REDUCTION OF POWER LOSSES IN 330kV TRANSMISSION NETWORK IN SOUTH-SOUTH AND SOUTH-EAST, NIGERIA

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Abstract— **Electricity has become part of humanity as it is needed in every area for infrastructural, economic and technological development of every institution and nation at large. However, abnormality in voltage profile and constant power losses has led to shortage in quantity of power received by the load station from the transmission and generation station. In this study, static synchronous series compensator (SSSC) flexible alternating current transmission system (FACTS) and static synchronous compensator (STATCOM). FACTS were utilized in voltage profile stability and reduction in power losses of a Nigerian 330 kV 10-bus transmission power system that cuts across two zones: South- East and South-South, Nigeria. Newton Raphson algorithm was used in carrying out the power flow analysis where the weak bus being Okpai generation station (GS) was identified, having a per unit voltage value of 0.87499. On incorporating the FACTS, it was observed that the system with FACTS showed a tremendous improvement as the voltage at Okpai GS improved to 0.9511 with shunt FACTS, and 0.9529 with series FACTS. Also, based on the results obtained, it was concluded that the series FACTS had a better performance in voltage profile stability and reduction in power losses.**

Keywords— FACTS, Power Loss, TransmissionNetwork, Voltage Profile, Synchronous Compensator, Newton Raphson Algorithm, Power Flow Analysis

1. INTRODUCTION

Nigeria has the largest population of over 201million people in Africa with a land mass of 356,667 sq. miles (923,768 sq. km) with six geopolitical zones [1]. Due to the constant growth of population and industrialization (small scale and medium scale enterprises), the demand for electricity has also increased. Adequate power is always a necessity and also a prerequisite for economic growth. Nigeria is ranked as one of the countries in Sub-Sahara Africa nations to possess the largest economy in Africa with regards to gross domestic product (GDP) with the main source of growth being agriculture. However, Nigerians ranked among the lowest as regards to access to electricity in the world [2]. Despite these rankings, there continues to be constant decline of quantity of power generated majorly as a result of losses on the transmission and distribution line networks. These line losses are not just prevalent in Nigeria as many developed and developing country also deal with high power losses.

Electricity generation, distribution and transmission are highly capital intensive as it needs huge funds to set up but the benefits are huge as it aids any nation to advance economically and technological thereby reducing the poverty index of that country. At the inception of electricity, the demand for electricity at earlier times were very minute leading to building and development of small power stations to supply lighting and heating loads [3]. The movement of electric power in the power lines from a power station to consumers' premises is known as electric supply system [4]. Therefore, an electric supply system consists of three main components which include the power generation, the transmission system and the distribution system. Electric power generated at power stations (usually located far away from consumers), is then stepped up and transmitted over long distances from the power stations to load centers by means of conductors known as transmission lines. Transmission lines consists of primary and secondary (or sub) transmission stages [5].

The essential reason for embarking on transmission power system network is to ensure appropriate generation and transmission of electricity. Transmission lines being a specialized cable or other structure designed to conduct electromagnetic waves in a contained manner are utilized for transmission of power at high voltages from the electricity generation stations to the transmission substations and various lower voltages distribution station as these are located in various areas of any electricity transmitting stations. Since power transmitted is directly proportional to product of voltage and current and the losses are directly proportional to the square of current signal transmitted, transmission of electricity at high voltage is usually applied to minimize the rate of power losses [6].

A power line (either transmission or distribution) is simply a medium (material medium) which can be situated overhead or underground line conductor whose function is simply to transmit power from one location to another. Part of the reason for occurrence of line losses are as a result of degeneration of the quality of the line as a result of environmental and climatic impact [2]. Electric power can be transmitted or distributed either by overhead lines or by underground cables. The underground cables are rarely used for power transmission due to the following reasons; In the first place, power is generally transmitted over long distances to load centers. So, the installation costs for underground transmission will be very high. The initial installation cost of underground system is almost double that of overhead system [7]. Electrical power can be transmitted and distributed by either Alternating Current (AC) or Direct Current (DC) systems. However, in practice, 3-phase, 3-wire AC system is generally used for transmission of large blocks of power and 3-phase, 4-wire AC system is used for the distribution of electric power [8]. Renewable energy (RE) technologies like solar photovoltaic (PV) and onshore wind turbines are often viable for applications in rural electrification [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. Nigeria has an average irradiation of 4.0 - 6.5 kWh/m2/day and about 4 to 7.5 hours of average sunshine per day [25]. Wind is estimated to have a potential of 14,369 MW at a capacity factor of 20% and assuming 0.25% of the land is available. Nonetheless, the geo-physical and demographic features of each settlement vary widely across the country and play a vital role in informing the feasible and financially viable source for generating electricity that can meet the growing energy demand [26,27,28].

In this study, the Nigerian 330 kV transmission lines in South-South and South- East of the country was analyzed. The power system network was extensively modelled in power system analytical tool (PSAT) with the power losses obtained. Various power loss techniques were introduced with the sole purpose of minimizing the transmission line losses. These techniques include introduction of various FACTS and increase in voltages of the current transmission systems.

