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PERFORMANCE IMPROVEMENT OF POWER SYSTEM NETWORKS USING FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS DEVICES: THE NIGERIAN 330 KV ELECTRICITY GRID AS A CASE STUDY

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ABSTRACT

A wide electricity supply-demand gap especially in developing economy such as Nigeria has created series of challenges such as frequent power outages, poor voltage profile and high power losses among others yet to be addressed. This work examines the effect of Static Var Compensator (SVC), a Flexible Alternating Current Transmission Systems (FACTS) device for performance improvement of power system networks with the Nigerian 330 kV, 28-bus electricity grid considered as a test network. The steady state performance of the system was modeled using Newton-Raphson load flow equations and was simulated without and with compensation on MATLAB/PSAT toolbox (version 2.1.9 'R2012a'). The obtained results showed that the system voltage profile improved to acceptable limit defined as $0.95 \leq V_i \leq 1.05\ p.u.$ with compensation compared to when voltage magnitudes of buses 9, 13, 14, 15, 16, 19, 22 and 26 of the test network fell outside of the acceptable limit without compensation. Also, the system total active power loss reduced from 15.727 MW without SVC to 14.709 MW with SVC, giving a 6.47% reduction in total active power loss. These results showed that the inclusion of SVC on the Nigerian electricity grid will improve both voltage profile and power transfer capability of the system.

Keywords: Voltage profile, Power loss, FACTS, SVC, Newton-Raphson load flow, Nigeria

INTRODUCTION

Over the last two decades, power demand has drastically increased while the expansion of power generation and transmission has been severely limited due to energy cost, environmental restrictions, difficulty in obtaining right of way, high cost of constructing a new generating plant and transmission lines (Lokanadham, 2010). Consequently, some transmission lines are heavily loaded which in turn affect the system stability and further lead to the delivery of low quality of power to the consumers (Alok and Amar, 2012). Also, the increasing power demand due to the growing population has led to the complexity associated with the interconnection of networks which has resulted in voltage instability, power security problem, total black outs, insufficient reactive power and large losses associated with long distance transmission (Ayodele *et al*., 2016; Oyedoja, 2014).

In power systems, vast majority of the loads are characteristically inductive in nature and consume high amount of reactive power. This causes an offset between the current and voltage leading to a heating effect, hence, more losses in the systems (Mehta and Mehta, 2005). For a good system, the power factor must be kept close to unity. At unity power factor, all the energy generated is consumed by the load (Mehta and Mehta, 2005; Theraja and Theraja, 2000). Hence, a good way of ensuring that the system power factor is close to unity is to have fast acting compensating devices on the network in order to ensure system stability, increased system loadability, increased power transfer capacity and to minimize the need for a new transmission line (Tong *et al*., 2017; Javid and Shamsudheen, 2012). There are various ways of achieving compensation in power systems. Conventional methods involve the use of more units of generators, capacitor banks, system reconfiguration, addition of new transmission lines etc. However, the recent and more technologically advanced means is to employ Flexible Alternating Current Transmission System (FACTS). The use of FACTS for performance improvement of power system networks has been assessed in several literature (Viswanath *et al.*, 2017; Arora *et al.*, 2016; Ali, 2015; Damor *et al.*, 2014; Kumar and Kumar, 2011; Murali *et al.*, 2010; Abido, 2008; Beek *et al.*, 2006). FACTS helps to enhance power system performance, improve quality of supply, increase power transfer capacity, increase loadability, increase system reliability, reduce transmission losses and also provide an optimal utilization of the existing resources (Surekha and Puttaswamy, 2011).

Therefore, the focus of this work is to apply Static

Var Compensator (SVC), a FACTS device for the performance improvement of power system using the Nigerian 330 kV electricity grid as a case study. SVC plays a pivotal role in voltage stabilization, reactive power compensation, improved power factor, increase voltage on the load bus among others (Surekha and Puttaswamy, 2011).

FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS (FACTS)

FACTS controllers are a group of power electronics controllers expected to revolutionize the power transmission and distribution system in many ways (Surekha and Puttaswamy, 2011). The development of FACTS devices is based on the advances in semiconductor technology and has opened up new opportunities for controlling the load flow and extending the loadability of the available transmission network. Parameters such as bus voltage magnitudes, bus voltage angles and transmission line flow can be controlled in a fast, flexible and efficient way by FACTS devices (Kour *et al*., 2012; Kalaivani and Kamaraj, 2012).

FACTS family comprises a number of devices such as Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC), Thyristor Controlled Breaking Reactor (TCR), Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC), Thyristor Switched Series Reactor (TSSR), Unified Power Flow Controller (UPFC) (Ayodele *et al.,* 2016; Jokojeje *et al*., 2015; Matthew *et al*., 2014).

