Steady State Characteristic Performance of the Nigerian 28-bus 330kV Transmission Network Incorporating Static Synchronous Series Compensator (SSSC)

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***Abstract* - This research paper elucidates a power (or load) flow analysis of the Nigerian 28-bus 330kV transmission network. This expressly reveals the steady state operation of the power system under consideration, which by extension may be applied to other similar networks. The load flow solution would reveal the affected lines whose power flow fall below the values expected, and buses whose voltage magnitude is outside the required range of $0.9 \leq V \leq 1.1$pu. The Static Synchronous Series Compensator, SSSC, is incorporated into the affected lines to control the flow of power in the network. The performance characteristics of SSSC, a member of the Flexible AC Transmission System (FACTS) devices, in controlling the power (active and reactive) flow, reducing the transmission losses and improving the voltage profile of the network is the objective of this research. The Newton-Raphson technique is used in analyzing the load flow problem without and with the FACTS device (i.e. SSSC) incorporated. The results obtained are compared to observe the performance of SSSC in the network. The SSSC model is validated and tested using the IEEE 14-bus test system. The analysis and simulation is done using the MATLAB R2007b software.**

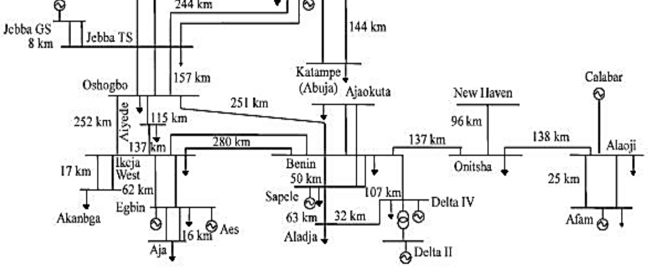
***Keywords*- FACTS, Power flow, Newton-Raphson technique, SSSC, Transmission loss, Voltage Profile, MATLAB, Control, IEEE.**

I. INTRODUCTION

The modern power system is a complex network comprising of numerous generators, transmission lines, variety of loads and transformers. There is a great need to improve electric power utilization while still maintaining reliability. However, while power flows in some of the transmission lines are within their normal limits, others are overloaded, which generally affect the power flow along the lines, deteriorate the voltage profile, decreases the stability and increase losses [1]. Hence the need to ensure effective power transfer by controlling the power flows in the transmission network of the system. Flexible AC Transmission Systems (FACTS), a fast developing solid-state technology, utilize high power semiconductor device to control the reactive power flow and thus the active power flow of transmission systems so that the ac power can be transmitted across long distance efficiently [2].

Power-flow is the basic tool for power system analysis which reveals the system operations in a normal operating condition (i.e. steady-state). It is the backbone of power system analysis and design [3]. Power flow calculations are carried out for power system planning, operational planning and in connection with system operation and control. It is a function of the sending end and receiving end voltage magnitude, the transmission line impedance and the phase angle between the voltages. Therefore in controlling one or combination of the power flow arrangements, it is possible to control the active, as well as reactive power in the transmission line [1].

The Nigerian 28-bus 330kV transmission system consist of ten generating stations, twenty-three load stations and thirty-two transmission lines. The system is divided into three major regions: North, South-East and South-West regions. North is connected to South by a triple circuit lines between Jebba and Osogbo, while West is linked to the East through one transmission line from Osogbo to Benin and a double circuit line from Ikeja to Benin [4] [8]. Fig. 1 shows the basic diagram of the network.



II. PRINCIPLES OF OPERATION OF SSSC

Static Synchronous Series Compensator (SSSC) is one of the most important members of the FACTS family which is generally connected in series with the transmission lines. SSSC is very effective in controlling power flow in a transmission line with the capability to change its reactance characteristic from capacitive to inductive. The SSSC device can provide either capacitive or inductive injected voltage compensation. The injected voltage is almost in quadrature with the line current. If AC injected voltage in SSSC lags behind the line current by 90°, capacitive series voltage compensation is obtained in the transmission line. Conversely, if AC injected voltage of the SSSC leads the line current by 90°, inductive series compensation is achieved. The injected voltage inserts either an inductive or capacitive reactance into the transmission line which influences the power (active and/or reactive) flow in the transmission line.

The basic building block of the SSSC is a dc-ac converter which is connected in series with the transmission line by a coupling transformer as shown in Fig. 2. It is a power electronic-based Synchronous Voltage Generator (SVG) that generates a three phase voltage (with a gate turn-off thyristor) from a dc capacitor bank, in quadrature with the line current. Fig. 3 shows the SSSC equivalent circuit.

