Optimization Of Power Losses And Voltages On Transmission Lines Using Fact-Device Technique

Udoetuk, Anietie Ita[1]
Department of Electrical/Electronic and Computer Engineering, University of Uyo, AkwaIbom, Nigeria

Okpura I. Nseobong[2]
Department of Electrical/Electronic and Computer Engineering, University of Uyo, AkwaIbom, Nigeria
okpuranseobong@yahoo.com

Njoku Felix Anayo[3]
Department of Electrical/Electronic and Computer Engineering,
University of Uyo, AkwaIbom, Nigeria

***Abstract*— This paper presented a study on the impact of unified power flow controller (UPFC) in the Nigeria 330kv integrated power network based on five (5) selected Southern States of Nigeria which included Abia, Akwa-Ibom, Cross-Rivers, Rivers and Imo states. The bus was at Akwa-Ibom State with five transmission lines. A Matlab program incorporating UPFC in Newton-Raphson power flow algorithm was developed. The results showed that the power flow study without flexible alternating current transmission systems (FACTS) devices had a total real and reactive power losses of 163.25MW and 128.900Mvar respectively. However with the introduction of the unified power flow controllers in the weak buses, it gave the real and reactive power losses to be 72.7517MW and 3.8630Mvar. The new bus voltage values obtained were all 1pu for each State except Akwa-Ibom State that gave 0.9702pu. Accordingly, UPFC saved (90.502MW to 125.03Mvar) power for the network.**

Keywords—Flexible Alternating Current Transmission Systems Device, Power Losses, Transmission Lines, Unified Power Flow Controller, Integrated Power Network, Newton-Raphson Method, Power Flow Program

I. INTRODUCTION

Over the years, power systems experts have been having running challenges of addressing the problems of power losses and voltage instabilities on power transmission lines [1,2,3,4,5]. In response, various strategies and particularly power electronic devices like the flexible alternating current transmission systems (FACTS) controllers have been developed to tackle such problems [6,7,8,9,10]. Among the various FACTS devices, the unified power flow controller (UPFC) has been identified as the most versatile as it has proven to be very flexible and it can simultaneously control the power system line active power, reactive power and node voltages [11,12,13,14,15].

The applicability of the UPFC device is contingent upon the proper understanding of the underlying mathematical models that are based on its operating principles and which also demonstrated how it can be incorporated into the existing power flow analysis. Consequently, in this paper, the key mathematical models that are used to describe the operation of the UPFC in a power system are presented and applied to a case study power line in Nigeria. The focus in this paper is to apply the UPFC in the selected case study power lines in the five Southern states of Nigeria and then use appropriate Mathlab program simulation to determine the power loss and voltage stability, with and without the UPFC. The essence of the study is to demonstrate the ability of the UPFC device in minimizing the power system losses and also ensure voltage stability in the case study power lines.

II. METHODOLOGY

In this paper, a study is carried out to determine the extent at which Unified Power Flow Controller (UPFC) reduces power losses in a grid generation buses. The methodology employed in the study is shown in Figure 1.