The objective of any FACTS device is to bring a system under control and to transmit power maximally. FACTS technology generally can boost power transfer capability, improve system reliability, voltage profile and transmission losses (Surekha and Puttaswamy, 2011). Inclusion of FACTS controllers in power system networks will help reduce transmission congestion and fully utilize the existing transmission system (Kour *et al*., 2012). Hence, FACTS can facilitate effective power flow control, security and stability of power systems.

Static Var Compensator (SVC)

SVC is one of the early generations of FACTS family. It is a power quality device which can provide a fast-acting reactive power compensation to regulate system voltages. Figure 1 shows the basic configuration of an SVC. It comprises thyristor controlled reactor (TCR), thyristor switched capacitors (TSCs) and harmonic filters connected in parallel to provide dynamic reactive power compensation. The TCR current is controlled by the thyristor valve which controls the fundamental current by changing the firing angle. This in effect regulates the voltage at the desired bus within the statutory limit. Current harmonics are unavoidable during the operation of thyristor controlled rectifiers (Singh *et al*., 2012). Therefore, it is imperative to have components such as filters capable of eliminating harmonics in the SVC system. The filter banks absorb harmonics and also produce the leading reactive power.

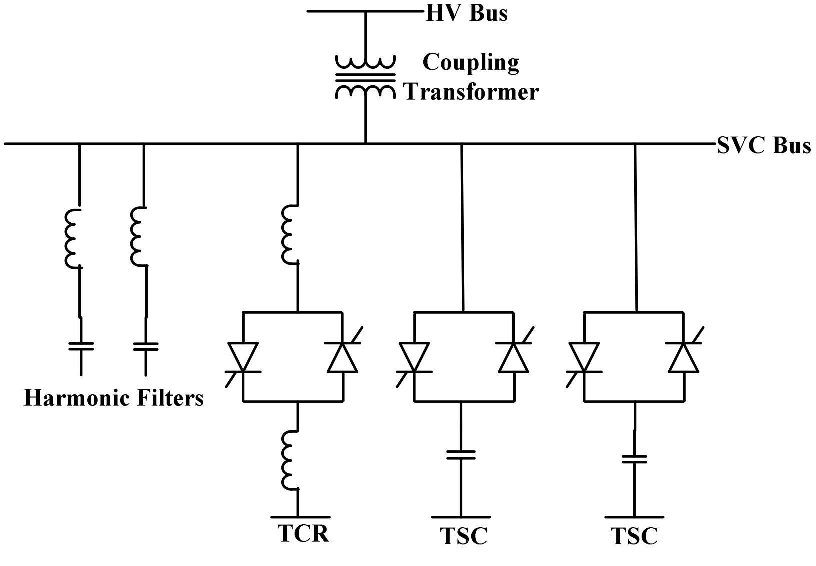

Figure 1: Basic configuration of an SVC (Singh *et al*., 2012)

Some of the inherent benefits of static var compensator include maximum utilization of the existing transmission lines, reduction in transmission losses, increased transmission capacity, reduction in voltage drop, increased loadability of the system network, improved system voltage profile among others (Ashish and Anand, 2013; Javid and Shamsudheen, 2012; Surekha and Puttaswamy 2011).

METHODOLOGY

In this section of the work, load flow analysis without and with compensation is presented.

Load Flow Analysis

Load flow analysis is an effective and efficient tool for assessing the performance of power systems. It aims to provide basic information such as bus voltage magnitudes and their phase angle, real and reactive power flow in the transmission lines which are very critical in evaluating the system performance and examining the impact of alternative plans for the future (Pabla, 2011).

Figure 2 shows a typical i^{th} bus model of a power system network. Application of KCL to bus i and Ohm's law between bus i and respective buses 1 to n result in an expression for the current I_i injected at the i^{th} bus in the system. This is given by equation (1) (Gupta, 2011; Kothari and Nagrath, 2008):

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k \; ; \; i, k = 1, 2, \ldots . n \qquad (1)$$