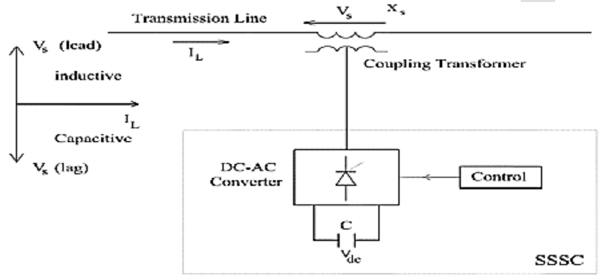


Fig.2 Basic Structure of SSSC

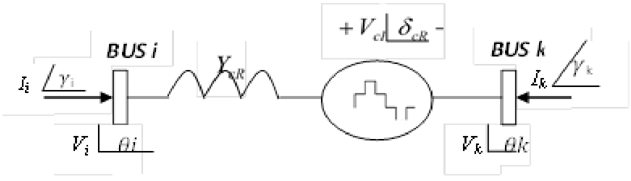


Fig.3 SSSC Equivalent Circuit

The series voltage source of the three-phase SSSC is given in the equation below

$$E_{cR}^{\rho} = V_{cR}^{\rho}\left(\cos\delta_{cR}^{\rho} + j\sin\delta_{cR}^{\rho}\right) \tag{1}$$

Where ρ indicates phase quantities a, b and c; V_{cR} is the converter voltage, δ_{cR} is the converter angle, V_i and V_k are the voltages at bus i and k respectively. From the SSSC equivalent circuit given in Fig. 3, the bus currents equation in matrix form is given by:

$$\begin{bmatrix} I_i \\ I_k \end{bmatrix} = \begin{bmatrix} Y_{cR} & -Y_{cR} & -Y_{cR} \\ -Y_{cR} & Y_{cR} & Y_{cR} \end{bmatrix} \begin{bmatrix} V_i \\ V_k \\ E_{cR} \end{bmatrix} \tag{2}$$

The boundary condition for V_{cR} and δ_{cR} are as given below

$$V_{cR,\min} \le V_{cR} \le V_{cR,\max} \tag{3}$$

$$0 \le \delta_{cR} \le 2\pi \tag{4}$$

From the SSSC Thevenin equivalent circuit and equation, the expressions for the active and reactive powers at bus i are:

$$\begin{aligned} P_i &= V_i^2 G_{ii} - V_i V_k\left[G_{ik}\cos(\theta_i - \theta_k) - B_{ik}\sin(\theta_i - \theta_k)\right] \\ &\quad - V_i V_{cR}\left[G_{ik}\cos(\theta_i - \delta_{cR}) - B_{ik}\sin(\theta_i - \delta_{cR})\right] \end{aligned} \tag{5}$$

$$\begin{aligned} Q_i &= V_i^2 B_{ii} - V_i V_k\left[G_{ik}\sin(\theta_i - \theta_k) - B_{ik}\cos(\theta_i - \theta_k)\right] \\ &\quad - V_i V_{cR}\left[G_{ik}\sin(\theta_i - \delta_{cR}) - B_{ik}\cos(\theta_i - \delta_{cR})\right] \end{aligned} \tag{6}$$

The active power and reactive power relations for the converter are given by the equations;

$$\begin{aligned} P_{cR} &= V_{cR}^2 G_{kk} - V_{cR} V_i\left[G_{ik}\cos(\delta_{cR} - \theta_i) - B_{ik}\sin(\delta_{cR} - \theta_i)\right] \\ &\quad - V_{cR} V_k\left[G_{kk}\cos(\delta_{cR} - \theta_k) - B_{kk}\sin(\delta_{cR} - \theta_k)\right] \end{aligned} \tag{7}$$

$$\begin{aligned} Q_{cR} &= -V_{cR}^2 B_{kk} - V_{cR} V_i\left[G_{ik}\sin(\delta_{cR} - \theta_i) - B_{ik}\cos(\delta_{cR} - \theta_i)\right] \\ &\quad - V_{cR} V_k\left[G_{kk}\sin(\delta_{cR} - \theta_k) - B_{kk}\cos(\delta_{cR} - \theta_k)\right] \end{aligned} \tag{8}$$