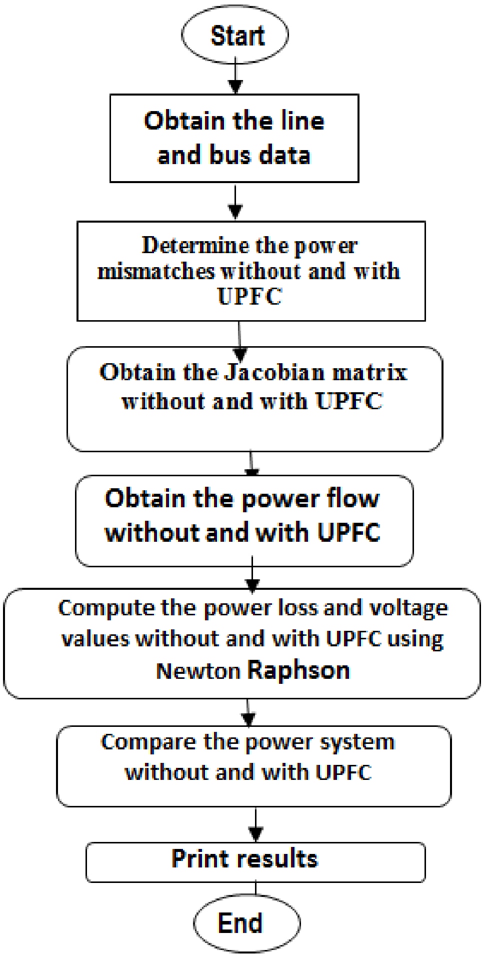

Figure 1: The methodology employed in the study

A. The Case Study Line And Bus Data

The cases study consists of the 330kV grid generation buses within five Southern States of Nigeria, as shown in Figure 2. From Figure 2, the five Southern States comprises of AkwaIbom, Cross-River, Abia, Rivers and Imo State. The insertion of the UPFC device is at a point between AkwaIbom and Abia States. The total capacity of the buses are shown in Table 1, the line data are shown in Table 2 and the bus voltages with their respective angles are shown in Table 3 respectively.

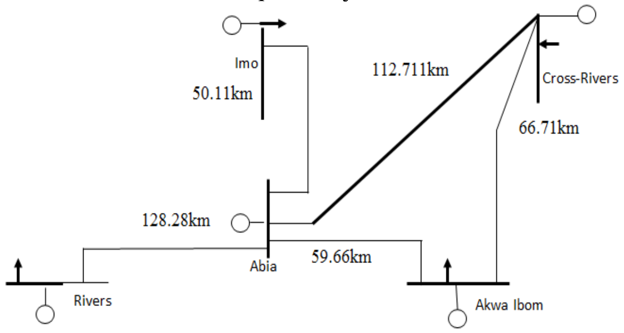

Figure 2 The selected 330kV grid generation buses within five Southern States of Nigeria

Table 1: Bus data

S/N	State	Total Capacity (MW)	Real Power Allocation (MW)	Reactive Power Allocation (MVar)
1	Abia	2404	820.42	328
2	AkwaIbom	1790	1134.87	458
3	Rivers	3924	1501.13	600
4	Cross-Rivers	1705	836.33	335
5	Imo	1425	1139.12	456

SOURCE: PHCN Port Harcourt 330kV Transmission Lines Data Sheet 2011.

Table 2: Line data

S/N	From Bus	To Bus	Length (km)	Impedance Z (PU)	B	Admittance (PU)
1	Cross-River	AkwaIbom	66.71	0.0126+j0.0139	0.208	6.494-j3.891
2	Abia	AkwaIbom	56.66	0.0155+j0.0172	0.257	6.494-j9.615
3	Rivers	Abia	128.28	0.009+j0.007	0.104	9.615+j16.129
4	Cross-River	Abia	112.71	0.0126+j0.0139	0.208	8-j4.808
5	Abia	Imo	50.11	0.006+j0.007	0.308	6.494+j3.891

Source: PHCN Port Harcourt 330kV Transmission Lines Data Sheet 2011

Table 3: Buses Voltages and Phase Angles for the Integrated 330kV Power system

Bus Number	Bus name	Voltage (PU)	Voltage (kV)	Angle (Degrees)
1	Rivers	1.041	343.53,	-18.23
2	AkwaIbom	1.024	337.92,	-23.17
3	Abia	1.034	341.22,	-12.43
4	Imo	1.023	337.59,	-9.21
5	Cross-River	1.035	341.55,	12.23

Source: PHCN Port Harcourt 330kV Transmission Lines Data Sheet 2011.

B. Modeling Of The Power System Without Facts Devices

The bus nodal point current (I_B), voltage (U_B) and Y_B admittance are related as follows ;

$$I_B = Y_B U_B \qquad (1)$$

The expression can be extended to matrix form as;

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ --- \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & --- & Y_{1n} \\ Y_{21} & Y_{22} & Y_{23} & --- & Y_{2n} \\ Y_{31} & Y_{32} & Y_{33} & --- & Y_{3n} \\ \vdots & \vdots & \vdots & \ddots & \\ Y_{n1} & Y_{n2} & Y_{n3} & --- & Y_{nn} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ --- \\ U_n \end{bmatrix} \qquad (2)$$

