Reactive Power Compensation in Nigeria Electricity Grid Using Static Synchronous Compensator (STATCOM)

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Abstract: *Persistent problem of voltage instability in electricity grids of most developing countries of the world including Nigeria highlights the need to address the challenges of reactive power compensation using advances in power electronic technologies such as the use of Flexible Alternating Current Transmission System (FACTS) with fast response time and low cost. This work examines the effect of application of Static Synchronous Compensator (STATCOM), a FACTS device for reactive power compensation in electricity grid using the Nigeria 330 kV, 28-bus power network as a case study. The steady state conditions of the system before and after compensation were modelled using the Newton-Raphson-based power flow equations. The developed equations were coded and simulated using Matlab software (Version 7.9.0.529 'R2009b'). The simulation results showed that before application of STATCOM, the voltage magnitudes of five (5) of the twenty eight (28) buses of the system under study fell outside the voltage bound constraint limit of $0.95 \leq V_i \leq 1.05$ p.u and were improved to 1.0 p.u. each with the application of STATCOM. Also, the total system active power loss was reduced by 5.88% from 98.21 to 92.44MW. The results of this work therefore revealed that application of STATCOM in the Nigeria electricity grid will stabilise the system voltage and reduce the transmission active power loss thereby providing additional capacities for the consumers.*
Keywords: *Voltage instability, Electricity grid, Reactive power compensation, FACTS, STATCOM, Nigeria.*

I. Introduction

Electric power system is a complex interconnected network of components such as generators, overhead conductors, underground cables, transformers, protective devices etc. The increasing problem of voltage instability among others on such a network is a serious operational challenge facing the electricity supply utilities in most developing countries of the world including Nigeria. The consumers at every level including domestic, commercial and industrial users have been on the receiving end of the voltage instability problem in Nigeria electricity grid, experiencing major discomforts in operating their electrical and electronic devices as well as unable to run smoothly their day-to-day activities since they depend largely on stable and quality electricity supply. More so, this problem to a very great extent has hindered the general socio-economic, technological and industrial advancements of the general Nigerian populace.

Despite the reform exercise and other corrective measures put in place by the Federal Government of Nigeria to address the operational challenges facing her electricity grid, voltage instability problem still persist. Most of voltage instability problems in the Nigeria electricity grid can be traced to inadequate and inefficient reactive power compensation in the system. Therefore, the need to devise means of compensating reactive power in Nigeria electricity supply network becomes highly imperative for efficient operation of the system. To address this, adoption of advanced control technologies such as FACTS is an important option for the Nigeria electricity system reactive power compensation in view of the slow response of the conventional traditional methods for improving power system performance [1].

FACTS technology is a novel concept based on the use of power electronics controllers which are fast acting and cost effective [1, 2, 3, 4, 5, 6] for controlling the power flow in electric power networks. The ability of FACTS to control the line impedance and the nodal voltage magnitudes and phase angles at both the sending and the receiving ends of key transmission lines, with almost no delay, has significantly increased the transmission capabilities of the network while considerably enhancing the security of the system [7]. Some of the common FACTS controllers in use are Interphase Power Controller (IPC), Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC), Thyristor Controlled Breaking Reactor (TCR), Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Thyristor Switched Series Reactor (TSSR), Unified Power Flow Controller (UPFC) [8]. These controllers have their distinct characteristics which are suitable for different applications and due to these various researches have been carried out to examine their potential applications and benefits [9, 10, 11, 12, 13, 14, 15].

In this study, our aim is to examine the effect of application of STATCOM for reactive power compensation in electricity grid using the Nigeria 330 kV, 28-bus power network as a case study. STATCOM is

a shunt-connected device capable of injecting or absorbing reactive power to regulate the voltageprofiles of the power system bus to which is connected [4, 16].

II.   Reactive Power and Reactive Compensation

Reactive power measured in volt ampere reactive (Var) is an integral part of an Alternating Current (AC) system essential for an optimised performance of power system components such as transformers, transmission lines, generators, motors etc. It is very important in maintaining efficient system operation and keeping voltage and load stable [17]. If a system is deficient in reactive power, the voltage sags and this hinders the power demanded by loads from being transferred through the lines. Hence, the generation of reactive power is vital for stabilizing the network voltage under normal and abnormal power system operations and to reduce system losses [17].

Generally, the unbalanced loads in an AC system produce undesired negative and zero sequence currents [18]. Negative sequence current is capable of causing excessive heating in electrical machines, saturation in transformers, ripples in rectifiers or even instability problems of generators. Zero sequence currenton the other hand can cause excessive power losses in neutral lines and protection and interference problems [18]. Therefore, to achieve a balanced operation for unbalanced AC system and improve power transfer capability, reactive power compensation problems must be adequately addressed. Also, most of the power outage issues in power system networks are related to voltage collapses which are direct consequences of lack of reactive power compensation in heavily stressed conditions, which are usually triggered by system faults. Therefore, the voltage collapse problems of power system networks are closely related to a reactive power planning problems including contingency analyses, where suitable conditions of reactive power reserves are analyzed for secure operations of power systems [19].