The representation of this power equation in matrix form gives the linearized SSSC model

$$\begin{bmatrix} \Delta P_i \\ \Delta P_k \\ \Delta Q_i \\ \Delta Q_k \\ \Delta P_{ik} \\ \Delta Q_{ik} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_i}{\partial\theta_i} & \frac{\partial P_i}{\partial\theta_k} & \frac{\partial P_i}{\partial V_i}V_i & \frac{\partial P_i}{\partial V_k}V_k & \frac{\partial P_i}{\partial\delta_{cR}} & \frac{\partial P_i}{\partial V_{cR}}V_{cR} \\ \frac{\partial P_k}{\partial\theta_i} & \frac{\partial P_k}{\partial\theta_k} & \frac{\partial P_k}{\partial V_i}V_i & \frac{\partial P_k}{\partial V_k}V_k & \frac{\partial P_k}{\partial\delta_{cR}} & \frac{\partial P_k}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_i}{\partial\theta_i} & \frac{\partial Q_i}{\partial\theta_k} & \frac{\partial Q_i}{\partial V_i}V_i & \frac{\partial Q_i}{\partial V_k}V_k & \frac{\partial Q_i}{\partial\delta_{cR}} & \frac{\partial Q_i}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_k}{\partial\theta_i} & \frac{\partial Q_k}{\partial\theta_k} & \frac{\partial Q_k}{\partial V_i}V_i & \frac{\partial Q_k}{\partial V_k}V_k & \frac{\partial Q_k}{\partial\delta_{cR}} & \frac{\partial Q_k}{\partial V_{cR}}V_{cR} \\ \frac{\partial P_{ik}}{\partial\theta_i} & \frac{\partial P_{ik}}{\partial\theta_k} & \frac{\partial P_{ik}}{\partial V_i}V_i & \frac{\partial P_{ik}}{\partial V_k}V_k & \frac{\partial P_{ik}}{\partial\delta_{cR}} & \frac{\partial P_{ik}}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_{ik}}{\partial\theta_i} & \frac{\partial Q_{ik}}{\partial\theta_k} & \frac{\partial Q_{ik}}{\partial V_i}V_i & \frac{\partial Q_{ik}}{\partial V_k}V_k & \frac{\partial Q_{ik}}{\partial\delta_{cR}} & \frac{\partial Q_{ik}}{\partial V_{cR}}V_{cR} \end{bmatrix} \begin{bmatrix} \Delta\theta_i \\ \Delta\theta_k \\ \frac{\Delta V_i}{V_i} \\ \frac{\Delta V_k}{V_k} \\ \Delta\delta_{cR} \\ \frac{\Delta V_{cR}}{V_{cR}} \end{bmatrix} \tag{9}$$

The residuals (i.e. power mismatches), $\Delta P_i^{(k)}\ and\ \Delta Q_i^{(k)}$ given by the specified value less by the calculated value are as presented by

$$\Delta P_i^{(k)} = P_{i,spec} - P_{i,calc} \tag{10}$$

$$\Delta Q_i^{(k)} = Q_{i,spec} - Q_{i,calc} \tag{11}$$

Also, the voltage magnitude and angle correction to be added to the original estimates $\left|V_i^{(k)}\right|\ and\ \delta_i^{(k)}$ to obtain the new estimates for computing $\Delta P_i^{(k+1)}$ and $\Delta Q_i^{(k+1)}$ for starting the next iteration are $\Delta\left|V_i^{(k)}\right|\ and\ \Delta\delta_i^{(k)}$, and the next iteration for the bus are given by

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)}$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right|$$

This process is repeated until the precision index applied to the quantities in either column matrix is satisfied.

III. POWER-FLOW MODELLING

The complex power at *bus i* of an n-bus system is given by

$$S_i^* = V_i^* I_i = P_i - jQ_i \tag{12}$$

Where

$$I_i = \sum_{k=1}^{N} Y_{ik} V_k \tag{13}$$

Substituting equation (13) into equation (12)

$$S_i^* = V_i^* \times \sum_{k=1}^{N} (V_k Y_{ik}) \tag{14}$$

By comparing equations (12) and (14), the real and reactive powers are obtained as

$$P_i = \mathrm{Re}\left[V_i^* \times \sum_{k=1}^{N} (V_k Y_{ik}) \right] \tag{15}$$

$$Q_i = -\mathrm{Im}\left[V_i^* \times \sum_{k=1}^{N} (V_k Y_{ik}) \right] \tag{16}$$

In polar coordinates, we have

Voltage at sending *bus i*, $V_i^* = |V_i| \angle -\delta_i$ (17)

Voltage at receiving *bus* k, $V_k = |V_k| \angle \delta_k$ (18)

Admittance between buses *i* and *k*,

$$Y_{ik} = G_{ik} + jB_{ik} = |Y_{ik}| \angle \theta_{ik} \tag{19}$$

Conductance between buses *i* and *k*,

$$G_{ik} = |Y_{ik}| \cos \theta_{ik} \tag{20}$$

Susceptance between buses *i* and *k*,

$$B_{ik} = |Y_{ik}| \sin \theta_{ik} \tag{21}$$

Substituting equations (17), (18) and (19) into equations (15) and (16) gives

$$P_i = \sum_{k=1}^{N} |V_i||V_k| \left[G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k) \right] \tag{22}$$

$$Q_i = \sum_{k=1}^{N} |V_i||V_k| \left[G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k) \right] \tag{23}$$

Equations (22) and (23) are known as the ***static power flow equations***.