Where Y_{ij} is the admittance and I and U are the current and voltage at the nodal points. Once Y_{ij} is verified, the power flow can be calculated. Normally, I and U are unknown but S (complex power) is known, so the voltage equation can be transformed to;

$$Y * U = \left[\frac{S}{U}\right]^* \qquad (3)$$

Where the complex power, denoted as S is given as:

$$S^* = Y * U\,(U) \qquad (4)$$

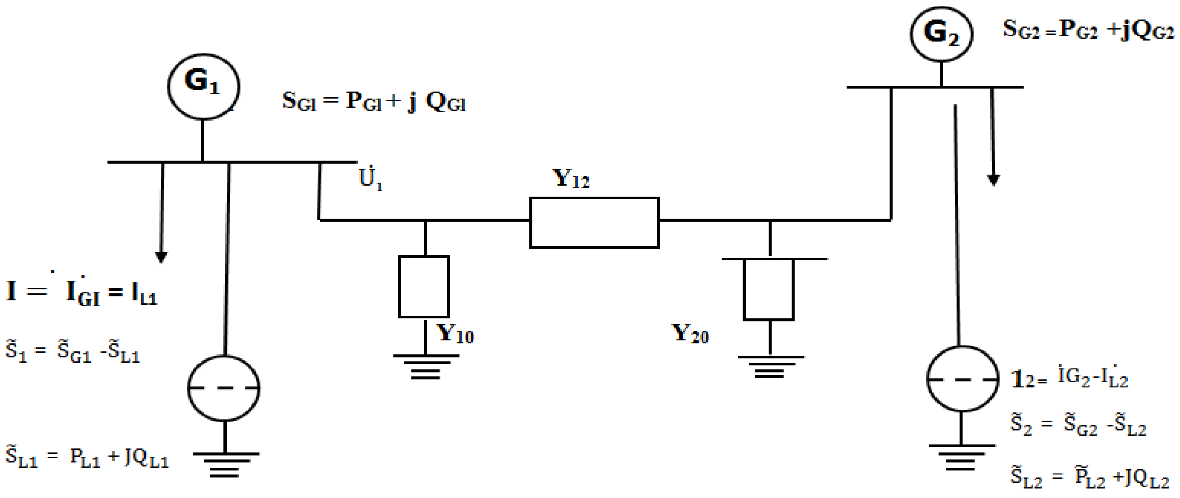

Figure 3 The equivalent circuit using admittance matrix model of the two bus transmission system

The equivalent circuit using admittance matrix model of the two bus transmission system is shown in Figure 3 where S_{G1} and S_{G2} arepower source from generator 1 and 2 respectively; S_{L1} and S_{L2} are the power at the loads ; S_1 and S_2 are the injecting power at the nodes 1 and 2. Then;

$$I_1 = Y_{11}\dot{U}_I + Y_{12}\dot{U}_2 = \left(\frac{\dot{S}_I}{\dot{U}_I}\right) \qquad (4)$$

$$\dot{I}_2 = Y_{21}\dot{U}_I + Y_{22}\dot{U}_2 = \left(\frac{\dot{S}_2}{\dot{U}_2}\right) \qquad (5)$$

$$S_1 = \dot{U}_I\dot{Y}_{11}(\dot{U}_I) + \dot{U}_1\dot{Y}_{12}(\dot{U}_2) \qquad (6)$$

$$S_2 = \dot{U}_2\dot{Y}_{21}(\dot{U}_2) + \dot{U}_2\dot{Y}_2 \qquad (7)$$

Let

$$Y_{11} = Y_{22} = y_{10} + y_{12} = y_{20} + y_{21} = y_{se^{-j(90-\alpha_s)}} \qquad (8)$$

$$Y_{12} = Y_{21} = -y_1 = -y_{21} = -y_{me^{-j(90-\alpha_m)}} \qquad (9)$$

$$\dot{U}_I = \dot{U}_I e^{j\delta 1}\dot{U}_2 = \dot{U}_2 e^{\delta 2} \qquad (10)$$

