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Assessment of the Effect of Hybrid Configured SSSC and SVC on Power Flow Control in the Nigerian 330 kV Electricity Grid

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ABSTRACT: *One of the innovative solutions for power flow control in an electricity grid involves the use of flexible alternating current transmission systems (FACTS) controllers. These controllers have capacity to increase system availability and utilization, improve voltage stability, reduce power losses and enhance power quality. Therefore, in this study, the impact of hybrid configured static synchronous series compensator (SSSC) and static var compensator (SVC) on power flow control in the Nigerian 330 kV, 28-bus electricity transmission grid was assessed. The Newton-Raphson power flow equations for modelling the power system static response were formulated. The system response before and after compensation via SSSC, SVC and hybrid SSSC-SVC respectively were simulated. The bus voltage magnitudes were determined to ascertain compliance with the voltage tolerance limit of 0.95 to 1.05 p.u. The total active and reactive power losses of the system were also evaluated. The cost equivalent of the electrical energy saved with enhancement was estimated. The results obtained showed that hybrid SSSC-SVC outclassed both SSSC and SVC in controlling power flow on the considered Nigerian electricity grid; an action accompanied with a very low revenue loss for electric power transfer over the grid. The use of SSSC and SVC in hybrid mode improved power flow on the Nigerian electricity grid with minimized cost.*

KEYWORDS: *Cost, FACTS, Power flow control, SSSC, SVC, Nigerian electricity grid*

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I. INTRODUCTION

The escalating population and industrial growth in the last few decades globally have placed enormous demand on the utilization of electrical energy by the consumers. The electricity utility companies, undoubtedly, have to cope with the persistently rising electrical energy need of the end-users using the existing power system facilities and as a result, drive the system to operate close to the stability limit [1], [2], [3]. The operation of power system near or above the stability limit exposes it to varying degrees of unhealthy events such as faults, loss of components including generators, transmission lines and transformers and cascading failures. Moreover, it increases the transmission losses with attendant poor voltage profile and in extreme cases, total collapse results [4], [5].

Addressing the challenges of persistent increase in electrical energy demand in power system traditionally requires building of more generation and transmission infrastructures, upgrading of the existing facilities and the application of control devices including mechanical switches, capacitor banks among others. The application of these techniques has some challenges including time delay, huge cost, high rate of the mechanical components wear and tear, release of hazardous materials to the environment and right-of-way constraint [2], [6], [7], [8]. However, inspite of these shortcomings, the electricity utility companies must strive to be able to cope with the customers' demands. This, therefore, creates the need for new and robust means of enhancing the existing power system facilities performance to reduce the huge losses that characterize the system so that more useful electrical energy can be made available to cater for the constantly growing energy need of the customers. One of the most viable options in this regards points towards the adoption of flexible alternating current transmission systems (FACTS) controllers [7], [9].

FACTS are economical devices with capacity for quick compensation of reactive power for the enhancement of power system controllability and power transfer capacity in real time [9], [10]. These controllers, aside possessing enormous potentials to eliminate issues such as dip in voltage at the receiving terminals, high losses and increase energy demand, are very helpful in achieving enhanced power quality and improved steady-state, transient and dynamic stability margin in power systems [11], [12].

FACTS devices are of four basic classifications depending on their connection mode in power networks and these include series, shunt, series-series and series-shunt controllers with thyristor controlled series capacitor (TCSC), static synchronous compensator (STATCOM), inter-line power flow controller (IPFC) and unified power flow controller (UPFC) as respective examples [12]. Each category of these FACTS classifications has unique qualities which adapt them suitably to any given application in which they are deployed. As a result of these interesting qualities of the FACTS controllers, many investigations have been previously conducted to examine their potentials in enhancing power flow and voltage profile of power networks [13], [14], [15], [16], [17], [18], [19].

The focus of this study, therefore, was to assess the effect of hybrid use of SSSC and SVC on power flow control in the Nigerian 330 kV electricity transmission network. The Nigerian power grid is characteristically marred with wide disparity between electricity supply and demand due to inadequate electrical energy generation to match the energy need of the customers which is growing geometrically as a result of the sky-rocketed population and industrial development [20], [21]. The effect of this disparity between electrical energy supply and demand is the instability of voltage which consequently results in high power losses and negatively affecting the flow of useful electrical energy that could have been deployed to address more customers' demand. This, therefore, creates the need for performance enhancement on the network using appropriate techniques and in this respect, hybrid configured SSSC-SVC is one of the viable options at the forefront. This hybrid compensator takes into account the advantages of the robust series and shunt compensations rendered by SSSC and SVC respectively for power system performance enhancement where voltage fluctuation is effectively regulated and power losses minimized for improved power flow control.

II. MATERIALSAND METHODS

2.1. Power Flow Formulation

Power flow is a useful tool for providing information regarding bus voltage magnitude, bus voltage angle, active and reactive line flows for assessment of power system static responses [22], [23], [24], [25]. The power flow formulation in this study involves the consideration of a typical n-bus power system model. The voltage, current and power relationship for the model is expressed by equations (1) [22], [24]:

$$S_i = P_i + jQ_i = V_i I_i^* \tag{1}$$

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

with I_i, Y_{ik}, V_i, S_i, P_i, Q_i, V_k and I_i^* as injected node *i* net current, transfer admittance between nodes *i* and *k*, node *i* voltage, node *i* net complex power input, node *i* net real power input, node *i* net reactive power input , node *k* voltage and complex conjugate of the node *i* net current input.