Some of the potential benefits of reactive power compensation in power systems include [20] high quality voltage and improved stability, reduced system losses, improved voltage regulation, improvedpower factor and decreased kVA demand of the source generators among others.

III.   Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is a controlled Voltage Source Inverter (VSI) usually shunt-connected across the transmission line (across the phases) through a coupling transformer [21]. This device provides control over the line voltage at the point of coupling and over the Direct Current (DC) bus voltage within it by respectively regulating reactive power injected into the network and the active power drawn from the network [21]. The amount of active power exchanged between the STATCOM and the power line is used to charge or discharge a capacitor across the DC link inside the inverter, and is therefore a relatively small amount, compared with the amount of reactive power exchanged. Fig. 1 is a simplified form of STATCOM consisting of a coupling transformer, a VSI and a capacitor.
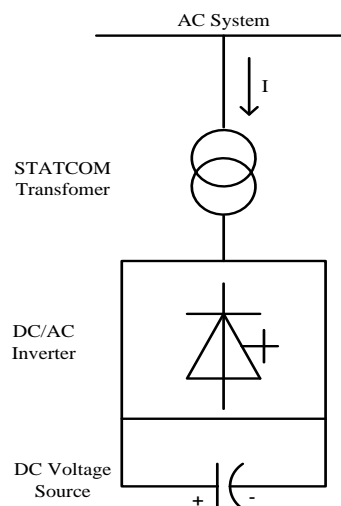

Figure 1: STATCOM functional model [16]

IV.   The System Modelling

Power flow equations are highly essential set of algebraic equations in the analysis of the performance of power systems because they provide suitable mathematical model of the systems from which important information regarding the voltage profile, reactive power compensation requirements etc. can easily be obtained

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[17]. For the analysis of the system model in this study, we consider a simplified i^{th} bus model of a power network shown in Fig. 2.
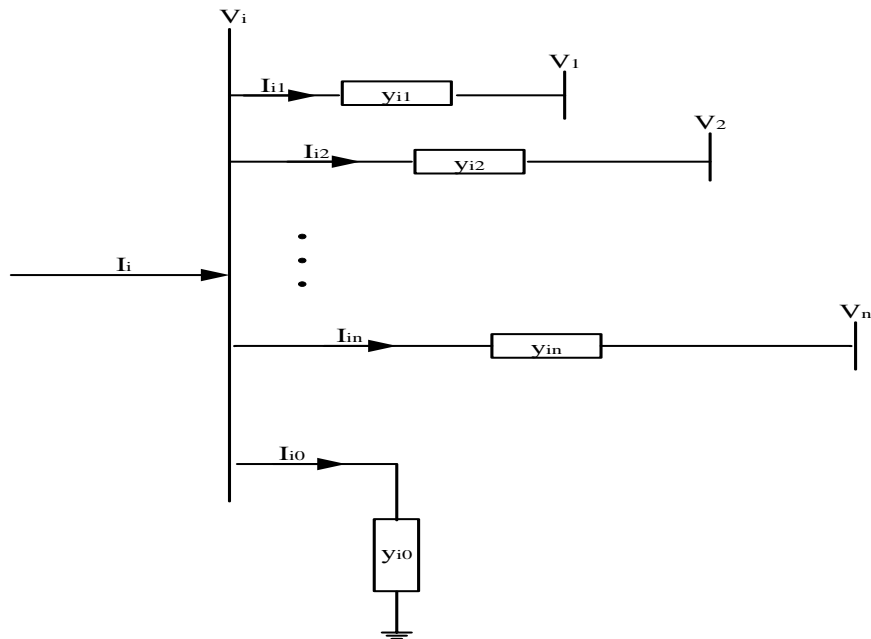

Figure 2: A simplified i^{th} bus model of a power system

Application of Kirchhoff's Current Law (KCL) to bus i gives an expression for the net current injected at the bus as:

$$I_i = I_{i0} + I_{i1} + I_{i2} + \cdots + I_{in} \tag{1}$$

Where I_i = current injected into bus i
$\quad$ I_{i0} = current flowing from bus i to ground
$\quad$ I_{i1} = current flowing from bus i to bus 1
$\quad$ I_{i2} = current flowing from bus i to bus 2
$\quad$ I_{in} = current flowing from bus i to bus n

If we apply Ohm's law to each bus 1 to n with reference to bus i, equation (1) is modified into equation (2) as:

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots + y_{in}(V_1 - V_n) \tag{2}$$

Where V_i = voltage at bus i
$\quad$ V_1 = voltage at bus 1
$\quad$ V_2 = voltage at bus 2
$\quad$ V_n = voltage at bus n