Then, the active power and reactive power is given as;

$$\begin{Bmatrix} P_I = P_{G1} - P_{LI} = y_s U_1^2 \sin\alpha_s + y_m U_I U_2 \sin[(\delta_1 - \delta_2)] - \alpha_m \\ P_2 = P_{G2} - P_{L2} = y_s U_2^2 \sin\alpha_s + y_m U_2 U_1 \sin[(\delta_2 - \delta_1)] - \alpha_m \\ Q_I = Q_{G1} - Q_{LI} = y_s U_2^2 \cos\alpha_s - y_m U_I U_2 \cos[(\delta_1 - \delta_2)] - \alpha_m \\ Q_2 = Q_{G2} - Q_{L2} = y_s U_2^2 \cos\alpha_s - y_m U_2 U_1 \cos[(\delta_2 - \delta_1)] - \alpha_m \end{Bmatrix} \qquad (11)$$

By applying Newton-Raphson optimization of reactive power and solving the resulting equations gives the expressions for computing the equilibrium point power, the line power Ss, Sij and Sji and the power loss ΔSij, as follows;

$$S_s = \dot{U}_s \qquad (12)$$

$$\dot{Y}_{s1}\dot{U}_1 = P_s + Q_s \qquad (13)$$

$$S_{ij} = \dot{U}_1 I_{ij} = \dot{U}_1[\dot{U}_1 \dot{y}_{10} + (\dot{U}_1 - \dot{U}_j)\dot{y}_{1J}] = P_{ij} + j\,Q_{ij} \qquad (14)$$

$$S_{ij} = \dot{U}_J I_{ji} = \dot{U}_J[\dot{U}_J \dot{y}_{Jo} + (\dot{U}_J - \dot{U}_1)\dot{y}_{J1}] = P_{ji} + j\,Q_{ji} \qquad (15)$$

$$\Delta S_{ij} = S_{ij} + S_{ji} = \Delta P_{ij} + j\Delta Q_{ij} \qquad (16)$$

C. Modeling Of The Power Flow With UPFC

The Voltage Source Converter (VSC) does the main function of the UPFC. Line diagram of a series connected VSC is shown in Figure 4. The voltage of bus i is taken as reference vector, V_i where ;

$$V_i = V_i = <\theta_i \qquad (17)$$

$$\bar{V}_i = V_s + V_i \qquad (18)$$

The voltage source, V_s is controllable in both the magnitude and phase angle, where V_s is given as;

$$V_s = rV_i e^{JY} \qquad (19)$$

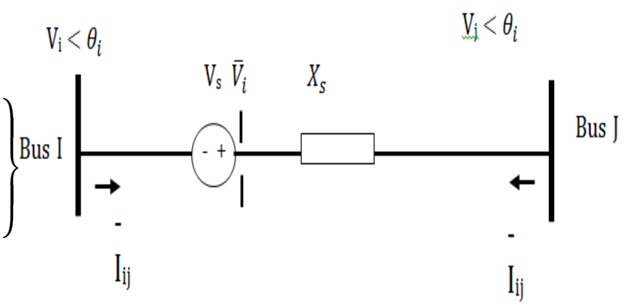

Figure 4 Representation of a series connected voltage source converter
(Source : [16])

The values of r and γ are defined within specified limits given as $0 \le r \le r_{max}$ a nd $0 < \gamma < 2\pi$

The steady-state UPFC mathematical model is developed by replacing voltage source, V_s by a current source, I_s parallel with the transmission line, where

$$b_s = \frac{1}{x_s} \quad (20)$$

$$I_s = -jb_sV_s \quad (21)$$

The current source, Is can be modeled by injection powers at the two auxiliary buses i and j as shown in Figure 4, where;

$$X_s = \frac{1}{bS} \quad (22)$$

Figure 5 shows the steady-state complete UPFC mathematical model.

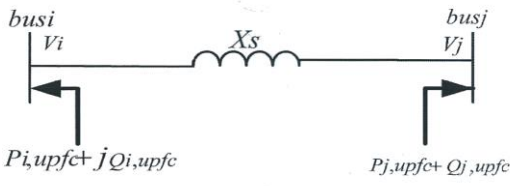

Figure 5 Steady-state complete UPFC mathematical model

(Source : [17, 18])

