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 ≤ V ≤ 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 reforms 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 voltage profiles 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 current on 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, improved power 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.

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.
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:

$$I_i = I_{i0} + I_{i1} + I_{i2} + \cdots + I_{in}$$  \hspace{1cm} (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:

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots + y_{in}(V_i - V_n)$$  \hspace{1cm} (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):

$$I_i = (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{in}V_n$$  \hspace{1cm} (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:
and substitute in equation (3), we obtain equation (5):

\[ I_i = Y_{ii}V_i^* + \sum_{k=1}^{P} Y_{ik}V_k \tag{5} \]

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

\[ I_i = Y_{ii}V_i^* + \sum_{k=1}^{P} Y_{ik}V_k \tag{6} \]

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

\[ S_i = P_i - jQ_i = V_i^*I_i \tag{7} \]

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:

\[ \frac{P_i - jQ_i}{V_i^*} = Y_{ii}V_i^* + \sum_{k=1}^{P} Y_{ik}V_k \tag{8} \]

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

\[ V_i^* = \left( \frac{P_i - jQ_i}{Y_{ii} + \sum_{k=1}^{P} Y_{ik}} \right) \tag{9} \]

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

\[ P_i = |V_i|^2G_{ii} + \sum_{k=1}^{P} |V_{ik}|V_{ik} \cos(\theta_{ik} + \delta_k - \delta_i) \tag{10} \]

\[ Q_i = |V_i|^2B_{ii} + \sum_{k=1}^{P} |V_{ik}|V_{ik} \sin(\theta_{ik} + \delta_k - \delta_i) \tag{11} \]

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):

\[ V_{i(min)} \leq V_i \leq V_{i(max)} \tag{12} \]

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):

\[ P_i = P_{g_i} - P_{hi} \tag{13} \]
Q_i = Q_{gi} - Q_{li} \quad (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):

\[
Q_{gi(\text{min})} \leq Q_{gi} \leq Q_{gi(\text{max})} \quad (15)
\]

Where \( Q_{gi(\text{min})} \) and \( Q_{gi(\text{max})} \) 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 \( Q_{gi(\text{max})} \) if \( Q_{gi} \) is greater than \( Q_{gi(\text{max})} \) and it is set to \( Q_{gi(\text{min})} \) if \( Q_{gi} \) is less than \( Q_{gi(\text{max})} \) 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:

\[
P_i = P_{gi} + P_{STCI} - P_{li} \quad (16)
\]
\[
Q_i = Q_{gi} - Q_{STCI} - Q_{li} \quad (17)
\]

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

\[
V_{STC} = V_i + Z_{SC}I_{STC} \tag{18}
\]

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:

\[
I_{STC} = I_N - Y_{SC}V_i \tag{19}
\]

Where \( I_N \) = Norton’s current
\( Y_{SC} \) = short-circuit admittance

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

\[
V_{STCmin} \leq V_{STC} \leq V_{STCmax} \tag{21}
\]

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:

\[
S_{STC} = V_{STC}I_{STC} = V_{STC}^*V_{STC} - V_{STC}Y_{SC}I_i^* \tag{22}
\]

\[
S_i = V_iI_{STC}^* = V_i^*V_i^* - V_i^*Y_{SC}^* \tag{23}
\]

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:

\[
V_i = e_i + jf_i \tag{24}
\]
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\( V_{STC} = \mathbf{e}_{STC} + j \mathbf{f}_{STC} \) \hspace{1cm} (25)

Where \( \mathbf{e}_i \)= real component of bus i voltage  
\( \mathbf{f}_i \)= imaginary component of bus i voltage  
\( \mathbf{e}_{STC} \)= real component of STATCOM voltage  
\( \mathbf{f}_{STC} \)= imaginary component of STATCOM voltage

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

\[
|V_{STC}| = (\mathbf{e}_{STC}^2 + \mathbf{f}_{STC}^2)^{\frac{1}{2}} \hspace{1cm} (26)
\]

\[
\delta_{STC} = \tan^{-1}\left( \frac{\mathbf{f}_{STC}}{\mathbf{e}_{STC}} \right) \hspace{1cm} (27)
\]