Expanding equations (22) and (23) in Taylor's series about the initial estimate neglecting all higher order terms result in equation (9) called the Jacobian.

The Newton-Raphson load flow algorithm for SSSC modelling is presented in the next section below. The admittance matrix of the system is modified to include the series source impedance. This gives

$Z_{ik} = (R_{ik} + R_{CR}) + j(X_{ik} + X_{CR})$ and

$$Y_{ik} = (1/Z_{ik}) = G_{ik} + jB_{ik} \tag{24}$$

R_{CR} and X_{CR} represent the resistance and inductive reactance of the series source, respectively.

The linearized power flow is given such that

$$[f(x)] = [J][\Delta x] \tag{25}$$

Where

$$[f(x)] = [\Delta P_i \;\; \Delta P_k \;\; \Delta Q_i \;\; \Delta Q_k]^T \tag{26}$$

$$[x] = \left[\Delta\theta_I \;\; \Delta\theta_k \;\; \frac{\Delta Vi}{Vi} \;\; \frac{\Delta Vk}{Vk}\right]^T \tag{27}$$

[J] is the system Jacobian.

IV. IMPLEMENTATION AND RESULTS

The Power system under study has nine PV or generator buses, nineteen PQ or load buses and one slack or reference bus. The reference bus is bus one (1) and has a phase angle of zero degree. The PV buses are 1, 2, 11, 18, 21, 23, 24, 27 and 28 while the PQ buses are 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17, 19, 20, 22, 25 and 26. After the whole data needed for the analysis have been inputted and mathematical modelling of the load flow and FACTS devices done, the actual implementation is done using MATLAB software without and with SSSC incorporated, and the results compared. The buses outside the voltage limit $0.9 \le |V| \le 1.1pu$ are identified from the Newton Raphson solution for the load flow problem, the minimum acceptable limit being 0.9pu.

A. *Newton-Raphson Power flow Algorithm with SSSC Incorporated*

1) For load buses, where $P_{i,spec}$ *and* $Q_{i,spec}$ are specified, voltage magnitude and phase angles are set equal to the swing bus values, or 1.0 and 0.0, i.e. $|V_i^{(0)}| = 1.0$ and $\delta_i^{(0)} = 0.0$, for the generator buses, where $|V_i|$ *and* $P_{i,spec}$ are known, phase angles are set equal to the swing bus angle, or '0', i.e $\delta_i^{(0)} = 0$.
2) For load buses, $P_i^{(k)}$ and $Q_i^{(k)}$ are calculated from equations (25a) and (26a) and $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are calculated from equations (10) and (11).

$$P_i = \sum_{k=1}^{n} |V_i V_k Y_{ik}| \cos(\theta_{ik} + \delta_k - \delta_i) \tag{25a}$$

$$Q_i = -\sum_{k=1}^{n} |V_i V_k Y_{ik}| \sin(\theta_{ik} + \delta_k - \delta_i) \tag{26a}$$

3) For the generator buses, $P_i^{(k)}$ and $\Delta P_i^{(k)}$ are calculated from the equations (25a) and (10) respectively.
4) For the SSSC, the active and reactive powers are calculated using equations (7) and (8) respectively.
5) The power mismatch of the SSSC is obtained by subtracting the calculated powers above from the specified powers given.

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6) The modified Jacobian is then obtained as written in equation (9). The parameters within the Jacobian are calculated using the expression in Appendix A.
7) The new voltage magnitudes and phase angles are computed using

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \qquad (27)$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \qquad (28)$$

8) The processes continue until the residuals $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are less than the specified accuracy given in equations below.

$$\left|\Delta \mathrm{P}_{\mathrm{i}}^{(\mathrm{k})}\right| \le \varepsilon \qquad (29)$$

$$\left|\Delta \mathrm{Q}_{\mathrm{i}}^{(\mathrm{k})}\right| \le \varepsilon \qquad (30)$$

Where ε is the accuracy specified. The specified value for this research = 0.001.

B. *Results and Discussion*

The result obtained for the power flow analysis of the power system under consideration is presented in Table 1 below. It shows the Newton-Raphson iterative load flow model for the Nigerian 28-bus power system. Convergence was achieved after six iterations. This result is vital in determining the transmission line(s) into which SSSC will be incorporated. These lines are between buses **13 and 14**, buses **16 and 19**, and buses **22 and 20**. The incorporated device will control the line flows (active and reactive power) and reduce the transmission losses also.