where Y_{ik} = Admittance between bus i and bus k

V_k = Voltage at bus k

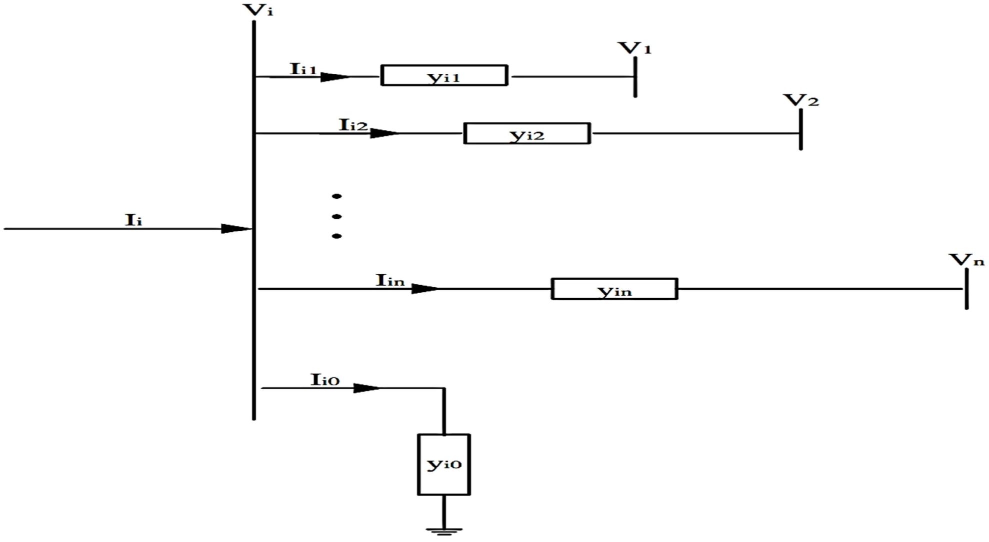

Figure 2: A typical power system (Gupta, 2011; Kothari and Nagrath, 2008)

The complex apparent power injected by the source into the ith bus is given by equations (2) (Gupta, 2011; Kothari and Nagrath, 2008):

$$S_i = P_i + jQ_i = V_i I_i^*; \; i = 1, 2, \ldots . n \qquad (2)$$

Making current I_i the subject in equation (2) leads to equation (3) which further modifies to equation (4) with a simple cross multiplication:

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \qquad (3)$$

$$P_i - jQ_i = V_i^* I_i \qquad (4)$$

Substitution of equation (1) in equation (4) gives equation (5) from which the real and reactive powers expressed by equations (6) and (7) are obtained.

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right); \; i = 1, 2, \ldots . n \qquad (5)$$

$$P_i = Re\left(V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right)\right) \qquad (6)$$

$$Q_i = -Im\left(V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right)\right) \qquad (7)$$

To reduce the number of equations to be handled, V_i, V_i^*, V_k and Y_{ik} are expressed in polar form as given by equations (8) to (11) (Gupta, 2011). Further use of equations (8) to (11) in equations (6) and (7) respectively yields equations (12) and (13).

$$V_i = |V_i| e^{j\delta_i} \qquad (8)$$

$$V_i^* = |V_i| e^{-j\delta_i} \qquad (9)$$

$$V_k = |V_k| e^{j\delta_k} \qquad (10)$$

$$Y_{ik} = |Y_{ik}| e^{j\theta_{ik}} \qquad (11)$$

$$P_i = |V_i| \sum_{k=1}^{n} |Y_{ik}||V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \qquad (12)$$

$$Q_i = -|V_i| \sum_{k=1}^{n} |Y_{ik}||V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \qquad (13)$$

Equations (12) and (13) are called static load flow equations. These equations give the steady state solutions of the system and are usually non-linear. Therefore, they are only solved using varieties of numerical techniques. For the purpose of this work, Newton-Raphson iterative technique is adopted because of its accuracy, reliability and faster rate of convergence (Gupta, 2011; Pabla, 2011; Kothari and Nagrath, 2008). The Newton-Raphson load flow equations are expressed by equation (14) which is written for short as equation (15) (Gupta, 2011; Pabla, 2011; Kothari and Nagrath, 2008):

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \Delta Q_3 \\ \vdots \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial \delta_3} & \cdots & \frac{\partial P_2}{\partial \delta_n} & \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_3} & \cdots & \frac{\partial P_2}{\partial V_n} \\ \frac{\partial P_3}{\partial \delta_2} & \frac{\partial P_3}{\partial \delta_3} & \cdots & \frac{\partial P_3}{\partial \delta_n} & \frac{\partial P_3}{\partial V_2} & \frac{\partial P_3}{\partial V_3} & \cdots & \frac{\partial P_3}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \delta_2} & \frac{\partial P_n}{\partial \delta_3} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial V_2} & \frac{\partial P_n}{\partial V_3} & \cdots & \frac{\partial P_n}{\partial V_n} \\ \frac{\partial Q_2}{\partial \delta_2} & \frac{\partial Q_2}{\partial \delta_3} & \cdots & \frac{\partial Q_2}{\partial \delta_n} & \frac{\partial Q_2}{\partial V_2} & \frac{\partial Q_2}{\partial V_3} & \cdots & \frac{\partial Q_2}{\partial V_n} \\ \frac{\partial Q_3}{\partial \delta_2} & \frac{\partial Q_3}{\partial \delta_3} & \cdots & \frac{\partial Q_3}{\partial \delta_n} & \frac{\partial Q_3}{\partial V_2} & \frac{\partial Q_3}{\partial V_3} & \cdots & \frac{\partial Q_3}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial Q_n}{\partial \delta_2} & \frac{\partial Q_n}{\partial \delta_3} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_n}{\partial V_2} & \frac{\partial Q_n}{\partial V_3} & \cdots & \frac{\partial Q_n}{\partial V_n} \end{bmatrix} \begin{bmatrix} \Delta \delta_2 \\ \Delta \delta_3 \\ \vdots \\ \Delta \delta_n \\ \Delta V_2 \\ \Delta V_3 \\ \vdots \\ \Delta V_n \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (15)$$

where ΔP = Real power mismatch
ΔQ = Reactive power mismatch
ΔV = Bus voltage mismatch
$\Delta \delta$ = Bus voltage angle mismatch