II. REVIEW OF RELATED WORKS

A nodal distribution loss analysis approach was proposed in nodal distribution loss analysis approach which the losses induced by loads and distributed generators (DG) were calculated recursively [29]. The authors did not apply any form of loss reduction technique in this study. [30] utilized modelling approach to restructure electrical network configuration, reduce drop voltage, reduce power losses and add new distribution transformer to enhance reliability of power systems distribution. However, cost of procuring devices for constant reconfiguration of the system may lead to loss and economic downsize. [30,31] modelled a 10-bus transmission power system using Newton Raphson power flow model. This was done with the aid of the matrix Laboratory (MATLAB) software. In order to reduce the power loss, the author evaluated the power index and normalized the index. The author on completing the simulation, had significant power loss reduction of 32% and a voltage profile improvement of 23%. [31, 32] developed an algorithm to simulate unbalanced short-circuit faults (SLG, LL, DLG) put on each line of the three-phase network. However, the author failed to consider possible ways of mitigating the constant increase in power loss and frequent abnormality of the voltage profile

III. NEWTON RAPHSON LOAD FLOW MODEL

Load flow studies are used to ensure that electrical power transfer from generators to consumers through the grid system is stable, reliable and economical. Load flow analysis forms an essential prerequisite for power system studies. The Newton-Raphson method is widely used for solving non-linear equations. It transforms the original non-linear problem into a sequence of linear problems whose solutions approach the solutions of the original problem [32].

Let V_n and I_n be the phasor voltage and current at bus n:

$$V_n = V_n e^{j\theta_n} \tag{1}$$
$$\theta_{nm} = \theta_n - \theta_m \tag{2}$$
$$Y_{nm} = G_{nm} + jB_{nm} \tag{3}$$

For an alternating current system, injected current at bus n is

$$I_n = \sum_{m=1}^{N_{Bus}} Y_{nm} V_m \tag{4}$$

Where V_n is the magnitude of the voltage at bus n in per unit (p.u), θ_n is the voltage angle of bus n in degrees or radians, Y_{nm} is the (n,m)th entry of the bus admittance matrix, G_{nm} is the (n,m)th entry of the real part of the bus admittance matrix, I_n is the phasor current and B_{nm} is the (n,m)th entry of the imaginary part of the bus admittance matrix.

Injected complex power at bus n becomes:

$$S_n = V_n I_n = V_n \sum_{m=1}^{N_{Bus}} Y_{nm} V_m \tag{5}$$

Inserting Equations 1, 2 and 3 in Equation 5 gives:

$$S_n = \sum_{m=1}^{N_{Bus}} V_n V_m e^{j\theta_{nm}} (G_{nm} - jB_{nm})$$
$$S_n = \sum_{m=1}^{N_{Bus}} V_n V_m (cos\theta_{nm} + jsin\theta_{nm})(G_{nm} - jB_{nm}) \tag{6}$$

Equation (6) can be resolved into real and imaginary parts to have active and reactive power equations

$$P_n = \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} cos\theta_{nm} + B_{nm} sin\theta_{nm}) \tag{7}$$

$$Q_n = \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} cos\theta_{nm} - B_{nm} sin\theta_{nm}) \tag{8}$$

where P_n and Q_n are real and imaginary powers respectively.

Suppose there are n nonlinear set of functions $(x) = 0$, roots x at kth iteration which is an $nx1$ vector can be obtained by utilizing Taylor Series:

$$x^{k+1} = x^k - [J(x^k)]^{-1} F(x^k) \tag{9}$$

where nxn Jacobian matrix J is

$$J(x) = \begin{bmatrix} \frac{dF_1}{dx_1} & \cdots & \frac{dF_1}{dx_n} \\ \vdots & \ddots & \vdots \\ \frac{dF_n}{dx_1} & \cdots & \frac{dF_n}{dx_n} \end{bmatrix} \tag{10}$$

Rearranging Equation 9 gives:

$$\Delta x^k = x^{k+1} - x^k = -[J^k]^{-1} F(x^k) \tag{11}$$

For an AC system, voltage magnitude and phase angle of the slack buses are known and hence it is skipped in the iterative process. Unless reactive limit of a generator bus the real power |P| and the voltage magnitude |V| (PV) are specified is violated, PV bus voltage magnitude is specified and hence, no need to take it is an unknown. Therefore, V and θ are unknowns for a load bus (PQ) and only θ is an unknown parameter for a PV bus, so there are $2N_{PQ} + N_{PV}$ unknowns. If bus 1 is assumed as the slack bus, the unknown vector x can be defined as;

$$x = \begin{bmatrix} \theta_2 \\ \vdots \\ \theta_i \end{bmatrix} \; and \; \begin{bmatrix} V_2 \\ \vdots \\ V_r \end{bmatrix} \; for \; i, r = 2,3, \cdots, N_{Bus} \; and \; r \neq PV \tag{12}$$

Solution procedure starts with an initial guess such that "1.0 p.u." for voltage magnitudes and "0 degrees" for phase angles are assigned. Then, using the assigned values of x, injected active and reactive power functions, $Pn(x)$ and $Qn(x)$ respectively, can be evaluated as;

$$P_n(x) = \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} cos\theta_{nm} + B_{nm} sin\theta_{nm}) \tag{13}$$

$$Q_n(x) = \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} cos\theta_{nm} - B_{nm} sin\theta_{nm}) \tag{14}$$