The SSSC is incorporated into the transmission lines 13-14, 16-19 and 20-22. The proposed SSSC model is implemented without modification in the NR Jacobian matrix. It does not require any update or changes in the Jacobian matrix. The proposed SSSC model is able to control both active and reactive power together or individually. The proposed SSSC model has been validated and tested using the IEEE 14-bus test system, where it is installed on line 2-4, 10-11, and 12-13. In that case the total power loss is reduced by approximately 60% and the total power (active and reactive) is effectively controlled. The power flow solution after incorporating SSSC into the Nigerian 28-bus 330kV transmission system is presented in Table 3. The injected voltage and angle of the device incorporated converges to the values given in the table 2 below at the sixth iteration of the power flow solution. It presents the values of the injected voltages and their angles into the transmission lines they are incorporated.

TABLE 1 NEWTON-RAPHSON ITERATIVE LOAD-FLOW MODEL WITHOUT SSSC

Bus No.	Bus Name	Voltage mag.	Voltage Angle (deg)	Load		Generation	
				MW	MVar	MW	MVar
1	Egbin	1.0500	0.0000	68.900	51.700	-477.606	764.094
2	Delta	1.0500	30.9202	0.000	0.000	670.000	156.452
3	Aja	1.0414	-0.5914	274.400	205.800	0.000	0.000
4	Akangba	0.9616	7.3524	344.700	258.500	0.000	0.000
5	Ikeja	0.9770	8.2362	633.200	474.900	0.000	0.000
6	Ajaokuta	0.9847	24.3471	13.800	10.300	0.000	0.000
7	Aladja	1.0472	29.4859	96.500	72.400	0.000	0.000
8	Benin	0.9917	24.7571	383.300	287.500	0.000	0.000
9	Ayede	0.9204	15.2054	275.800	206.800	0.000	0.000
10	Ososgbo	0.9555	25.8923	201.200	150.900	0.000	0.000
11	Afam	1.0500	34.3814	52.500	39.400	431.000	605.461
12	Alaoji	1.0039	33.1818	427.000	320.200	0.000	0.000
13	**New Haven**	**0.8863**	**22.2196**	**22.2196**	**133.400**	**0.000**	**0.000**
14	Onitsha	0.9290	24.7169	184.600	138.400	0.000	0.000
15	Binnin-Kebbi	0.9551	58.3091	114.500	85.900	0.000	0.000
16	**Gombe**	**0.8019**	**33.8059**	**130.600**	**97.900**	**0.000**	**0.000**
17	Jebba	1.0492	56.7994	11.000	8.200	0.000	0.000
18	Jebba GS	1.0500	57.9161	0.000	0.000	495.000	55.382
19	Jos	0.9041	39.7813	70.300	52.700	0.000	0.000
20	Kaduna	0.9350	37.9527	193.000	144.700	0.000	0.000
21	Kainji	1.0500	63.4604	7.000	5.200	624.700	61.971
22	**Kano**	**0.8179**	**30.0947**	**220.600**	**142.900**	**0.000**	**0.000**
23	Shiroro	1.0500	42.9531	70.300	36.100	388.900	647.966
24	Sapele	1.0500	27.3689	20.600	15.400	190.300	419.141
25	Abuja	0.9602	45.7018	110.000	89.000	0.000	0.000
26	Okpai	0.9977	38.7580	290.100	145.000	0.000	0.000
27	AES	1.0500	69.6336	0.000	0.000	750.000	209.868
28	Calabar	1.0500	12.5867	0.000	0.000	750.000	575.078
			TOTAL	4371.800	3173.200	3822.294	3384.647

Base MVA = 100; Accuracy = 0.001; Number of iterations = 6

TABLE II INJECTED VOLTAGES AND ANGLES OF THE SSSC

Transmission Lines	Voltage Magnitude (pu)	Angle (deg)
13-14	0.068	90
16-19	0.125	86
22-20	0.126	86

When SSSC is incorporated into the Nigerian 28-bus transmission system, the active and the reactive power flow along the transmission is controlled as presented in Table 4. It was observed that for transmission line between buses 13 and 14, the active and reactive power flow without SSSC is -18.093MW and -136.702MVar; which is controlled to 3.170MW and 29.646MVar when SSSC is incorporated. For line 16-19, it is controlled from -12.083MW and -90.828MVar (without SSSC), to 2.998MW and 25.949MVar (with SSSC). While for line 20-22, it gives -18.310MW and -138.343MVar (without SSSC) and, 3.021MW and 26.716MVar as controlled by the device. This in effect leads to a reduction in the transmission losses.