By rearranging equation (2), we obtain a simplified expression given by equation (3):

$$I_i = (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{in}V_n \tag{3}$$

Where y_{i0} = admittance of transmission line between bus i and ground
$\quad$ y_{i1} = admittance of transmission line between bus i and bus 1
$\quad$ y_{i2} = admittance of transmission line between bus i and bus 2
$\quad$ y_{in} = admittance of transmission line between bus i and bus n

Also, if we define:

$$\begin{cases} Y_{ii} = y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in} \\ Y_{i1} = -y_{i1} \\ Y_{i2} = -y_{i2} \\ \vdots \quad \vdots \quad \vdots \\ Y_{in} = -y_{in} \end{cases} \qquad (4)$$

and substitute in equation (3), we obtain equation (5):

$$I_i = Y_{ii}V_i + Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{in}V_n \qquad (5)$$

Equation (5) is equivalently expressed as equation (6):

$$I_i = Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k \qquad (6)$$

Recalling from the expression for complex power [17, 22, 23] injected at bus i, we obtain equation (7):

$$S_i = P_i - jQ_i = V_i^* I_i \qquad (7)$$

Where S_i = apparent power injected at bus i
  P_i = real power injected at bus i
  Q_i = reactive power injected at bus i
  V_i^* = complex conjugate of bus i voltage

Using equation (6) in (7) we obtain equation (8) expressed as:

$$\frac{P_i - jQ_i}{V_i^*} = Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k \qquad (8)$$

If we make V_i the subject in equation (8), we obtain equation (9):

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k\right] \qquad (9)$$

Also, by decoupling equation (8) into real and imaginary parts and expressing the components parts in polar form, we obtain equations (10) and (11):

$$P_i = |V_i|^2 G_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik}V_kV_{ik}|\cos(\theta_{ik} + \delta_k - \delta_i) \qquad (10)$$

$$Q_i = |V_i|^2 B_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik}V_kV_{ik}|\sin(\theta_{ik} + \delta_k - \delta_i) \qquad (11)$$

Where G_{ii} = self-conductance of bus i
  B_{ii} = self-susceptance of bus i

Since the voltage at the buses must be maintained within certain specified statutory limit, the voltage bound constraint limit at bus i is then defined by equation (12):

$$V_{i(min)} \leq V_i \leq V_{i(max)} \qquad (12)$$

Where $V_{i(min)}$ and $V_{i(max)}$ are minimum and maximum values of voltage at bus i.

If we consider that P_i and Q_i give a measure of the net real and reactive power at the bus i, then they can be equivalently expressed by equations (13) and (14):

$$P_i = P_{gi} - P_{li} \qquad (13)$$

$$Q_i = Q_{gi} - Q_{li} \qquad (14)$$

Where P_{gi} = real power supply at bus i

P_{li} = real power demand at bus i

Q_{gi} = reactive power supply at bus i

Q_{li} = reactive power demand at bus i

The reactive power supply constraint at bus i is specified by equation (15):

$$Q_{gi(min)} \leq Q_{gi} \leq Q_{gi(max)} \qquad (15)$$

Where $Q_{gi(min)}$ and $Q_{gi(max)}$ are minimum and maximum values of reactive power supply at bus i.

If the constraint defined by equation (15) is not satisfied that is Q_{gi} does not lie within the limit, it must be set to appropriate limit. Q_{gi} is set to $Q_{gi(max)}$ if Q_{gi} is greater than $Q_{gi(max)}$ and it is set to $Q_{gi(min)}$ if Q_{gi} is less than $Q_{gi(max)}$ and the constraint that voltage at bus i is fixed must be released [24].

By considering further a situation when STATCOM is shunt-connected at bus i in Fig. 2 and it is treated as Var source, equations (13) and (14) can be modified as equations (16) and (17) respectively:

$$P_i = P_{gi} + P_{STCi} - P_{li} \qquad (16)$$
$$Q_i = Q_{gi} - Q_{STCi} - Q_{li} \qquad (17)$$

Where P_{STCi} = STATCOM real power at bus i

Q_{STCi} = STATCOM reactive power at bus i

Equations (16) and (17) represent a case where STATCOM injects Var into the system at bus i and for Var absorption, the signs of P_{STCi} and Q_{STCi} become reversed.

Due to the non-linearity of algebraic equations (10) and (11) describing the power flow, their solution is usually based on an iterative technique. Hence, the method of solution adopted in this work for power flow equations (10) and (11) with a shunt-connected STATCOM at bus i is Newton-Raphson iterative method and it was adopted because of its faster rate of convergence and accuracy when compared with other methods of solution for non-linear power flow equations such as Gauss-Siedel method [22, 23].