Note that functions in Equations (13) and (14) are evaluated using the unknown vector x and they are going to be referred as;

$$P_n^{calc} = P_n(x) \tag{15}$$

$$Q_n^{calc} = Q_n(x) \tag{16}$$

Reactive power limit for each generator bus should be checked at each iteration point. A generator bus is regarded as a PV bus only if reactive power generation stays within limits. If a reactive power limit is reached, a PV bus is changed to a PQ bus with a reactive power injection equal to the violated limit. If this is the case, then the voltage magnitude of that bus appears as a variable in the unknown vector and the mismatch vector and Jacobian matrix are modified accordingly.

$$if \; Q_G > Q_G^{max}, Q_G = Q_G^{max} \;\; and \; if \; Q_G > Q_G^{min}, Q_G = Q_G^{min} \tag{17}$$

After continuing with next iterations, if reactive power generation of a PQ bus, which was formerly a PV bus, falls in limits, this time bus type changes from PQ to PV again with a fixed voltage magnitude. Next, specified powers are calculated.

$$P_n^{spec} = P_n^{G.AC} - P_n^{L.AC} \tag{18}$$

$$Q_n^{spec} = Q_n^{G.AC} - Q_n^{L.AC} \tag{19}$$

To match specified powers with the calculated ones;

$$P_n^{spec} = P_n^{calc} \tag{20}$$

$$Q_n^{spec} = Q_n^{calc} \tag{21}$$

$$F1(x) = \begin{bmatrix} P_2^{spec} & \cdots & P_2^{calc} \\ \vdots & \ddots & \vdots \\ P_i^{spec} & \cdots & P_i^{calc} \end{bmatrix} for \; i, r = 2,3, \cdots, N_{Bus} \tag{22}$$

$$F2(x) = \begin{bmatrix} Q_2^{spec} & \cdots & Q_2^{calc} \\ \vdots & \ddots & \vdots \\ Q_r^{spec} & \cdots & Q_r^{calc} \end{bmatrix} for \; r \neq PV \tag{23}$$

This constitutes a power mismatch vector denoted in Equation (24)

$$x = \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_i \end{bmatrix} \; and \; \begin{bmatrix} \Delta Q_2 \\ \vdots \\ \Delta Q_r \end{bmatrix} \; for \; i, r = 2,3, \cdots, N_{Bus} \; and \; r \neq PV \tag{24}$$

Where:

$$P_n(x) = P_n^{spec} - \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} cos\theta_{nm} + B_{nm} sin\theta_{nm}) \tag{25}$$

$$Q_n(x) = Q_n^{spec} - \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} cos\theta_{nm} - B_{nm} sin\theta_{nm}) \tag{26}$$

ΔPn is defined for each PV and PQ bus whereas ΔQn is defined for only PQ buses. So there are $2N_{PQ} + N_{PV}$ power mismatch equations. To drive these mismatch equations to zero and Newton-Raphson iteration is utilized. Rearranging equation (11) gives;

$$F(x^k) = [J^k] \Delta x^k \tag{27}$$

Forming the Jacobian matrix;

$$J^k = \begin{bmatrix} J^1 & J^2 \\ J^3 & J^4 \end{bmatrix}^k \tag{28}$$

Where:

$J_{nm}^1 = \frac{dP_n(x)}{d\theta_m}$, $J_{nm}^2 = \frac{dP_n(x)}{dV_m}$, $J_{nm}^3 = \frac{dQ_n(x)}{d\theta_m}$, $J_{nm}^4 = \frac{dQ_n(x)}{dV_m}$

After obtaining Δx^k convergence is checked with a prespecified power mismatch threshold ε.

$$\text{If max} \begin{bmatrix} \Delta P_n \\ \Delta Q_n \end{bmatrix}^k < \varepsilon \tag{29}$$

Solution converges and iterations stop. If this is not the case, iteration continues with the updated x vector until the mismatch criterion is satisfied.

IV METHODOLOGY

The materials utilized in the course of this study comprise of a laptop with power system analytical tool (PSAT), Microsoft word and MATLAB 2020a. The flow chart indicating the procedures that were applied to realize the objectives of this study is shown in Figure 1.

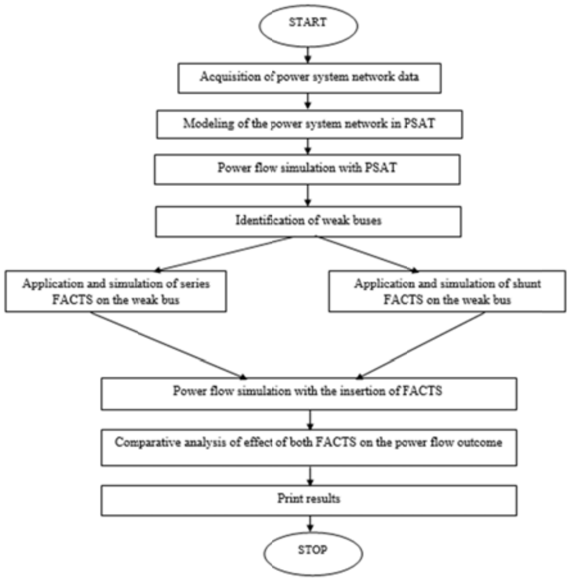

Figure 1: Flow chart of the research procedure.

The network line diagram shown in Figure 2 cuts across two regions in Nigeria, the South-South and South-East.