The power losses (active and reactive) are reduced considerably also as shown in Table 5. As the line flow is controlled using SSSC, the voltage magnitudes at the affected buses are also improved as shown in the bar chart and graph below

TABLE III POWER FLOW SOLUTION WITH SSSC INCORPORATED

Bus No.	Bus Name	Voltage mag. (pu)	Voltage Angle (deg)	Load		Generation	
				MW	MVar	MW	MVar
1	Egbin	1.0500	0.0000	68.900	51.700	228.882	612.512
2	Delta	1.0500	14.5472	0.000	0.000	670.000	157.614
3	Aja	1.0414	-0.5914	274.400	205.800	0.000	0.000
4	Akangba	0.9616	0.1842	344.700	258.500	0.000	0.000
5	Ikeja	0.9770	1.0681	633.200	474.900	0.000	0.000
6	Ajaokuta	0.9843	7.9769	13.800	10.300	0.000	0.000
7	Aladja	1.0472	13.1129	96.500	72.400	0.000	0.000
8	Benin	0.9913	8.3869	383.300	287.500	0.000	0.000
9	Ayede	0.9202	1.6248	275.800	206.800	0.000	0.000
10	Osogbo	0.9553	6.9291	201.200	150.900	0.000	0.000
11	Afam	1.0500	14.1914	52.500	39.400	431.000	519.597
12	Alaoji	1.0100	12.9449	427.000	320.200	0.000	0.000
13	**New Haven**	**0.9665**	**11.5997**	**177.900**	**133.400**	**0.000**	**0.000**
14	Onitsha	0.9270	5.2723	184.600	138.400	0.000	0.000
15	Binnin-Kebbi	0.9551	23.1349	114.500	85.900	0.000	0.000
16	**Gombe**	**1.0889**	**8.7203**	**130.600**	**97.900**	**0.000**	**0.000**
17	Jebba	1.0488	21.6288	11.000	8.200	0.000	0.000
18	Jebba GS	1.0500	21.9069	0.000	0.000	495.000	38.596
19	Jos	1.0434	16.8637	70.300	52.700	0.000	0.000
20	Kaduna	1.0314	10.7196	193.000	144.700	0.000	0.000
21	Kainji	1.0500	28.2862	7.000	5.200	624.700	63.975
22	**Kano**	**0.9873**	**-4.5843**	**220.600**	**142.900**	**0.000**	**0.000**
23	Shiroro	1.0500	14.0058	70.300	36.100	388.900	250.953
24	Sapele	1.0500	10.9959	20.600	15.400	190.300	421.642
25	Abuja	1.0170	24.1878	110.000	89.000	0.000	0.000
26	Okpai	0.9977	9.8108	290.100	145.000	0.000	0.000
27	AES	1.0500	48.5538	0.000	0.000	750.000	117.901
28	Calabar	1.0500	5.4188	0.000	0.000	750.000	574.847
			TOTAL	4371.800	3173.200	4528.782	2757.638

TABLE IV LINE FLOWS WITH AND WITHOUT SSSC

Transmission Line		Without SSSC		With SSSC	
From Bus	To Bus	MW	MVar	MW	MVar
13		-177.900	133.400	-177.900	-133.400
13	14	-18.093	-136.702	3.170	29.646
14		-184.600	-138.400	-184.600	-138.400
14	13	18.964	143.287	-3.040	-28.436
16		-130.600	-97.900	-130.600	-97.900
16	19	-12.083	-90.828	2.998	25.949
19		-70.300	-52.700	-70.300	-52.700
19	16	13.624	102.409	-2.872	-24.863
20		-193.000	-144.700	-193.000	-144.700
20	22	20.930	158.136	3.021	26.716
22		-220.600	-142.900	-220.600	-142.900
22	20	-18.310	-138.343	-2.892	-25.574

TABLE V ACTIVE AND REACTIVE POWER LOSS

POWER LOSS	WITHOUT SSSC	WITH SSSC	Percentage decrease with SSSC incorporated
Active (MW)	81.414	54.592	32.9%
Reactive Power (MVAR)	608.804	408.786	32.8%

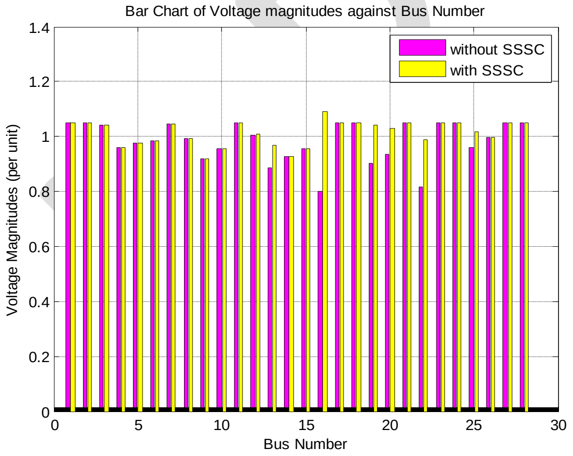

Figure 4 Bar Chart of Voltage magnitude against Bus Number as SSSC controls the line flows