In this work, the modelling and analysis of STATCOM with adopted the Newton-Raphson method using rectangular coordinates system was a modified form of the version considered in Adepoju and Komolafe [25]. The Thevenin's equivalent circuit of the fundamental frequency operation of the switched mode voltage source inverter (STATCOM) and its transformer is shown in Fig. 3.
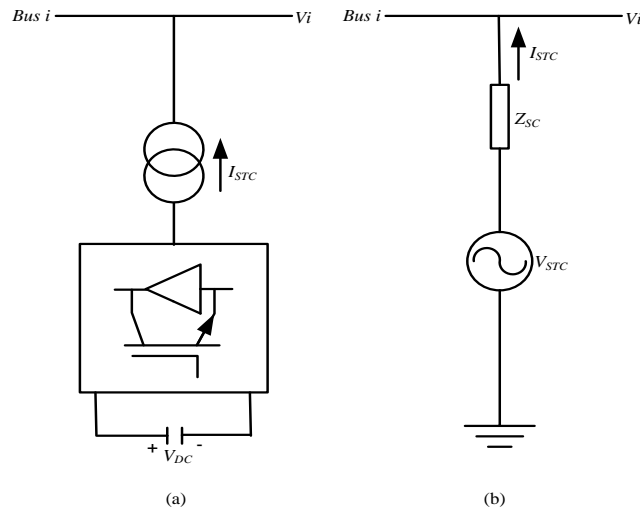
Figure 3: Thevenin's equivalent circuit diagram of STATCOM: (a) STATCOM schematic diagram; (b) STATCOM equivalent circuit [25]

From the above Fig. 3, we obtain equation (18):

$$V_{STC} = V_i + Z_{SC}I_{STC} \qquad (18)$$

Where V_{STC} = STATCOM voltage
      I_{STC} = STATCOM current
      Z_{SC} = transformer's impedance

Expressing equation (18) in its Norton's equivalent, we again obtain equation (19) given as:

$$I_{STC} = I_N - Y_{SC}V_i \qquad (19)$$

With $I_N = Y_{SC}V_{STC}$ (20)
Where I_N = Norton's current
      Y_{SC} = short-circuit admittance

The voltage injection bound constraint of STATCOM is given by equation (21)[25]:

$$V_{STC\ min} \leq V_{STC} \leq V_{STC\ max} \qquad (21)$$

Where V_{STCmin} and V_{STCmax} are the STATCOM's minimum and maximum voltages.

Equation (19) is transformed into a power expression for STATCOM and power injected into bus i by equations (22) and (23) respectively:

$$S_{STC} = V_{STC} I_{STC}^{*} = V_{STC}V_{STC}^{*}Y_{SC}^{*} - V_{STC}Y_{SC}^{*}V_i^{*} \qquad (22)$$

$$S_i = V_i I_{STC}^{*} = V_i V_i^{*} Y_{SC}^{*} - V_i V_{STC}^{*} Y_{SC}^{*} \qquad (23)$$

Where S_{STC}= STATCOM injected apparent power
      I_{STC}^{*}= complex conjugate of STATCOM current
      V_{STC}^{*} = complex conjugate of STATCOM voltage
      Y_{SC}^{*}= complex conjugate of short-circuit admittance

The bus i and STATCOM voltages in rectangular coordinates system are expressed as equations (24) and (25) respectively:

$$V_i = e_i + jf_i \qquad (24)$$

$$V_{STC} = e_{STC} + jf_{STC} \qquad (25)$$

Where e_i = real component of bus i voltage

f_i = imaginary component of bus i voltage

e_{STC} = real component of STATCOM voltage

f_{STC} = imaginary component of STATCOM voltage

The STATCOM's voltage magnitude and angle are expressed as equations (26) and (27) respectively:

$$|V_{STC}| = (e_{STC}^2 + f_{STC}^2)^{\frac{1}{2}} \qquad (26)$$

$$\delta_{STC} = \tan^{-1}\left(\frac{f_{STC}}{e_{STC}}\right) \qquad (27)$$

Where $|V_{STC}|$ = STATCOM voltage magnitude

δ_{STC} = STATCOM voltage angle

The active and reactive power components for the STATCOM and bus i on the basis of equations (22) to (25) are respectively expressed by equations (28) to (31):

$$P_{STC} = G_{SC}\{(e_{STC}^2 + f_{STC}^2) - (e_{STC}e_i + f_{STC}f_i)\} + B_{SC}(e_{STC}f_i - f_{STC}e_i) \qquad (28)$$

$$Q_{STC} = G_{SC}(e_{STC}f_i - e_if_{STC}) + B_{SC}\{e_{STC}e_i + f_{STC}f_i - (e_{STC}^2 + f_{STC}^2)\} \qquad (29)$$

$$P_i = G_{SC}\{e_i^2 + f_i^2 - (e_ie_{STC} + f_if_{STC})\} + B_{SC}(e_if_{STC} - f_ie_{STC}) \qquad (30)$$

$$Q_i = G_{SC}(e_if_{STC} - f_ie_{STC}) + B_{SC}\{e_ie_{STC} + f_if_{STC} - (e_i^2 + f_i^2)\} \qquad (31)$$