$J_1, J_2, J_3,$ and J_4 are the elements of Jacobian matrix which are obtained by partial differentiation of the equations (12) and (13) with respect to the state variables (δ, V). The off-diagonal and diagonal elements of $J_1, J_2, J_3,$ and J_4 are as expressed in equations (16) to (23) (Gupta, 2011; Kothari and Nagrath, 2008):

The off-diagonal and diagonal elements of J_1:

$$\frac{\partial P_i}{\partial \delta_k} = V_i V_k Y_{ik} \sin(\theta_{ik} + \delta_i - \delta_k)\,;\ \mathrm{k} \neq i \quad (16)$$

$$\frac{\partial P_i}{\partial \delta_i} = -\sum_{\substack{k=1 \\ \mathrm{k}\neq i}}^{n} V_i V_k Y_{ik} \sin(\theta_{ik} + \delta_i - \delta_k) \quad (17)$$

The off-diagonal and diagonal elements of J_2:

$$\frac{\partial P_i}{\partial V_k} = V_i Y_{ik} \cos(\theta_{ik} + \delta_i - \delta_k)\,;\mathrm{k} \neq i$$

$$\frac{\partial P_i}{\partial V_i} = 2V_i Y_{ii} \cos\theta_{ii} + \sum_{\substack{k=1 \\ \mathrm{k}\neq i}}^{n} Y_{ik} V_k \cos(\theta_{ik} + \delta_i - \delta_k)$$

The off-diagonal and diagonal elements of J_3:

$$\frac{\partial Q_i}{\partial \delta_k} = -V_i V_k Y_{ik} \cos(\theta_{ik} + \delta_i - \delta_k)\,;\ \mathrm{k} \neq i \quad (20)$$

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ \mathrm{k}\neq i}}^{n} V_i V_k Y_{ik} \cos(\theta_{ik} + \delta_i - \delta_k) \quad (21)$$

The off-diagonal and diagonal elements of J_4:

$$\frac{\partial Q_i}{\partial V_k} = V_i Y_{ik} \sin(\theta_{ik} + \delta_i - \delta_k)\,;\mathrm{k} \neq i \quad (22)$$

$$\frac{\partial Q_i}{\partial V_i} = 2V_i Y_{ii} \sin\theta_{ii} + \sum_{\substack{k=1 \\ \mathrm{k}\neq i}}^{n} Y_{ik} V_k \sin(\theta_{ik} + \delta_i - \delta_k) \quad (23)$$

The real and reactive power mismatches at each iteration with new estimates of bus voltage angles and bus voltage magnitude are expressed by equations (24) to (27):

$$\Delta P_i^r = P_i^{spec} - P_i^r$$

$$\Delta Q_i^r = Q_i^{spec} - Q_i^r$$

$$\delta_i^{r+1} = \delta_i^r - \Delta \delta_i^r$$

$$V_i^{r+1} = V_i^r - \Delta V_i^r$$

where r = iteration count
ΔP_i^r = Real power mismatch at iteration r
P_i^{spec} = Specified value of real power
P_i^r = Calculated value of real power at iteration r
ΔQ_i^r = Reactive power mismatch at iteration r
Q_i^{spec} = Specified value of reactive power
Q_i^r = Calculated value of reactive power at iteration r
δ_i^{r+1} = New estimate of bus voltage angle at iteration $r + 1$
δ_i^r = Calculated value of bus voltage angle at iteration r
$\Delta \delta_i^r$ = Bus voltage angle mismatch at iteration r
V_i^{r+1} = New estimate of bus voltage at iteration $r + 1$ (18)
V_i^r = Calculated value of bus voltage at iteration r
ΔV_i^r = Bus voltage mismatch at iteration r

The voltage and reactive power (19) constraints at each bus i are given by equations (28) and (29) respectively:

$$V_{imin} \leq V_i \leq V_{imax} \quad (27)$$

$$Q_{imin} \leq Q_i \leq Q_{imax} \quad (29)$$

where V_{imin}= Minimum voltage value at bus i
V_{imax} = Maximum voltage value at bus i
Q_{imin} = Minimum reactive power supply at bus i
Q_{imax} = Maximum reactive power supply at bus i

Modeling of SVC

An SVC is a shunt connected FACTS device which controls a given bus voltage by adjusting its equivalent susceptance. For reactive power compensation and voltage control analyses, two basic models of an SVC commonly (24) employed are variable shunt susceptance and firing angle models

(Ramdan *et al.*, 2016; Bahadur *et al.*, 2012; Auchariyamet and Sirisumrannukul, 2010; Hassan *et al.*, 2009). However, in this work, firing angle model in which equivalent susceptance is a function of the changing firing angle, $\propto$, of the thyristor controlled reactor (TCR) was considered because it requires no additional iterative loop to solve for the firing angle (Bahadur *et al.*, 2012). This model is presented in Figure 3.