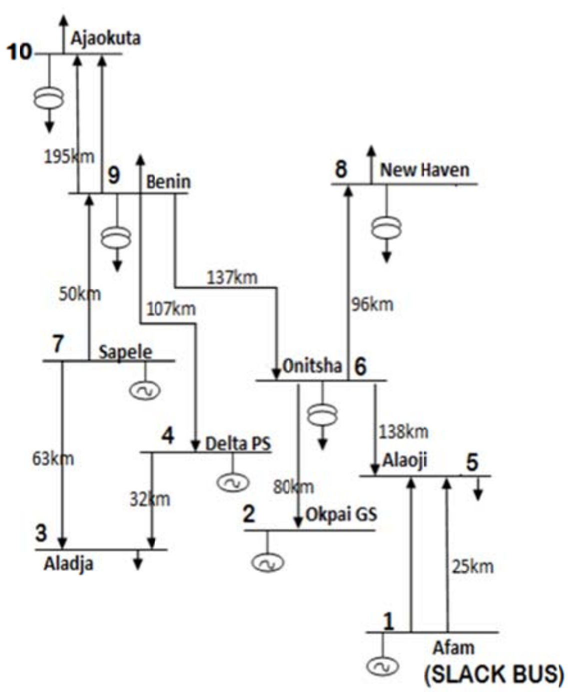

Figure 2: Line diagram of the 330kV transmission line network.

The 330kV line data that runs across the power system network is shown in Table 1. The generator and load buses are shown in Table 2 and 3 respectively.

Table 1: Line data

S/N	Line Locations	Length(kM)	Impedance(pu)	Admittance (pu)	Susceptance (pu)
1	Benin-Ajaokuta	195	0.007+j0.056	1.429-j12.180	0.745
2	Benin-Delta PS	107	0.0022+j0.019	6.013-j51.935	0.239
3	Benin-Onitsha	137	0.0049+j0.0416	2.80-j33.771	0.521
4	Sapele-Benin	50	0.0018+j0.0139	3.194-j17.555	0.208
5	Sapele-Aladja	63	0.0023+j0.019	5.284-j51.913	0.239
6	Delta PS-Aladja	32	0.0011+j0.0088	13.995-j1.119	0.171
7	Onitsha-Okpai GS	80	0.009+j0.007	59.230-j53.846	0.104
8	Onitsha-Alaoji	138	0.0049+j0.0419	2.754-j33.553	0.524
9	Onitsha-New Haven	96	0.0034+j0.00292	3.935-j3.379	0.355
10	Afam-Alaoji	25	0.009+j0.007	59.230-j53.846	0.104

Table 2: Bus data for generation buses

Bus No	Bus Name	P(MW)	P(pu)	Q(MVar)	Q(pu)
1	Afam	390	3.9	210	2.1
2	Okpai GS	220.00	2.20	112.70	1.127
4	Delta PS	55	0.55	28.16	0.2816
7	Sapele	75	0.75	38.42	0.3842

Table 3: Bus data for load buses

Bus No	Bus name	P(MW)	P(pu)	Q(MVar)	Q(pu)
3	Aladja	47.99	0.4799	24.59	0.2459
5	Alaoji	163.95	1.6395	83.98	0.8398
6	Onitsha	130.51	1.3051	66.86	0.6686
8	New Haven	113.05	1.1305	57.91	0.5791
9	Benin	160.56	1.6056	82.24	0.8224
10	Ajaokuta	63.22	0.6322	32.38	0.3238

The step used in obtaining the Newton Raphson model is shown in the flow diagram presented in Figure 3. It is necessary to obtain the bus data and the line data which are the primary parameter needed for Newton Raphson load flow method to compute the voltage profile and the power losses from the transmission line.

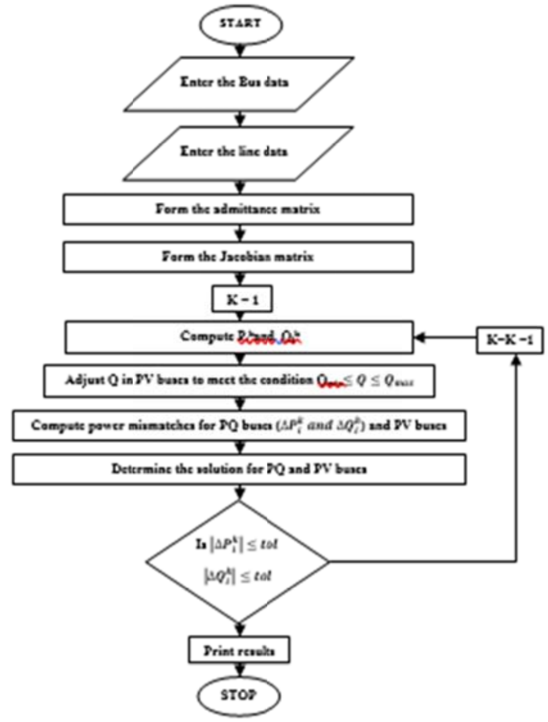

Figure 3: Flow diagram for Newton power flow analysis.

PSAT is known for its robust ability to simulate power system and perform power flow analysis [33] with different numerical and optimization models. The 10 bus network line diagram shown in Figure 2 was modelled in PSAT software. The steps taken in modelling the network with PSAT are as outlined:

Step 1: The PSAT software icon installed in a laptop was launched. The various power flow models available in this software are: Newton Raphson, XB fast decoupled, BX fast decoupled, Runge Kutta, Iwamoto and simple robust with the integrators being backward Euler and trapezoidal rules.