The steady-state UPFC mathematical model can be constructed by combining the series and shunt power injections at both bus 'i' and bus 'j' as shown in Figure 5, where the elements of the equivalent power injections in Figure 5 are given as follows;

$$P_{i,upfc} = rb_sV^2_i \sin \gamma - rb_sV_iV_j \sin(\theta_i - \theta_j + \gamma) \quad (23)$$

$$P_{j,upfc} = rb_sV_iV_j \sin(\theta_i - \theta_j + \gamma) \quad (24)$$

$$Q_{i,upfc} = -rb_sV^2_i \cos\gamma \quad (25)$$

$$Q_{i,upfc} = rb_sV_iV_j \cos(\theta_i - \theta_j + \gamma) \quad (26)$$

D. Incorporation Of The UPFC Injection Model In Load Flow Analysis

From the steady-state UPFC model, the general nodal power flow equations and the linearized power system model are expressed in rectangular form by the following equations;

$$P = f_1 (V, \theta, G, B) \quad (27)$$

$$Q = f_1 (V, \theta, G, B) \quad (28)$$

Where *P* and *Q* are the vectors of real and reactive nodal power injections, which are functions of nodal voltages, (V <θ), and network conductance and susceptance, (*G* and *B*), respectively. ($\Delta P = P_{spe} - P_{cal}$) is the real power mismatch vector and ($\Delta Q = Q_{spe} - Q_{cat}$) is the reactive power mismatch vector. (ΔV and $\Delta\theta$) are vectors of incremental changes in nodal voltages. H, N, J and L are denoting the basic elements in the Jacobian matrix. Table 4 shows the modification of the Jacobian matrix with UPFC. In Table 4 the superscript ° denotes the Jacobian elements without UPFC and the superscript upfcdenotes the Jacobian elements with UPFC.

Table 4: Modification of Jacobian matrix

$H_{(i,i)} = H^o_{(i,i)} + H_{ii}^{upfc}$ $H_{(i,j)} = H^o_{(i,j)} + H_{ij}^{upfc}$ $H_{(j,i)} = H^o_{(j,i)} + H_{ji}^{upfc}$ $H_{(j,j)} = H^o_{(j,j)} + H_{jj}^{upfc}$	$N_{(i,i)} = H^o_{(i,i)} + N_{ii}^{upfc}$ $N_{(i,j)} = H^o_{(i,j)} + N_{ij}^{upfc}$ $N_{(j,i)} = H^o_{(j,i)} + N_{ji}^{upfc}$ $N_{(j,j)} = H^o_{(j,j)} + N_{jj}^{upfc}$
$J_{(i,i)} = J^o_{(i,i)} + J_{ii}^{upfc}$ $J_{(i,j)} = J^o_{(i,j)} + J_{ij}^{upfc}$ $J_{(j,i)} = J^o_{(j,i)} + J_{ji}^{upfc}$ $J_{(j,j)} = J^o_{(j,j)} + J_{jj}^{upfc}$	$L_{(i,i)} = L^o_{(i,i)} + L_{ii}^{upfc}$ $L_{(i,j)} = L^o_{(i,j)} + L_{ij}^{upfc}$ $L_{(j,i)} = L^o_{(j,i)} + L_{ji}^{upfc}$ $L_{(j,j)} = L^o_{(j,j)} + L_{jj}^{upfc}$

(Source :[16])

The power flow equations with UPFC are given as follows;

$$P_i = \Sigma_j^n = i\,|Vi||Vj|Yij|\cos(\theta_{ij} - \theta_i + \theta_j) \quad (29)$$

$$Q_i = \Sigma_j^n = i\,|Vi|\,Vj|Yij|\sin(\theta_{ij} - \theta_i + \theta_j) \quad (30)$$

In all, when the UPFC is inserted between nodes i and j of the network, then it will cause the admittance matrix to be modified by adding reactance equivalent to Xs (as shown in Figure 5), between the bus i and bus j and this will cause the Jacobian matrix to be modified accordingly using the expressions specified in the Table 4. Then the load flow analysis is performed according to the Newton-Raphson method (as shown in Figure 1) is then performed to determine the effect of the UPFC on power loss minimization and on voltage stability.

III. RESULTS AND DISCUSSION

The system was simulated with MATLAB software using voltage of Akwa Ibom as the reference voltage at 330kV. The simulation was done with the UPFC device installed between bus 1 (Abia) and bus 2 (Akwa Ibom) as shown in Figure 1. The simulation was conducted with the bus and the line data in Table 1, Table 2 and Table 3. The simulations were carried out without the UPFC device and then, the simulations were repeated with the UPFC device.