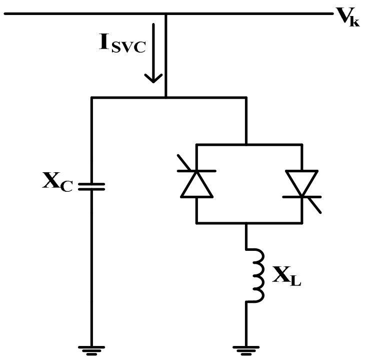

Figure 3: Firing angle model of an SVC (Ramdan *et al.*, 2016; Auchariyamet and Sirisumrannukul, 2010; Hassan *et al.*, 2009)

In Figure 3, the equivalent susceptance of the SVC, B_{SVC}, is obtained as an inverse of the SVC reactance, X_{SVC}, which is a parallel combination of TCR equivalent reactance (X_{L-TCR}) and SVC capacitive reactance (X_C). While X_{L-TCR} is described by equations (30) to (33), X_{SVC} is described by equations (34) and (35) (Auchariyamet and Sirisumrannukul, 2010; Hassan *et al.*, 2009):

$$X_{L-TCR} = \frac{\pi X_L}{\propto_{eq}} \qquad (30)$$

where $X_L = \text{TCR inductive reactance} = \omega L$ (31)

$\propto_{eq} = Equivalent\ TCR$ firing angle $= 2(\pi - \propto_{SVC}) + \sin(2 \propto_{SVC})$ (32)

with $\frac{\pi}{2} \leq \propto_{SVC} \leq \pi$ (33)

$$X_{SVC} = \frac{X_C X_L}{\frac{X_C \propto_{eq}}{\pi} - X_L} \qquad (34)$$

where $X_C = \frac{1}{\omega C}$ (35)

Therefore, B_{SVC} is obtained from equation (36):

$$B_{SVC} = \frac{1}{X_{SVC}} = \frac{\frac{X_C(2(\pi - \propto_{SVC}) + \sin(2\propto_{SVC}))}{\pi} - X_L}{X_C X_L} \qquad (36)$$

When the voltage magnitude at SVC connection point ($V_{SVC} = V_k$) is specified, SVC reactive power (Q_{SVC}) can be calculated by equation (37) (Bahadur *et al.*, 2012; Auchariyamet and Sirisumrannukul, 2010; Hassan *et al.*, 2009):

$$Q_{SVC} = Q_k = -V_k^2 B_{SVC} = \frac{V_k^2}{X_C X_L} \left\{ X_L - \frac{X_C}{\pi} \left[2(\pi - \propto_{SVC}) + \sin(2 \propto_{SVC}) \right] \right\} \qquad (37)$$

An observation on equation (37) reveals that Q_{SVC} is maximum when $\propto_{SVC} = \frac{\pi}{2}$ and minimum when $\propto_{SVC} = \pi$. These respectively give equations (38) and (39):

$$Q_{SVC}^{max} = \frac{V_k^2}{X_C X_L} \{X_L - X_C\} \qquad (38)$$

$$Q_{SVC}^{min} = \frac{V_k^2}{X_C} \qquad (39)$$

The linearized Newton-Raphson load flow equations for this SVC model are expressed by equations (40) and (41) (Bahadur *et al.*, 2012):

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^{(r)} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{2V_k^2}{\pi X_L}[\cos(2\alpha_{SVC}) - 1] \end{bmatrix}^{(r)} \begin{bmatrix} \Delta\delta_k \\ \Delta\propto_{SVC} \end{bmatrix}^{(r)} \qquad (40)$$

$$\propto_{SVC}^{(r)} = \propto_{SVC}^{(r-1)} + \propto_{SVC}^{(r)} \qquad (41)$$

The Newton-Raphson load flow equations (40) and (41) of the SVC model are combined with the system's linearized power load equations to obtain the complete set of linearized load flow equations describing the system including the SVC. This in effect will increase the size of the Jacobian matrix. Since the SVC consumes no real power, all the partial derivatives of its real power with respect to the state variables (δ, V) are zero.

Application of MATLAB/PSAT Software

PSAT is a MATLAB toolbox for electrical system analysis and control. It incorporates varieties of power system analyses such as power flow, continuation power flow, optimal power flow, small signal stability analysis and time domain simulation (Federico, 2008). All operations can be assessed by means of Graphical User Interfaces (GUIs) and a SIMULINK based library provides a user friendly tool for network design. The core of PSAT is the power flow routine which also takes care of state variable initialization (Federico, 2008).