Step 2: Open the PSAT library. This was done by clicking on the PSAT library. The library environment contains various power modelling tools.

Step 3: Open the PSAT modelling environment and assembling of network model component. The modeling environment of the PSAT was opened and the network model component were assembled without FACTS.

Step 4: Simulate the Power System model. On completion of the power system model as shown in, the model was saved in'mdl' formation. The power flow model utilized in PSAT for this study is Newton Raphson iteration method.

Step 5: Attach the FACTS devices on the weak bus. On completing the power flow analysis, the weak bus is identified and the FACTS device were introduced to the weak bus and simulated. The result of the model with FACTS device was compared with the model without FACTS device to determine the rate of improvement of the power systems for shunt FACTS (StatCom) and series FACTS (SSSC).

V. RESULTS AND DISCUSSION

The result of Newton Raphson power flow analysis for the 10 bus considered in this study is shown in Table 4 as obtained from PSAT graphic user interface (GUI).

Table 4: Newton Raphson power flow analysis in PSAT

Bus	Bus Name	Voltage magnitude (pu)	Voltage angle (radians)
1	Afam 1	1.033	0
2	Ajaokuta 10	0.92445	-0.39379
3	Aladja 3	0.96603	-0.36743
4	Alaoji 5	1.0166	-0.02083
5	Benin 9	0.95594	-0.36053
6	Delta PS 4	0.973	-0.36032
7	New heaven 8	0.89413	-0.26537
8	Okpai GS 2	0.87449	-0.28809
9	Onitsha 6	0.89488	-0.26499
10	Sapele 7	0.973	-0.35914

The voltage magnitude which is the basis of determining the appropriate location of installing the shunt FACTS (STATCOM) device shows that Okpai generating station has the weakest bus voltage magnitude of 0.87449 pu. Hence, the proposed FACTS must be installed in that location to ensure voltage improvement not just in the location but also for the entire power system stations studied. The line flow results is presented in Table 5.

Table 5: Line flow data for the 10 bus network

From Bus	To bus	Line	P flow (pu)	Q flow (pu)	P loss(pu)	Q loss (pu)
Afam 1	Alaoji 5	1	3.4078	2.0189	0.0133	0.1012
Onitsha 6	New heaven	2	1.2006	0.9004	0.0006	0.0004
Benin 9	Ajaokuta 10	3	0.6046	0.4848	0.0046	0.0348
Benin 9	Ajaokuta 10	4	0.6046	0.4848	0.0046	0.0348
Onitsha 6	Benin 9	5	1.7913	1.4299	0.0321	0.2723
Okpai GS 2	Onitsha 6	6	1.2	-0.9	0.0063	0.0483
Sapele 7	Benin 9	7	0.2437	1.1610	0.0026	0.0197
Sapele 7	Benin 9	8	0.2437	1.1610	0.0026	0.0197
Delta PS 4	Benin 9	9	0.1706	1.3114	0.0027	0.0221
Aladja 3	Delta PS 4	10	0.7582	0.6014	0.0011	0.0088
Aladja 3	Sapele 7	11	0.4418	0.2985	0.0006	0.0048
Onitsha 6	Alaoji 5	12	1.5984	1.3187	0.1905	1.6165
Afam 1	Alaoji 5	13	3.4078	2.0189	0.0133	0.1012

From Table 5, it is observed that the large chunk of the power losses occurred in transmission line 12 that connects Onitsha station to Alaoji generation station (Active Power (P) being 0.1905pu and Reactive Power (Q) loss of 1.6165pu). This implies that the transmission line to that location needs to be replaced or proper maintenance being carried out on it. The series FACTS (SSSC) device was installed on the transmission line that runs between Onitsha and Alaoji as a contingency and to minimize the rate of power loss on that transmission line. The plot of the losses for active power is shown in Figure 4.

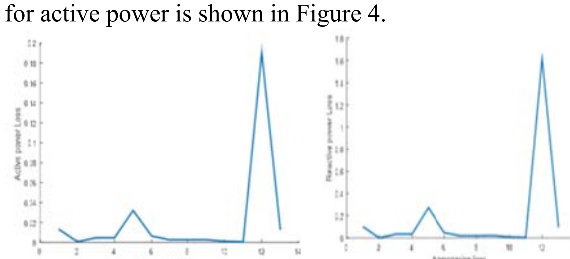

Figure 4: Active power losses for system at normal condition

Figure 5: Reactive power losses for system at normal condition

It is observed that line 12 (transmission line connecting Onitsha and Alaoji) had the highest active power loss of 0.1905 pu which is in agreement with the data shown in Table 5. The reactive power loss is shown in Figure 5 shows that transmission line 12 is the point where the highest reactive power loss of 1.6165 pu occurs. The total power generated, load consumed and power loss for active and reactive power are summarized in Table 6.

Table 6: Total losses for the power system without FACTS

Parameters		Values (pu)
Total power generated	Real power	8.6756
	Reactive power	8.5850
Total load	Real power	8.4
	Reactive power	6.3
Total loss	Real power	0.2756
	Reactive power	2.2850

The values of the total power generated, total power load and total power loss obtained from the power flow simulation is shown in Table 6. This Table shows that 3.1767% of the real power generated was lost and 26.6162% of the total reactive power generated was lost as such, FACTS were introduced to the system. The power flow analysis of the power when a shunt FACTS (STATCOM) was introduced at Okapi bus station. is shown in Table 7 and the plot of the bus voltage with and without STATCOM FACTS is shown in Figure 6.