Where \( |V_{STC}| \)= STATCOM voltage magnitude  
\( \delta_{STC} \)= 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):

\[
P_{STC} = G_{SC} \{ (\mathbf{e}_{STC}^2 + \mathbf{f}_{STC}^2) - (\mathbf{e}_{STC} \mathbf{e}_i + \mathbf{f}_{STC} \mathbf{f}_i) \} + B_{SC} \{ (\mathbf{e}_{STC} \mathbf{f}_i - \mathbf{f}_{STC} \mathbf{e}_i) \} \hspace{1cm} (28)
\]

\[
Q_{STC} = G_{SC} \{ \mathbf{e}_{STC} \mathbf{f}_i - \mathbf{f}_{STC} \mathbf{e}_i \} + B_{SC} \{ (\mathbf{e}_{STC} \mathbf{f}_i - \mathbf{f}_{STC} \mathbf{e}_i) \} \hspace{1cm} (29)
\]

\[
P_i = G_{SC} \{ \mathbf{e}_i^2 + \mathbf{f}_i^2 - (\mathbf{e}_{STC} \mathbf{e}_i + \mathbf{f}_{STC} \mathbf{f}_i) \} + B_{SC} \{ (\mathbf{e}_{STC} \mathbf{f}_i - \mathbf{f}_{STC} \mathbf{e}_i) \} \hspace{1cm} (30)
\]

\[
Q_i = G_{SC} \{ \mathbf{e}_i \mathbf{f}_{STC} - \mathbf{f}_i \mathbf{e}_{STC} \} + B_{SC} \{ \mathbf{e}_i \mathbf{e}_{STC} + \mathbf{f}_i \mathbf{f}_{STC} - (\mathbf{e}_i^2 + \mathbf{f}_i^2) \} \hspace{1cm} (31)
\]

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):

\[
\begin{bmatrix}
\Delta P_i \\
\Delta |V_i| \\
\Delta P_{STC} \\
\Delta Q_{STC}
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P_i}{\partial V_i} & \frac{\partial P_i}{\partial \theta_i} & \frac{\partial P_i}{\partial V_{STC}} & \frac{\partial P_i}{\partial \theta_{STC}} \\
\frac{\partial |V_i|}{\partial V_i} & \frac{\partial |V_i|}{\partial \theta_i} & 0 & 0 \\
\frac{\partial P_{STC}}{\partial V_i} & \frac{\partial P_{STC}}{\partial \theta_i} & \frac{\partial P_{STC}}{\partial V_{STC}} & \frac{\partial P_{STC}}{\partial \theta_{STC}} \\
\frac{\partial Q_{STC}}{\partial V_i} & \frac{\partial Q_{STC}}{\partial \theta_i} & \frac{\partial Q_{STC}}{\partial V_{STC}} & \frac{\partial Q_{STC}}{\partial \theta_{STC}}
\end{bmatrix}
\begin{bmatrix}
\Delta \mathbf{e}_i \\
\Delta \mathbf{f}_i \\
\Delta \mathbf{e}_{STC} \\
\Delta \mathbf{f}_{STC}
\end{bmatrix}
\hspace{1cm} (32)
\]

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):
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]

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Bus Name</th>
<th>Bus Code</th>
<th>Voltage Magnitude</th>
<th>Angle Degree</th>
<th>Load MW</th>
<th>MVar</th>
<th>Generator MW</th>
<th>MVar</th>
<th>Qmin</th>
<th>Qmax</th>
<th>Static MVar +Qc/-Ql</th>
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Reactive Power Compensation in Nigeria Electricity Grid Using Static Synchronous ...  

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

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<th>Resistance (p.u.)</th>
<th>Reactance (p.u.)</th>
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DOI: 10.9790/1676-10240820
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 $0.95 \leq V_i \leq 1.05 \text{ p.u.}$ 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.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Resistance (p.u.)</th>
<th>Reactance (p.u.)</th>
</tr>
</thead>
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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.
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 $0.95 \leq V \leq 1.05$ 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.

References

Reactive Power Compensation in Nigeria Electricity Grid Using Static Synchronous ...