Test Case

The load flow equations without and with SVC model presented in this work were applied on the Nigerian 330 kV electricity grid considered as a test case. The single-line diagram of the system is shown in Figure 4. It consists of twenty-eight (28) buses, nine (9) generation stations, and fifty-two (52) transmission lines. The network and generator data shown in Tables 1 and 2 respectively on 330 kV, 50 Hz and 100 MVA base were obtained from the National Control Centre of the Transmission Company of Nigeria in 2013.

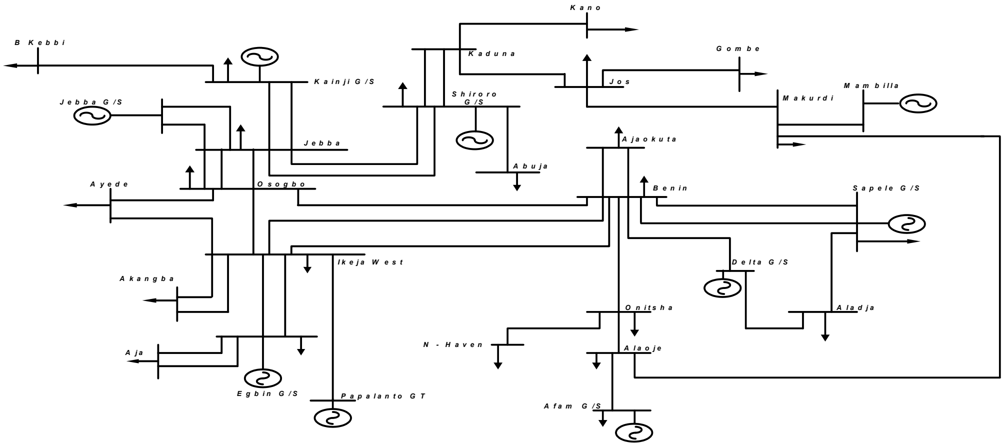

Figure 4: The Nigerian 330 kV electricity grid (National Control Centre, 2013)

Table 1: Network data of the test network

Bus Identification		Bus Loads		Transmission Lines Data			
Name	No	MW	MVAR	BUS FROM	TO	Resistance R(pu)	Reactance X(pu)
Egbin	1	68.90	51.70				
Delta	2	0.00	0.00	1	3	0.0006	0.0044
Aja	3	274.40	205.80	4	5	0.0007	0.0050
Akangba	4	244.70	258.50	1	5	0.0023	0.0176
Ikeja-West	5	633.20	474.90	5	8	0.0110	0.0828
Ajaokuta	6	13.80	10.30	5	9	0.0054	0.0405
Aladja	7	96.50	72.40	5	10	0.0099	0.0745
Benin	8	383.30	287.50	6	8	0.0077	0.0576
Ayede	9	275.80	206.8	2	8	0.0043	0.0317
Osogbo	10	201.20	150.90	2	7	0.0012	0.0089
Afam	11	52.50	39.40	7	24	0.0025	0.0186
Alaoji	12	427.00	320.20	8	14	0.0054	0.0405
New-Heaven	13	177.90	133.40	8	10	0.0098	0.0742
Onitsha	14	184.60	138.40	8	24	0.0020	0.0148
B/Kebbi	15	114.50	85.90	9	10	0.0045	0.0340
Gombe	16	130.60	97.90	15	21	0.0122	0.0916
Jebba	17	11.00	8.20	10	17	0.0061	0.0461
Jebba G	18	0.00	0.00	11	12	0.0010	0.0074
Jos	19	70.30	52.70	12	14	0.0060	0.0455
Kaduna	20	193.00	144.70	13	14	0.0036	0.0272
Kanji	21	7.00	5.20	16	19	0.0118	0.0887
Kano	22	220.60	142.90	17	18	0.0002	0.0020
Shiroro	23	70.30	36.10	17	23	0.0096	0.0271
Sapele	24	20.60	15.40	17	21	0.0032	0.0239
Abuja	25	110.00	89.00	19	20	0.0081	0.0609
Makurdi	26	290.10	145.00	20	22	0.0090	0.0680
Mambila	27	0.00	0.00	20	23	0.0038	0.0284
Papalanto	28	0.00	0.00	23	25	0.0038	0.0284
				12	26	0.0071	0.0532
				19	26	0.0059	0.0443
				26	27	0.0079	0.0591
				5	28	0.0016	0.0118

Table 2: Generator data of the test network

Bus Identification		Voltage	Generator		Reactive Limits	
Name	No	Magnitude (pu)	MW	MVAR	Q_{min}	Q_{max}
Egbin	1	1.05	0.00	0.00	-1006	1006
Delta	2	1.05	670.00	0.00	-1030	1000
Afam	11	1.05	431.00	0.00	-1000	1000
Jebba G	18	1.05	495.00	0.00	-1050	1050
Kanji	21	1.05	624.70	0.00	-1010	1010
Shiroro	23	1.05	388.90	0.00	-1010	1010
Sapele	24	1.05	190.30	0.00	-1010	1010
Mambila	27	1.05	750.00	0.00	-1010	1010
Papalanto	28	1.05	750.00	0.00	-1010	1010

RESULTS AND DISCUSSION

In this section, the obtained results from the Newton-Raphson load flow simulation of the Nigerian 330 kV electricity grid without and with compensation using the MATLAB/PSAT toolbox are presented. The parameters used for designing the firing-angle model of the SVC for the test network are presented in Table 1.