Table 7: Bus voltage data with shunt FACTS

Bus Location	Voltage Values (pu) with STATCOM	Voltage Values (pu) without FACTS
Afam 1	1.033	1.033
Ajaokuta 10	0. 97336	0.92445
Aladja 3	0.98221	0.96603
Alaoji 5	1.0087	1.0166
Benin 9	0.97011	0.95594
Delta PS 4	0.9788	0.973
New Heaven	0.9451	0.89413
Okpai GS 2	0.9511	0.87449
Onitsha 6	0.9612	0.89488
Sapele 7	0.9801	0.973

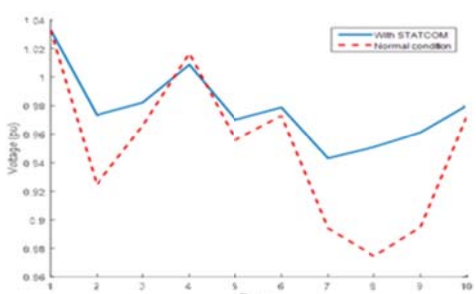

Figure 6: Bus voltages for system with and without STATCOM FACTS

It is observed from Figure 6 that there is an improvement of the bus voltages with the introduction of STATCOM FACTS. Okpai station that had the least bus voltage at normal condition was improved from 0.87449 to 0.9511 pu. Though there was a drop in voltage at Delta PS but not at significant level. This shows that FACTS device is necessary in minimizing voltage drop that comes with power losses. The plot of the active power losses with STATCOM as shown in Table 8 is shown in Figure 7.

Table 8: Power losses with STATCOM FACTS

From Bus	To Bus	Line	P loss (pu)	Q loss (pu)
Afam 1	Alaoji 5	1	0.0083	0.0125
Onitsha 6	New heaven	2	0.0003	0.0002
Benin 9	Ajaokuta 10	3	0.0014	0.0128
Benin 9	Ajaokuta 10	4	0.0023	0.0133
Onitsha 6	Benin 9	5	0.0112	0.1342
Okpai GS 2	Onitsha 6	6	0.0051	0.0313
Sapele 7	Benin 9	7	0.0018	0.0099
Sapele 7	Benin 9	8	0.0014	0.0107
Delta PS 4	Benin 9	9	0.0017	0.0091
Aladja 3	Delta PS 4	10	0.0008	0.0048
Aladja 3	Sapele 7	11	0.0004	0.0018
Onitsha 6	Alaoji 5	12	0.0056	0.0165
Afam 1	Alaoji 5	13	0.0042	0.0112

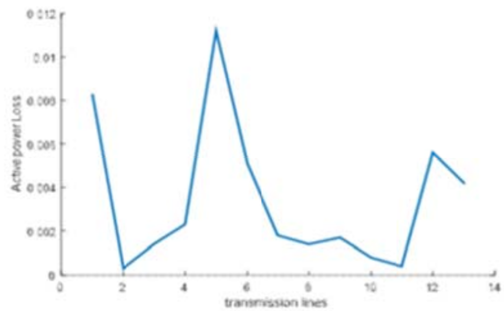

Figure 7: Active power losses with STATCOM

There was a reduction of power loss when STATCOM was introduced and line 5 (line connecting Onitsha and Benin) had the highest power loss of 0.0112 pu. The reactive power loss is shown in Figure 8.

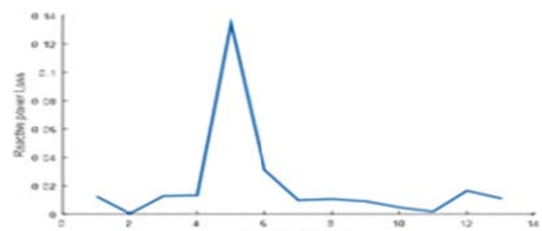

Figure 8: Reactive power losses with STATCOM

As seen in the active power loss (Figure 7), line 5 (transmission line connecting Onitsha and Benin) had the highest power loss of 0.1342 pu. This is an improvement compared with the power system at normal condition of 0.0112 pu. A comparative plot of the active power loss of the system with and without STATCOM FACTS is shown in Figure 9.

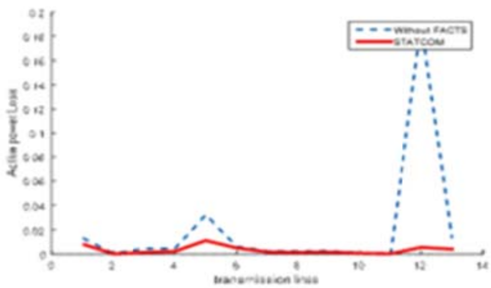

Figure 9: Comparative analysis of the active power losses with and without FACTS

From Figure 9, the introduction of STATCOM FACTS there was an improvement in reduction of the active power loss. The spike in the 12th line was reduced to the minimum. The reactive power losses with and without STATCOM is shown in Figure 10.