Where P_{STC} = STATCOM real power

Q_{STC} = STATCOM reactive power

G_{SC} = short-circuit conductance

B_{SC} = short-circuit susceptance

The Newton-Raphson set of linearized equations for power flow equations (10), (11), (16) and (17) obtained taken into consideration the modelling of shunt-connected STATCOM at bus i is given by equation (32):

$$
\begin{bmatrix} \Delta P_i \\ \Delta |V_i| \\ \Delta P_{STC} \\ \Delta Q_{STC} \end{bmatrix} =
\begin{bmatrix}
\frac{\partial P_i}{\partial e_i} & \frac{\partial P_i}{\partial f_i} & \frac{\partial P_i}{\partial e_{STC}} & \frac{\partial P_i}{\partial f_{STC}} \\
\frac{\partial |V_i|}{\partial e_i} & \frac{\partial |V_i|}{\partial f_i} & 0 & 0 \\
\frac{\partial P_{STC}}{\partial e_i} & \frac{\partial P_{SCT}}{\partial f_i} & \frac{\partial P_{STC}}{\partial e_{STC}} & \frac{\partial P_{STC}}{\partial f_{STC}} \\
\frac{\partial Q_{STC}}{\partial e_i} & \frac{\partial Q_{STC}}{\partial f_i} & \frac{\partial Q_{STC}}{\partial e_{STC}} & \frac{\partial Q_{STC}}{\partial f_{STC}}
\end{bmatrix}
\begin{bmatrix} \Delta e_i \\ \Delta f_i \\ \Delta e_{STC} \\ \Delta e_{STC} \end{bmatrix} \qquad (32)
$$

Where the partial derivatives of the Jacobian matrix are defined on the basis of equations (24) and (28) to (31) by the expressions given in equation (33):

$$
\begin{cases}
\frac{\partial P_i}{\partial e_i} = G_{SC}(2e_i - e_{STC}) + B_{SC}f_{STC} \\[4pt]
\frac{\partial P_i}{\partial f_i} = G_{SC}(2f_i - f_{STC}) - B_{SC}f_{STC} \\[4pt]
\quad \frac{\partial P_i}{\partial e_{STC}} = -G_{SC}e_i - B_{SC}f_i \\[4pt]
\quad \frac{\partial P_i}{\partial f_{STC}} = -G_{SC}f_i + B_{SC}e_i \\[4pt]
\quad\quad \frac{\partial |v_i|}{\partial e_i} = \frac{e_i}{\sqrt{e_i^2 + f_i^2}} \\[8pt]
\quad\quad \frac{\partial |v_i|}{\partial f_i} = \frac{e_i}{\sqrt{e_i^2 + f_i^2}} \\[8pt]
\quad \frac{\partial P_{STC}}{\partial e_i} = -G_{SC}e_{STC} - B_{SC}f_{STC} \\[4pt]
\quad \frac{\partial P_{SCT}}{\partial f_i} = -G_{SC}f_{STC} + B_{SC}e_{STC} \\[4pt]
\frac{\partial P_{STC}}{\partial e_{STC}} = G_{SC}(2e_{STC} - e_i) + B_{SC}f_i \\[4pt]
\frac{\partial P_{STC}}{\partial f_{STC}} = G_{SC}(2f_{STC} - f_i) - B_{SC}e_i \\[4pt]
\quad \frac{\partial Q_{STC}}{\partial e_i} = -G_{SC}f_{STC} + B_{SC}e_{STC} \\[4pt]
\quad \frac{\partial Q_{STC}}{\partial f_i} = G_{SC}e_{STC} + B_{SC}f_{STC} \\[4pt]
\frac{\partial Q_{STC}}{\partial e_{STC}} = G_{SC}f_i + B_{SC}(e_i - 2e_{STC}) \\[4pt]
\frac{\partial Q_{STC}}{\partial f_{STC}} = -G_{SC}e_i + B_{SC}(f_i - 2f_{STC})
\end{cases}
\qquad (33)
$$

4.1 Choice of Simulation Software
The developed power flow equations were implemented using Matlab software, version 7.9.0.529 (R2009b). Matlab is a high efficient and user-friendly programming language. It was basically adopted for this work because it provides a simple, easy-to-use programming platform for manipulation of mathematical equations.