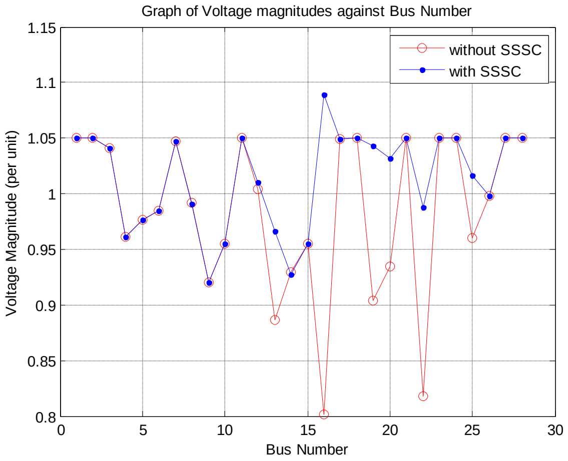

Figure 5 Graph of Voltage magnitude against Bus Number as SSSC controls the line flows

V. CONCLUSION

In this research paper, the power flow analysis of the Nigerian 28 bus 330kV transmission system was carried out and scrutinized using Newton-Raphson technique and MATLAB was used to simulate. The buses with low voltages were identified from the results obtained. The effect of applying SSSC for power flow control, voltage magnitude improvement, transmission loss reduction and improvement in system performance was vividly demonstrated. With the application of SSSC, the active and reactive power flow is effectively controlled, the voltage profile of the system is kept within acceptable limit, thereby reinforcing the grid and the system losses were also reduced significantly. Active Power loss is reduced by 32.9% and reactive power loss reduced by 32.8%. The proposed SSSC model was validated and tested using the IEEE 14 bus test system, where it was installed on line 2-4, 10-11, and 12-13. In that case the total power loss is reduced by approximately 60% and the total power (active and reactive) is effectively controlled.

The reinforcement of the network by incorporating SSSC is therefore an alternative to reduce the flows in heavily loaded lines, resulting in reduced transmission loss, increased loading ability, improved stability of the network and reduced cost of production by controlling the power flows in the network. Further works on this research involves the use of Unified Power Flow Controller (UPFC) which has the ability to adjust the three control parameters, i.e. the bus voltage, the transmission line reactance, and phase angle between two buses, either simultaneously or independently. The relationship between UPFC and IPFC (Interline Power Flow Controller) in designing two power flow control schemes, which is applicable to any FACTS controller in producing controllable voltage, is the work in progress.

APPENDIX

A. *The Jacobian Equations*

$$\frac{\partial P_i}{\partial \theta_i} = |V_i V_k Y_{ik}| \sin(\theta_{ik} + \theta_k - \theta_i) \tag{i}$$

$$\frac{\partial P_i}{\partial \theta_k} = -|V_i V_k Y_{ik}| \sin(\theta_{ik} + \theta_k - \theta_i) \tag{ii}$$

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i Y_{ii}| \cos\theta_{ii} + \sum_{i \neq k} |V_k Y_{ik}| \cos(\theta_{ik} + \theta_k - \theta_i) \tag{iii}$$

$$\frac{\partial P_i}{\partial |V_k|} = |V_i Y_{ik}| \cos(\theta_{ik} + \theta_k - \theta_i) \qquad k \neq i \tag{iv}$$

$$\frac{\partial Q_i}{\partial \theta_i} = \sum_{k \neq i} |V_i V_k Y_{ik}| \cos(\theta_{ik} + \theta_k - \theta_i) \tag{v}$$

$$\frac{\partial Q_i}{\partial \theta_k} = -|V_i V_k Y_{ik}| \cos(\theta_{ik} + \theta_k - \theta_i) \qquad k \neq i \tag{vi}$$

$$\frac{\partial Q_i}{\partial |V_i|} = -2|V_i Y_{ii}| \sin\theta_{ii} - \sum_{k \neq i} |V_k Y_{ik}| \sin(\theta_{ik} + \theta_k - \theta_i) \tag{vii}$$

$$\frac{\partial Q_i}{\partial |V_k|} = -|V_i Y_{ik}| \sin(\theta_{ik} + \theta_k - \theta_i) \qquad k \neq i \tag{viii}$$