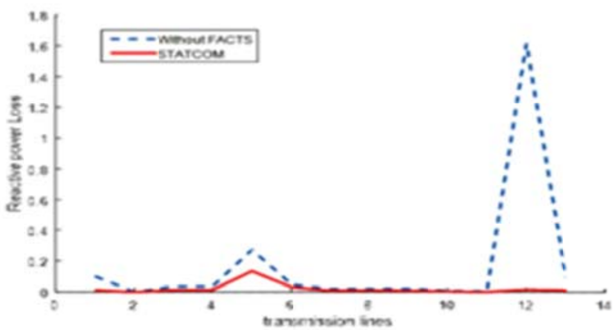

Figure 10: Reactive power loss with and without STATCOM

The spike line in the Figure 10 was lowered with the introduction of FACTS device. The power flow analysis for the series FACTS (SSSC) is presented in Table 9. The plot of voltage profile with SSSC is shown in Figure 11.

Table 9: Voltage profile with SSSC FACTS device

Bus location	Voltage values (pu) with SSSC	Voltage values (pu) without FACTS
Afam 1	1.033	1.033
Ajaokuta 10	0. 98356	0.92445
Aladja 3	0.9917	0.96603
Alaoji 5	1.0007	1.0166
Benin 9	0.9802	0.95594
Delta PS 4	0.9889	0.973
New Heaven	0.9531	0.89413
Okpai GS 2	0.9529	0.87449
Onitsha 6	0.9733	0.89488
Sapele 7	0.9911	0.973

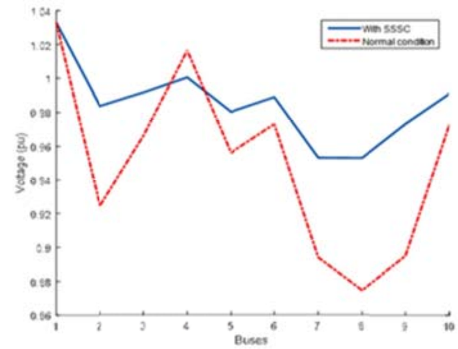

Figure 11: The plot of voltage profile with SSSC

There was an improved voltage profile when SSSC was introduced. The comparative analysis of the voltage profile with SSC and with STATCOM is shown in Figure 12.

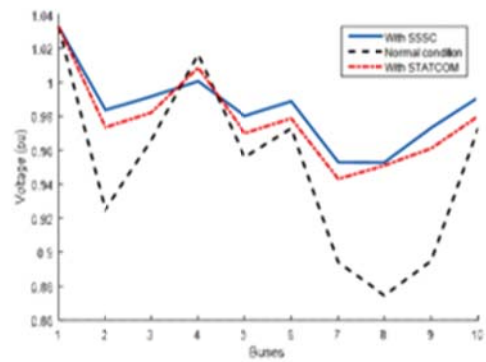

Figure 12: Voltage profile of the power system with and without FACTS

It can be seen in Figure 12 that with the introduction of FACTS, there was an improvement on the voltage profile. SSSC in the case had an optimum voltage values as the pu values are closer to 1.0 pu (330kV). As such, application of FACTS device is a sure way of ensuring improved voltage profile once introduced in Nigerian's power systems.

The active and reactive power loss of the power system with SSSC device is shown in Table 9 and its plot of active power losses with SSSC as shown in Table 10 is shown in Figure 13.

Table 10: Power Loss with SSSC FACTS

From Bus	To Bus	Line	P loss (pu)	Q loss (pu)
Afam 1	Alaoji 5	1	0.0080	0.0021
Onitsha 6	New heaven	2	0.0001	0.0001
Benin 9	Ajaokuta 10	3	0.0009	0.0123
Benin 9	Ajaokuta 10	4	0.0009	0.0107
Onitsha 6	Benin 9	5	0.0019	0.0042
Okpai GS 2	Onitsha 6	6	0.0031	0.0113
Sapele 7	Benin 9	7	0.0010	0.0029
Sapele 7	Benin 9	8	0.0008	0.0100
Delta PS 4	Benin 9	9	0.0017	0.0071
Aladja 3	Delta PS 4	10	0.0004	0.0018
Aladja 3	Sapele 7	11	0.0002	0.0009
Onitsha 6	Alaoji 5	12	0.0025	0.0095
Afam 1	Alaoji 5	13	0.0022	0.0101

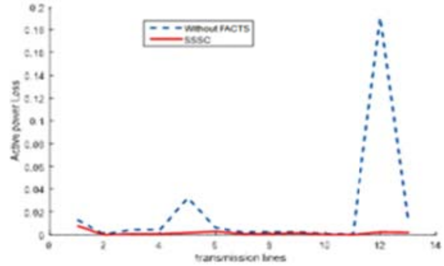

Figure 13: Active power loss with SSSC

From Figure 13, the active power loss with SSSC almost had a flat line at zero. Almost all the spike area at normal condition was reduced to values that are closer to zero. This shows that FACTS play a vital role in minimizing power loss. The comparative analysis of active power with SSSC and STATCOM is shown in Figure 14.