A. Results Of The Analysis Of The Voltage With And Without The UPFC

The results of the bus voltages without the UPFC device and with the UPFC FACT device are shown in Table 5 and Figure 6. After simulating the system without using UPFC, the results show that the second bus (AkwaIbom) has the highest pu voltage because it is the reference voltage. Bus 1(Abia) has the least pu voltage. Apart from bus 2, the rest of the buses have very low voltages which will be fixed when the FACT device is installed. This also contributes to the low power transmission in the Southern part of the country. Also, according to Table 5 and Figure 6, with the UPFC all the buses have their voltage values normalized at 1pu except Akwa Ibom State that has its value at 0.9702pu. In order words, when the FACT device is installed between bus 1 (Abia) and bus 2 (Akwa Ibom), the voltage will operate at a reference voltage of 1pu (330kV).

Table 5: Bus Voltages without and With UPFC

Buses	Locations	Voltage (pu) (without UPFC)	Voltage (pu) with UPFC
1	Abia	0.0759	1.000
2	AkwaIbom	0.9967	0.9702
3	Rivers	0.1767	1.0000
4	Cross-Rivers	0.1826	1.0000
5	Imo	0.2068	1.0000

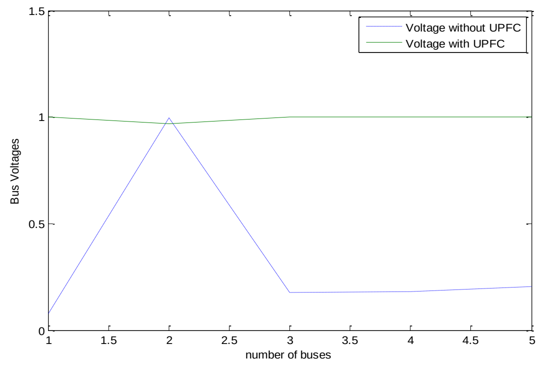

Figure 6: Graph of voltages without and with UPFC against the number of Buses

B. Results Of The Analysis Of Power Loss With And Without The UPFC

The results of the simulation with and without using the FACT device (UPFC) are given in Table 6 and Figure 7 , The results show that without using the FACT device the highest power loss on the transmission line is on line 3 (the transmission line connecting Rivers to Abia states) which has a power loss value of 75.6926MW. Furthermore, the results in Table 6 and Figure 7 show that the power loss of line 1, 3 and 4 were drastically minimized when the UPFC was introduced into the system. This confirms the fact that when a UPFC is inserted into the transmission lines, it normalizes the voltages of the buses and also minimizes the power losses of the transmission lines.

Table 6: Power Losses without and with UPFC devices

Transmission Lines	Locations	Power Loss (MW) Without UPFC	Power Loss (MW) With UPFC
1	Cross-River to Akwa-Ibom	30.9434 -25.9328i	12.7339 + 2.1972i
2	Abia to Akwa-Ibom	2.9319 - 3.1423i	33.9471 -28.1377i
3	Rivers to Abia	75.6926 -46.7766i	10.9375 +14.4078i
4	Imo to Rivers	52.1471 -51.8515i	7.1332 + 2.8616i
5	Abia to Imo	1.5389 - 1.1935i	8.0000 + 4.8080i