Table 1: Parameters used for the SVC Design

Parameter	Value
Inductive reactance	0.1pu
Capacitive reactance	0.01pu
Reference voltage	1.0pu
Regulator time constant	10s
Regulator gain	100pu
Integral deviation constant	0.001pu
Transient time constant	0.05s
Measurement gain	1.000pu
Time delay	0.01s
Firing angle range	pi/2 ≤ ∝ ≤ pi

While Figures 5 and 6 respectively show the PSAT Models of the Nigerian 330 kV electricity grid without and with compensation, the resulting voltage profiles and total active power losses of models in Figures 5 and 6 are respectively shown in Figures 7 and 8.

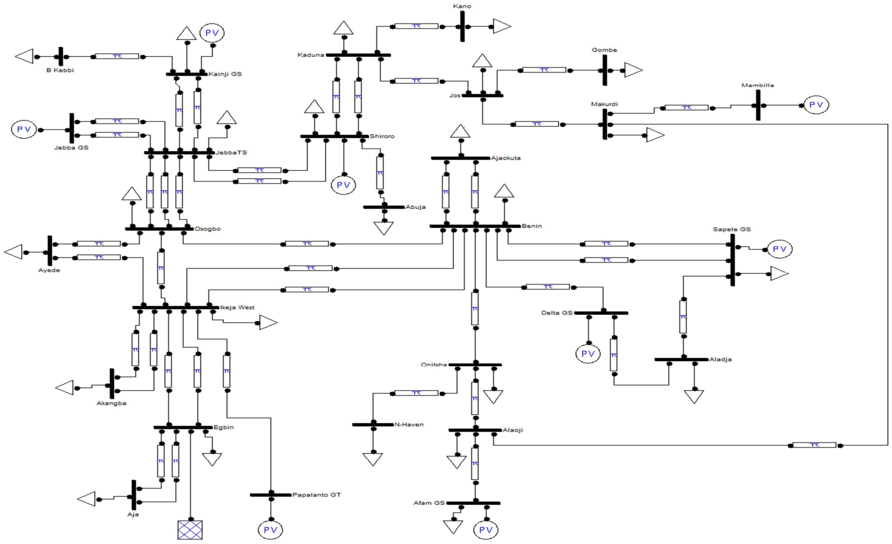

Figure 5: PSAT Model of the Nigerian 330 kV electricity grid without compensation