$$[J] = \begin{bmatrix}
\frac{\partial P_i}{\partial \theta_i} & \frac{\partial P_i}{\partial \theta_k} & \frac{\partial P_i}{\partial V_i} V_i & \frac{\partial P_i}{\partial V_k} V_k & \frac{\partial P_i}{\partial \delta_{cR}} & \frac{\partial P_i}{\partial V_{cR}} V_{cR} \\
\frac{\partial P_k}{\partial \theta_i} & \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_i} V_i & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{cR}} & \frac{\partial P_k}{\partial V_{cR}} V_{cR} \\
\frac{\partial Q_i}{\partial \theta_i} & \frac{\partial Q_i}{\partial \theta_k} & \frac{\partial Q_i}{\partial V_i} V_i & \frac{\partial Q_i}{\partial V_k} V_k & \frac{\partial Q_i}{\partial \delta_{cR}} & \frac{\partial Q_i}{\partial V_{cR}} V_{cR} \\
\frac{\partial Q_k}{\partial \theta_i} & \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_i} V_i & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{cR}} & \frac{\partial Q_k}{\partial V_{cR}} V_{cR} \\
\frac{\partial P_{ik}}{\partial \theta_i} & \frac{\partial P_{ik}}{\partial \theta_k} & \frac{\partial P_{ik}}{\partial V_i} V_i & \frac{\partial P_{ik}}{\partial V_k} V_k & \frac{\partial P_{ik}}{\partial \delta_{cR}} & \frac{\partial P_{ik}}{\partial V_{cR}} V_{cR} \\
\frac{\partial Q_{ik}}{\partial \theta_i} & \frac{\partial Q_{ik}}{\partial \theta_k} & \frac{\partial Q_{ik}}{\partial V_i} V_i & \frac{\partial Q_{ik}}{\partial V_k} V_k & \frac{\partial Q_{ik}}{\partial \delta_{cR}} & \frac{\partial Q_{ik}}{\partial V_{cR}} V_{cR}
\end{bmatrix} \tag{ix}$$

B. *SSSC Data*

Bus i	Bus k	Vse	Theta	Q_{min}	Q_{max}	V_{mi}	V_{mk}	degi	degk	B_{ik}
13	14	0.068	90	0	0	0.8863	0.9290	22.2196	24.7169	0.1807
16	19	0.125	86	0	0	0.8019	0.9041	33.8059	39.7813	0.5892
22	20	0.126	86	0	0	0.8179	0.9350	0.8179	37.9527	0.4516

Conductance of SSSC, $\mathbf{g_{se} = 0.9901}$
Susceptance of SSSC, $\mathbf{b_{se} = -9.901}$
$\mathbf{V_{se}}$= injected SSSC voltage magnitude
Theta= SSSC angle
$\mathbf{V_{mi}}$ = Sending end voltage magnitude
$\mathbf{V_{mk}}$= Receiving ends voltage magnitude

REFRENCES

[1]. A. M. El-Zonkoly, "Optimal Sizing of SSSC Controllers to Minimize Transmission loss and a Novel Model of SSSC to Study Transient Response," World Academy of Science, Engineering and Technology, pp. 825–830, Oct. 2008.

[2]. Ahmad Rohani, M. Reza Safari, Reza Noroozian, "Combined Design of PSS and STATCOM Controllers for Power System Stability Enhancement", Journal of Power Electronics, vol. 11, no. 5, pp.734-740, Sept. 2011.

[3]. Hadi Sadaat, Power System Analysis, 2nd Edition, McGraw- Hill Primis Custom Publishing. 2006.

[4]. Adebayo I. G., Adejumobi, I. A., and Adepoju, G. A. (2013). Application of Load Tap-Changer Transformer (LTCT) to the Optimal Economic Dispatch of Generation of the Nigerian 330kV Grid System. International Journal of Emerging Technologies in Science and Engineering, Vol.5 (03), pp40-50.

[5]. CIGRÉ 95 TP108, FACTS Overview, IEEE Power Engineering Society, 1995.

[6]. Abdul Haleem, Ravireddy Malgireddy, “Power Flow Control with Static Synchronous Series Compensator (SSSC)”, Proc of the International Conference on Science and Engineering (ICSE 2011), pp. 1-5, 2011.

[7]. ArthitSode-Yome, NadarajahMiithulananthan and Kwang Y. Lee, "Static Voltage Stability Margin Enhancement Using STATCOM, TCSC and SSSC," IEEE/PES Transmission and Distribution Conference and Exibition, Asia and Pacific Dalian, China, pp. 1-6, 2005.

[8]. Onohaebi O. Sunday, “ Power Outage in the Nigeria Transmission Grid”, Medwell Journal for Scientific Research Publishing, vol. 4, issue 1, pp.1-9, 2009.

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