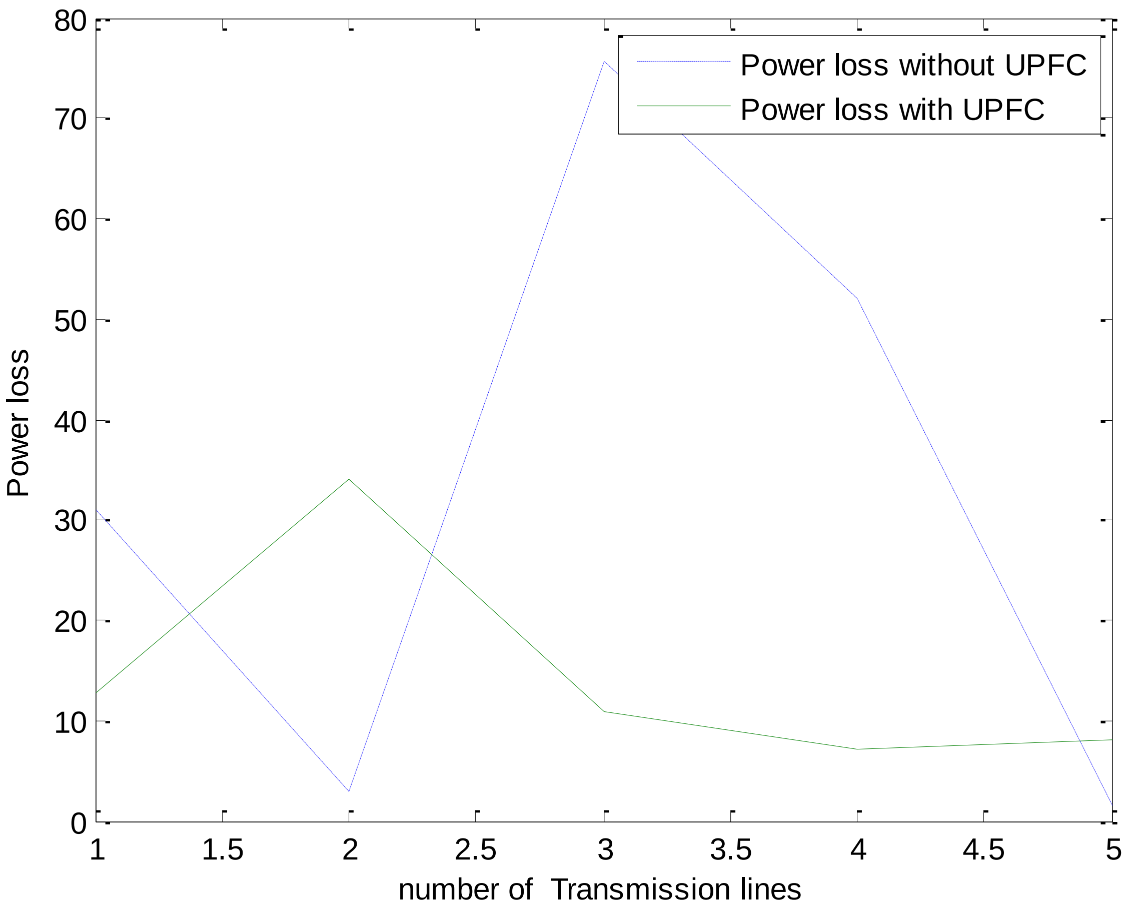

Figure 7: Graph of power losses without and with UPFC against the number of Buses.

IV CONCLUSION

This work investigated the optimization of power losses and voltages on transmission lines using FACTS-devices. Newton Raphson model was used to model the system with and without the FACTS-device. The power losses and voltages were optimized when FACTS-device was introduced into the buses and transmission lines MATLAB codes were generated and used for the simulations. Various results were found and presented in tables and graphs for both power losses and voltages on the power transmission lines. Five Sothern States in Nigeria 330kV transmission lines were considered in the case study. The voltage at Akwa Ibom State line was taken to be the reference voltage at 330kV. In all, the results show that the UPFC device is effective minimizing power losses in the buses and transmission lines within the States studied especially, if the FACT device is inserted between Cross-River and Akwa Ibom.