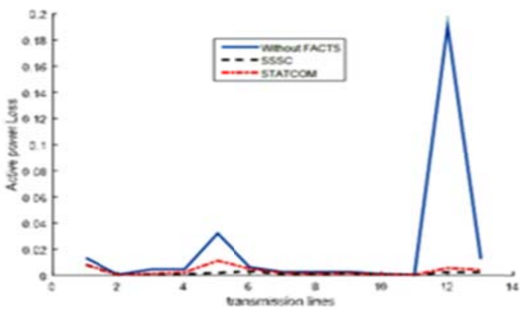

Figure 14: Comparative analysis of active power

SSSC had a more reduced power loss when implemented with STATCOM as shown in Figure 14 as such, SSSC should be used in minimizing power loss in power system under review that STATCOM. The comparative plot of STATCOM and SSSC for reactive power loss is shown in Figure 15 and Figure 16. It can be seen from Figure 16, that SSSC had a better reactive power loss reduction than STATCOM as such for the two TCN regions considered in this study, SSSC should be used.

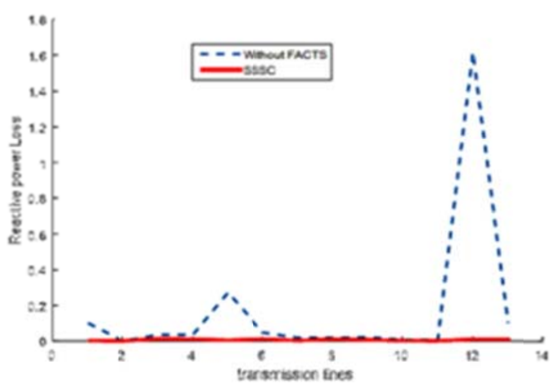

Figure 15: Reactive power loss with SSSC

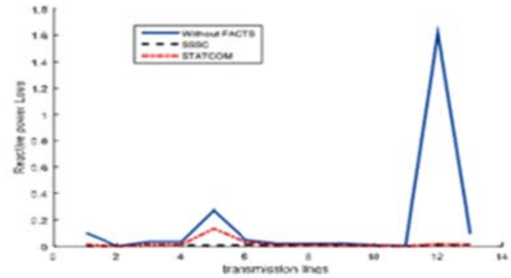

Figure 16: Reactive power comparative analysis

Tables 11 and Table 12 shows the percentage loss reduction with STATCOM FACTS and SSSC FACTS.

Table11: Percentage loss reduction with STATCOM FACTS device

Lines	Power loss before (without FACTS)		Power loss after (with STATCOM)		% Loss Reduction	
	P loss (pu)	Q loss (pu)	P loss (pu)	Q loss (pu)	P loss	Q loss
1	0.0133	0.10123	0.0083	0.0125	37.6	87.7
2	0.0006	0.0004	0.0003	0.0002	33.3	50
3	0.0046	0.0348	0.0014	0.0128	69.6	63.2
4	0.0046	0.0348	0.0023	0.0133	50	61.8
5	0.0321	0.2723	0.0112	0.1342	65.1	50.7
6	0.0063	0.0483	0.0051	0.0313	19	35.2
7	0.0026	0.0197	0.0018	0.0099	30.8	49.7
8	0.0026	0.0197	0.0014	0.0107	46.2	45.7
9	0.0027	0.0221	0.0017	0.0091	37	58.8
10	0.0011	0.0088	0.0008	0.0048	27.3	45.5
11	0.0006	0.0048	0.0004	0.0018	33.3	62.5
12	0.1905	1.6165	0.0056	0.0165	97	99
13	0.0133	0.1012	0.0042	0.0112	68.4	88.9

Table 12: Percentage loss reduction with SSSC FACTS device

Lines	Power loss before (without FACTS)		Power loss after (with SSSC)		% Loss Reduction	
	P loss (pu)	Q loss (pu)	P loss (pu)	Q loss (pu)	P loss	Q loss
1	0.0133	0.10123	0.0080	0.0021	39.8	97.9
2	0.0006	0.0004	0.0001	0.0001	83.3	75
3	0.0046	0.0348	0.0009	0.0123	80.4	64.7
4	0.0046	0.0348	0.0009	0.0107	80.4	69.3
5	0.0321	0.2723	0.0019	0.0042	94.1	98.5
6	0.0063	0.0483	0.0031	0.0113	50.8	76.6
7	0.0026	0.0197	0.0010	0.0029	61.5	85.3
8	0.0026	0.0197	0.0008	0.0100	69.2	49.2
9	0.0027	0.0221	0.0017	0.0071	37	67.9
10	0.0011	0.0088	0.0004	0.0018	63.6	79.5
11	0.0006	0.0048	0.0002	0.0009	66.7	81.3
12	0.1905	1.6165	0.0025	0.0095	98.7	99.4
13	0.0133	0.1012	0.0022	0.0101	83.5	90

VI CONCLUSION

A 10-bus Nigerian 330kV transmission network that incorporates South-East and South-Southern region of Nigeria was simulated using power system analytical toolbox. From the power analysis performed, the weak bus in terms of low voltage stability was Okpai GS where STATCOM FACTS was inserted and simulated. The system voltage showed tremendous improvement with the introduction of STATCOM FACTS as the weak bus improved from 0.87449 pu to 0.9511 pu and to 0.9529 pu for SSSC FACTS. The active and reactive power losses showed a tremendous improvement with the introduction of the shunt and series FACTS. The series FACTS having a better improvement on power loss reduction than the shunt FACTS. As such, it can be concluded that the series

FACTS should be applied in the voltage stability and power loss reduction of the 10-bus network considered in this study.

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