V.   Simulation Results and Discussion

The load flow and transmission line data of the Nigeria 330 kV, 28-bus power network used as a case study were collected from the Transmission Company of Nigeria [26]. The Nigeria 28-bus power network consisting of twenty-eight (28) buses, nine (9) generation stations, and fifty-two (52) transmission lines is shown in Fig. 4.
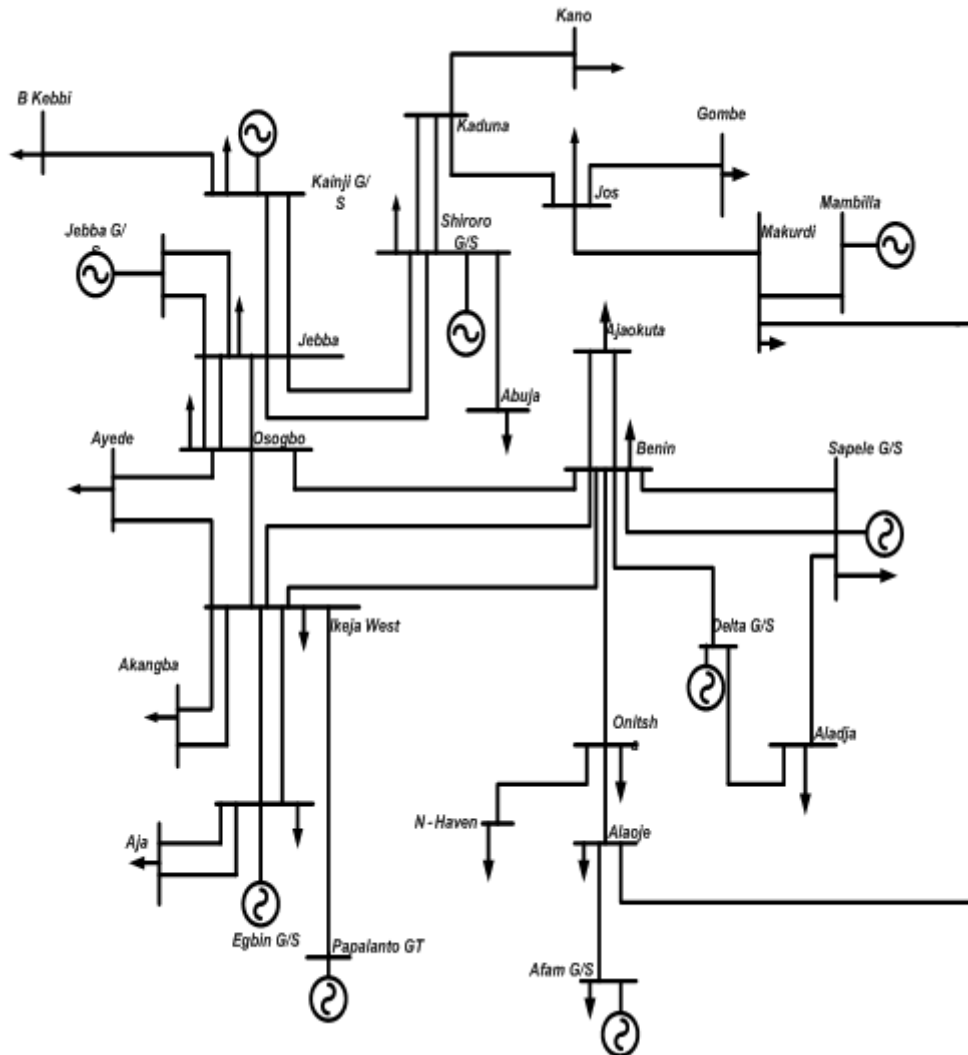
Figure 4: The single line diagram of the Nigeria 28-bus network [25]

The load flow data showing the load and generation at the buses is shown in Tables 1 while the transmission line data is shown in Table 2.

Table 1: Load flow data showing load and generation at the buses [26]

Bus No	Bus Name	Bus Code	Voltage Magnitude	Angle Degree	Load		Generator				Static MVar +Qc/-Ql
					MW	MVar	MW	MVar	Qmin	Qmax	
1	Egbin	1	1.05	0	68.90	51.70	0.00	0.00	-1006	1006	0.00
2	Delta	2	1.05	0	0.00	0.00	670.00	0.00	-1030	1000	0.00
3	Aja	0	1.00	0	274.40	205.80	0.00	0.00	0.00	0.00	0.00
4	Akangba	0	1.00	0	244.70	258.50	0.00	0.00	0.00	0.00	0.00
5	Ikeja-West	0	1.00	0	633.20	474.90	0.00	0.00	0.00	0.00	0.00
6	Ajaokuta	0	1.00	0	13.80	10.30	0.00	0.00	0.00	0.00	0.00
7	Aladja	0	1.00	0	96.50	72.40	0.00	0.00	0.00	0.00	0.00
8	Benin	0	1.00	0	383.30	287.50	0.00	0.00	0.00	0.00	0.00
9	Ayede	0	1.00	0	275.80	206.8	0.00	0.00	0.00	0.00	0.00
10	Osogbo	0	1.00	0	201.20	150.90	0.00	0.00	0.00	0.00	0.00
11	Afam	2	1.05	0	52.50	39.40	431.00	0.00	-1000	1000	0.00
12	Alaoji	0	1.00	0	427.00	320.20	0.00	0.00	0.00	0.00	0.00
13	New-Heaven	0	1.00	0	177.90	133.40	0.00	0.00	0.00	0.00	0.00
14	Onitsha	0	1.00	0	184.60	138.40	0.00	0.00	0.00	0.00	0.00
15	B/Kebbi	0	1.00	0	114.50	85.90	0.00	0.00	0.00	0.00	0.00
16	Gombe	0	1.00	0	130.60	97.90	0.00	0.00	0.00	0.00	0.00
17	Jebba	0	1.00	0	11.00	8.20	0.00	0.00	0.00	0.00	0.00
18	Jebba G	2	1.05	0	0.00	0.00	495.00	0.00	-1050	1050	0.00
19	Jos	0	1.00	0	70.30	52.70	0.00	0.00	0.00	0.00	0.00
20	Kaduna	0	1.00	0	193.00	144.70	0.00	0.00	0.00	0.00	0.00