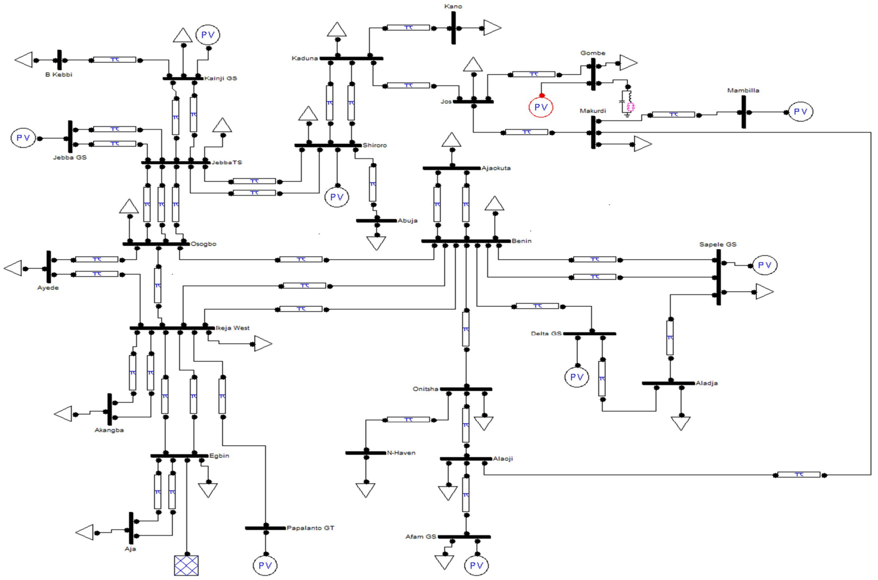

Figure 6: PSAT Model of the Nigerian 330 kV electricity grid with compensation

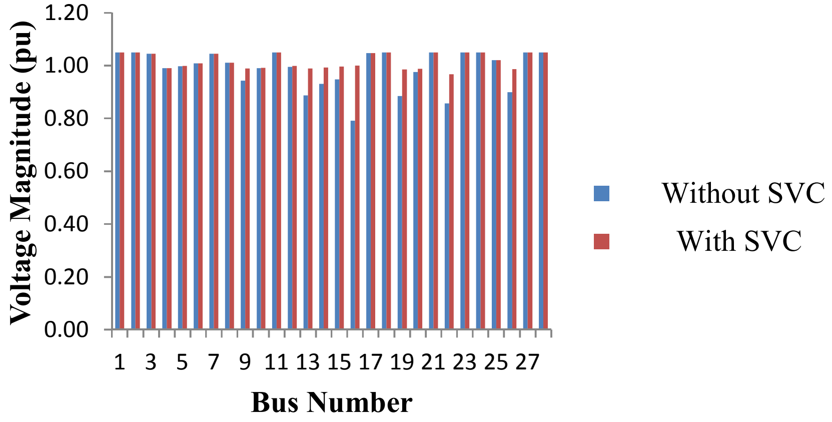

Figure 7: Bar chart showing the voltage profile of the Nigerian 330 kV electricity grid without and with compensation.

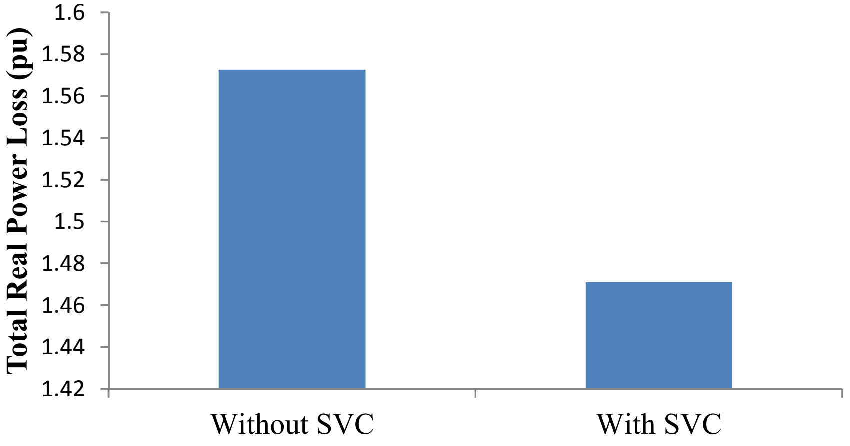

Figure 8: Bar chart showing the total active power loss of the Nigerian 330 kV electricity grid without and with compensation.

From Figure 7, it was observed that without compensation applied to the test network, the voltage magnitudes of eight buses, that is, buses 9, 13, 14, 15, 16, 19, 22 and 26 which were respectively 0.9428, 0.8876, 0.9306, 0.9480, 0.7908, 0.8851, 0.8565, 0.8993 fell outside of the acceptable limit defined by $0.95 \leq V_i \leq 1.05$ p.u. However, when SVC was incorporated in the test network, the buses whose voltage magnitudes were outside the acceptable limit and some other buses whose voltage magnitudes were already within the acceptable limit had their voltage magnitudes improved. The voltage magnitudes of buses 9, 13, 14, 15, 16, 19, 22 and 26 respectively improved to 0.9884, 0.9889, 0.9932, 0.9960, 1.0000, 0.9853, 0.9663 and 0.9851. Also, the voltage magnitudes of buses 5, 6, 8, 10 and 12 among others increased from 0.9977, 1.0078, 1.0113, 0.9906 and 0.9953 respectively without SVC to 0.9983, 1.0082, 1.0117, 0.9919 and 0.9988 with SVC.

Equally, from Figure 8, it was observed that the total active power loss on the test network improved with application of compensation. The total active power loss which was 1.5727 p.u. (15.727 MW on MVA of 100) without SVC reduced to 1.4709 p.u. (14.709 MW on MVA base of 100) with SVC, giving a 6.47% reduction in total active power loss.

These results are indication that SVC is not only capable of improving and maintaining the system's voltage profile within an acceptable limit but will also reduce power loss and in effect improve power transfer capability of the system if applied.

CONCLUSION

One of the efficient ways by which an improved and cost-effective performance of power systems can be guaranteed is to have quick-acting compensating devices such as FACTS in the systems. FACTS devices can increase system stability, loadability and power transfer capacity without need for more units of generators, new transmission lines, system reconfiguration, capacitor banks etc. In this work, performance improvement of power system networks has been examined using SVC, a FACTS controller with the Nigerian 330 kV electricity grid considered as a test network. The simulation results showed that the system voltage profile improved to acceptable limit specified as $0.95 \leq V_i \leq 1.05$ p.u. with compensation compared to when buses 9, 13, 14, 15, 16, 19, 22 and 26 of the test network had their voltage magnitudes outside of the acceptable limit without compensation. More so, the system total active power loss improved with application of SVC. The total active power loss reduced from 15.727 MW without SVC to 14.709 MW with SVC, giving a 6.47% reduction in total active power loss. These results showed that SVC, if deployed in the Nigerian electricity grid will improve the system voltage profile and power transfer capability.

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