REFERENCES

1. Valverde, G., & Araya-Padilla, E. A. (2014). Long-term voltage stability assessment using Quasi-Steady State Simulation in Matlab. *Ciencia y Tecnología*, *30*(1), 11-27.
2. Ramakrishna, K., Revana, G., & Gopala, V. (2014). Reactive power loss control in power flow controller using Adaptive learning. *energy*, *2*(3).
3. Sullivan, D., Paserba, J., Reed, G., Croasdaile, T., Westover, R., Pape, R., ...& Kuroda, K. I. (2006, October). Voltage control in southwest utahwith the St. George static VAr system. In *2006 IEEE PES Power Systems Conference and Exposition* (pp. 459-465). IEEE.
4. Hasani, M., & Parniani, M. (2005). Method of combined static and dynamic analysis of voltage collapse in voltage stability assessment. In *2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific* (pp. 1-6). IEEE.
5. Li, Z., Guo, Q., Sun, H., Wang, J., Xu, Y., & Fan, M. (2018). A distributed transmission-distribution-coupled static voltage stability assessment method considering distributed generation. *IEEE Transactions on Power Systems*, *33*(3), 2621-2632.
6. Van Cutsem, T., Kabouris, J., Christoforidis, G., &Vournas, C. D. (2005). Application of real-time voltage security assessment to the Hellenic interconnected system. *IEE Proceedings-Generation, Transmission and Distribution*, *152*(1), 123-131.
7. Adamczyk, A., Teodorescu, R., Mukerjee, R. N., & Rodriguez, P. (2010, July). Overview of FACTS devices for wind power plants directly connected to the transmission network. In *2010 IEEE International Symposium on Industrial Electronics* (pp. 3742-3748). IEEE.
8. Mohanty, A. K., & Barik, A. K. (2011). Power system stability improvement using FACTS devices. *International Journal of Modern Engineering Research (IJMER)*, *1*(2), 666-672.
9. Eslami, M., Shareef, H., Mohamed, A., & Khajehzadeh, M. (2012). A survey on flexible AC transmission systems (FACTS). *PrzeglądElektrotechniczny*, *88*, 1-11.
10. Pilotto, L. A., Ping, W. W., Carvalho, A. R., Wey, A., Long, W. F., Alvarado, F. L., & Edris, A. (1997). Determination of needed FACTS controllers that increase asset utilization of power systems. *IEEE Transactions on Power Delivery*, *12*(1), 364-371.
11. Wadhawan, J., & Mohar, A. (2012). INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & MANAGEMENT. *Int. J. of Engg. Sci. & Mgmt.(IJESM)*, *2*(1), 101-111.
12. Sunday, O. O., & Friday, O. O. (2011). Use of flexible alternating current transmission systems (facts) to improve the power flow control in the Nigeria transmission network. *Global Journal of Pure and Applied Sciences*, *17*(3), 335-343.
13. Soto-Sanchez, D. E., & Green, T. C. (2001). Voltage balance and control in a multi-level unified power flow controller. *IEEE Transactions on Power Delivery*, *16*(4), 732-738.
14. Xinyao, Z. H. U., Meng, J. I. N., Xiangping, K. O. N. G., Jingbo, Z. H. A. O., Jiankun, L. I. U., &Qian, Z. H. O. U. (2018). Subsynchronous resonance and its mitigation for power system with unified power flow controller. *Journal of Modern Power Systems and Clean Energy*, *6*(1), 181-189.
15. Jalboub, M. K. (2013). *Investigation of the application of UPFC controllers for weak bus systems subjected to fault conditions. An investigation of the behaviour of a UPFC controller: the voltage stability and power transfer capability of the network and the effect of the position of unsymmetrical fault conditions* (Doctoral dissertation, University of Bradford).
16. P. BALACHENNAIAH "Optimization Of Real Power Loss and Voltage Stability Limit Using Firefly and Symbiotic Organisms Search Algorithms" Doctorate degree thesis at Jawaharlal Nehru Technological University India 2016 Pp24 -28 Available at http://shodhganga.inflibnet.ac.in/bitstream/10603/175645/10/10_chapter%203.pdf Accessed on December 7th 2017
17. El-Sadek, M. Z., Abo-Zahhad, M., Ahmed, A., & Zidan, H. E. Injection Power UPFC Model for Incorporation of Unified Power Flow Controller In Load Flow Studies. Journal of Engineering Sciences, Assiut University, Vol. 35, No.1, pp.207-224, January 2007 Available at http://www.aun.edu.eg/journal_files/11_J_3756.pdfAccessed on December 5th 2017
18. Tumay, M., & Vural, A. M. (2004). ANALYSIS AND MODELING OF UNIFIED POWER FLOW CONTROLLER: MODIFICATION OF NEWTON-RAPHSON ALGORITHM AND USER-DEFINED MODELING APPROACH FOR POWER FLOW STUDIES. *Arabian Journal for Science & Engineering (Springer Science & Business Media BV)*, Volume 29, Number 2B