21	Kanji	2	1.05	0	7.00	5.20	624.70	0.00	-1010	1010	0.00
22	Kano	0	1.00	0	220.60	142.90	0.00	0.00	0.00	0.00	0.00
23	Shiroro	2	1.05	0	70.30	36.10	388.90	0.00	-1010	1010	0.00
24	Sapele	2	1.05	0	20.60	15.40	190.30	0.00	-1010	1010	0.00
25	Abuja	0	1.00	0	110.00	89.00	0.00	0.00	0.00	0.00	0.00
26	Makurdi	0	1.00	0	290.10	145.00	0.00	0.00	0.00	0.00	0.00
27	Mambila	2	1.05	0	0.00	0.00	750.00	0.00	-1010	1010	0.00
28	Papalanto	2	1.05	0	0.00	0.00	750.00	0.00	-1010	1010	0.00

Table 2: Transmission line data of the Nigeria 28-bus power network [26]

Bus		Resistance (p.u.)	Reactance (p.u.)
From	To		
3	1	0.0006	0.0044
3	1	0.0006	0.0044
3	1	0.0006	0.0044
4	5	0.0007	0.0050
4	5	0.0007	0.0050
1	5	0.0023	0.0176
1	5	0.0023	0.0176
5	8	0.0110	0.0828
5	8	0.0110	0.0828
5	9	0.0054	0.0405
5	10	0.0099	0.0745
6	8	0.0077	0.0576
6	8	0.0077	0.0576
2	8	0.0043	0.0317
2	7	0.0012	0.0089
7	24	0.0025	0.0186
8	14	0.0054	0.0405
8	10	0.0098	0.0742
8	24	0.0020	0.0148
8	24	0.0020	0.0148
9	10	0.0045	0.0340
15	21	0.0122	0.0916
15	21	0.0122	0.0916
10	17	0.0061	0.0461
10	17	0.0061	0.0461
10	17	0.0061	0.0461
11	12	0.0010	0.0074
11	12	0.0010	0.0074
12	14	0.0060	0.0455
13	14	0.0036	0.0272
13	14	0.0036	0.0272
16	19	0.0118	0.0887
17	18	0.0002	0.0020
17	18	0.0002	0.0020
17	23	0.0096	0.0721
17	23	0.0096	0.0271
17	21	0.0032	0.0239
17	21	0.0032	0.0239
19	20	0.0081	0.0609
20	22	0.0090	0.0680
20	22	0.0090	0.0680
20	23	0.0038	0.0284
20	23	0.0038	0.0284
23	25	0.0038	0.0284
23	25	0.0038	0.0284
12	26	0.0071	0.0532
12	26	0.0071	0.0532

Bus		Resistance (p.u.)	Reactance (p.u.)
19	26	0.0059	0.0443
19	26	0.0059	0.0443
26	27	0.0079	0.0591
26	27	0.0079	0.0591
5	28	0.0016	0.0118
5	28	0.0016	0.0118

The simulation results of developed power flow equations using Matlab programming codes showed that before the application of STATCOM, five (5) of the 28 buses namely buses 9, 13, 14, 16 and 22 had their voltage magnitudes fell outside the voltage bound constraint limit defined by $0.95 \leq V_i \leq 1.05$ p.u. As a result, STATCOM was applied on them. Fig. 5 shows the voltage magnitudes of the 28-bus network with and without application of STATCOM.
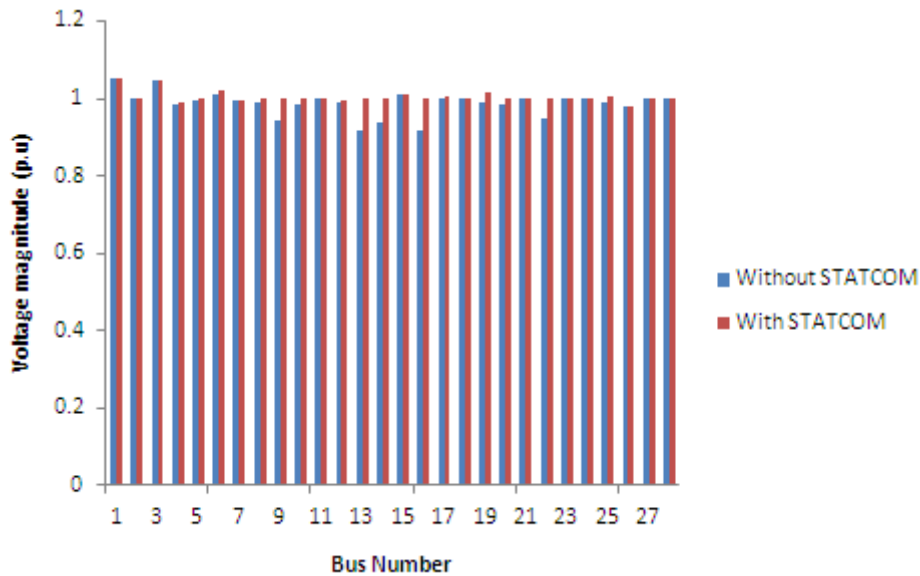

