obtained from the simulation of the seven-bus transmission lines network used for this research without inserting the STATCOM and IPFC FACT device showed that the power losses experienced by the seven buses were significant. When the STATCOM FACTS device was inserted into the transmission network, the power losses were reduced significantly. Still, with the insertion of the IPFC FACTS device, the power losses for both active and reactive power were reduced to the minimum. The results in Table 8 clearly show these observations. The results also highlighted that without STATCOM and IPFC FACTS devices inserted into the 7-bus transmission lines network, buses 2, 3, 5and 6 had voltage fluctuations below unity. In contrast, bus 7 voltage fluctuates above unity. With the insertion of STATCOM FACTS, the voltages of the buses improved, and when the IPFC FACTS device was inserted, the voltages of the buses improved to unity, as shown in Table 8.

Without the STATCOM and IPFC inserted into the 7-bus transmission lines network, it was observed that the total power losses of the seven buses for both active and reactive power were $0.2935 + J\,3.1710$, as presented in Table 8. With the insertion of the STATCOM FACTS device in the 7-bus transmission lines network, power losses were optimised on all seven buses and reduced to $0.1906 + j\,1.6890$. With the insertion of IPFC in the 7-bus transmission lines network, the power losses of the network were further reduced to $0.1137 + j\,0.7713$. The overall power loss optimisation of the busses was about 80% since power losses were reduced to a very minimal value.

Comparing the results of this research with the results obtained by [13] showed that only six out of the ten buses used for the study had their power losses minimised and reduced to about 60% performance improvement.

IV. CONCLUSION

In this research, the minimisation of power losses on the 330 kV Nigerian transmission lines using Static Synchronous Shunt Compensator (STATCOM) and Interline Power Flow Controller (IPFC) was painstakingly done. This research examined the effects of STATCOM and IPFC on bus voltages and transmission line power losses using a seven-bus transmission network with seven transmission lines as a case study. The seven buses are located in Geregu, Ajaokuta, Benin City, Omotosho, Ikeja West, Onitsha, and Okpai. The 7-bus transmission lines network was modelled without and with STATCOM and IPFC. Data for the seven buses and the seven transmission lines were TCN operational data. A PSAT simulation environment in MATLAB/SIMULINK was used to simulate the developed models. Newton-Raphson algorithm was employed to perform the optimisation without and with STATCOM and IPFC incorporated in the 7-bus transmission lines network. The results obtained showed that with the incorporation of IPFC into the network, power losses were reduced to (0.1137 + j 0.7713), indicating 80% optimisation, and the bus voltages in all the seven buses were improved to unity without deviation from the acceptable voltage deviation range of V = 1.0±6% p.u; which represents a 100 % improvement in the bus voltages.

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