Figure 5: Bar chart showing voltage magnitude of Nigeria 28-bus power network with and without STATCOM.

From the above Fig. 5, it was observed that the voltage magnitudes in per unit of buses 9, 13, 14, 16 and 22 improved to 1.0 p.u. each within the limit of voltage bound constraint with the application of STATCOM.

The improvement in the voltage profile of the system was as a result of the reactive power compensation by STATCOM. Since the voltage magnitudes of buses 9, 13, 14, 16 and 22 were lower than the lower limit of the voltage bound constraint, STATCOM injects reactive power into the system to compensate for the drop in voltage on the affected buses and thereby improving their voltage magnitudes to 1.0 p.u. each.

Also, the results revealed that there was an improvement on the transmission of active power at the inclusion of STATCOM on buses 9, 13, 14, 16 and 22. Fig. 6 shows the system's total active power loss with and without the application of STATCOM.
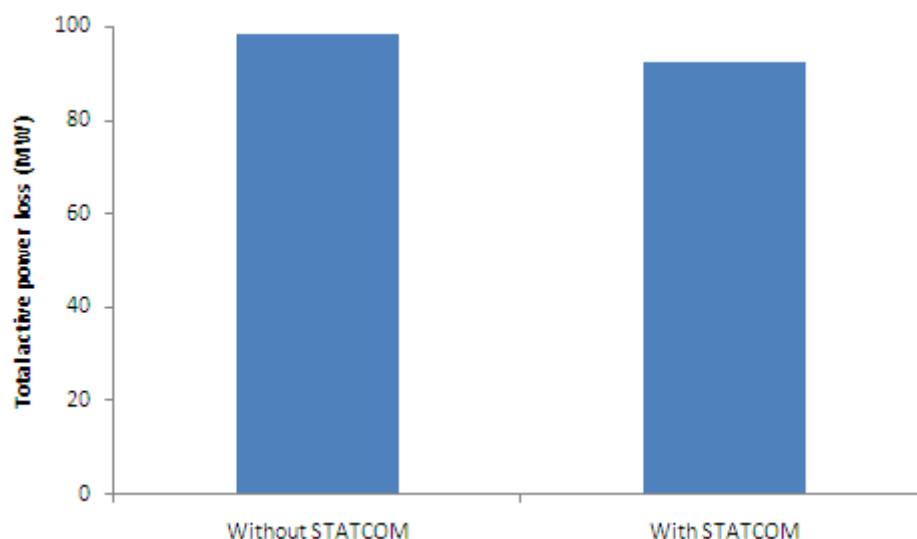
Figure 6: System's total active power loss with and without STATCOM

From the above Fig. 6, there was a reduction of 5.88% in total active power loss from 98.21 MW to 92.44 MW, thereby improving the active power transmission capacity of the transmission lines. These results show that STATCOM has the capability to improve the voltage at buses and reduce active power loss on the power system.

VI.   Conclusion

The increasing voltage instability problem in the Nigeria electricity grid is a serious operational challenge facing the electricity supply utilities. In this work, the effect of application of STATCOM for reactive power compensation in electricity grid using the Nigeria 28-bus power network as case a study was examined. Since the quality of power supply for any given system depends on voltage at the buses and transmitted power, it is imperative to keep the bus voltage within the specified voltage bound constraint limit and reduce the transmission active power loss to minimum and to achieve this, effective reactive power compensation in the electricity grid must be enhanced. Application of STATCOM on five (5) buses of the Nigeria 28-bus power network whose voltage value fell outside the voltage bond constraint limit of $0.95 \leq V_i \leq 1.05$ p.u. showed improvement on voltage magnitudes of the buses to 1.0 p.u and also reduced the transmission total active power loss from 98.21 MW to 92.44 MW, giving a 5.88% reduction in the total active power loss for the system. The improvement in voltage and active power transmission of the system was due to injection of reactive power by STATCOM to compensate for the drop in voltage on the affected buses. Hence, adequate reactive power compensation in Nigeria electricity grid using a fast acting and low cost FACTS device such as STATCOM should be given the needed priority since this will go a long way towards improving the overall voltage and power profiles of the system and in turn enhance efficient power transmission control.

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