Equation (1) is modified into equation (3) via the complex conjugate manipulation which further results into equation (4) and finally decouples into real and imaginary parts given by equations (5) and (6):

$$S_i^* = P_i - jQ_i = V_i^* I_i \tag{3}$$

$$P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k \tag{4}$$

$$P_i = Re\{V_i^* \sum_{k=1}^{n} Y_{ik} V_k\} \tag{5}$$

$$Q_i = -Im\{V_i^* \sum_{k=1}^{n} Y_{ik} V_k\} \tag{6}$$

The use of polar form representation of V_i, V_i^*, V_k, and Y_{ik} given by equation (7) into equations (5) and (6) respectively produced equations (8) and (9):

$$\left.\begin{aligned} V_i &= |V_i|e^{j\delta_i} \\ V_i^* &= |V_i|e^{-j\delta_i} \\ V_k &= |V_k|e^{j\delta_k} \\ Y_{ik} &= |Y_{ik}|e^{j\theta_{ik}} \\ e^{j\varphi} &= \cos\varphi + j\sin\varphi \\ e^{-j\varphi} &= \cos\varphi - j\sin\varphi \end{aligned}\right\} \tag{7}$$

$$P_i = V_i \sum_{k=1}^{n} Y_{ik} V_k \cos(\theta_{ik} + \delta_k - \delta_i) \tag{8}$$

$$Q_i = -V_i \sum_{k=1}^{n} Y_{ik} V_k \sin(\theta_{ik} + \delta_k - \delta_i) \tag{9}$$

where δ_i, δ_k and θ_{ik} respectively denote the voltage angle of node *i*, voltage angle of node *k* and the admittance angle between node *i* and *k*.

The expressions of equations (8) and (9) are known as static power flow equations. They are very helpful in the assessment of the power system steady state conditions. These equations are non-linear and are usually linearized through numerical iterative technique. Among the numerical iterative methods that can be employed for solving these equations are Newton-Raphson, Gauss-Seidel and Fast-Decoupled methods. However, Newton-Raphson iterative method was chosen for this study due to suitability for large-scale power networks, faster and quadratic convergence and accuracy [22], [23], [24]. Newton-Raphson iterative method application to equations (8) and (9) produces a matrix expressed by equation (10) with equation (11) as its modification [22], [24]:

$$\begin{bmatrix} \Delta P_2^{(r)} \\ \vdots \\ \Delta P_n^{(r)} \\ \hline \Delta Q_2^{(r)} \\ \vdots \\ \Delta Q_n^{(r)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(r)}}{\partial \delta_n} & \frac{\partial P_2^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(r)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(r)}}{\partial \delta_n} & \frac{\partial P_n^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(r)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(r)}}{\partial \delta_n} & \frac{\partial Q_2^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(r)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(r)}}{\partial \delta_n} & \frac{\partial Q_n^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(r)}}{\partial |V_n|} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(r)} \\ \vdots \\ \Delta \delta_n^{(r)} \\ \hline \Delta\left|V_2^{(r)}\right| \\ \vdots \\ \Delta\left|V_n^{(r)}\right| \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{11}$$

where ΔV, $\Delta\delta$ ΔP and ΔQ respectively denote voltage magnitude, phase angle, real power, and reactive power mismatches and J_1 , J_2 , J_3 and J_4 are the elements of Jacobian matrix obtained by partial differential manipulations of equations (8) and (9).

The system real and reactive powers are calculated from equations (11) and (12) respectively while the new updates of the bus voltage angle (δ_i) and bus voltage magnitude (V_i) are respectively computed from equations (13) and (14) [22], [24]:

$$\Delta P_i^{(r)} = P_i^{sp} - P_i^{(r)} \tag{11}$$

$$\Delta Q_i^{(r)} = Q_i^{sp} - Q_i^{(r)} \tag{12}$$

$$\delta_i^{(r+1)} = \delta_i^{(r)} + \Delta\delta_i^{(r)} \tag{13}$$

$$\left|V_i^{(r+1)}\right| = \left|V_i^{(r)}\right| + \Delta\left|V_i^{(r)}\right| \tag{14}$$

where r is the iteration count, $\Delta P_i^{(r)}$ and $\Delta Q_i^{(r)}$ denote iteration r real and reactive power mismatches respective, $P_i^{(r)}$ and $Q_i^{(r)}$ respectively represent iteration r calculated real and reactive powers, P_i^{sp} and Q_i^{sp} are specified real and reactive powers respectively, $\delta_i^{(r+1)}$ and $|V_i^{(r+1)}|$ respectively denote new update of bus voltage angle and bus voltage magnitude at iteration $r+1$, δ_i^r and $|V_i^{(r)}|$ are iteration r calculated bus voltage angle and calculated bus voltage magnitude and $\Delta\delta_i^{(r)}$ and $\Delta|V_i^{(r)}|$ are iteration r bus voltage angle and bus voltage magnitude mismatches respectively.

The specified system voltage and reactive power constraints are respectively given by equations (15) and (16) respectively:

$$V_{imin} \leq V_i \leq V_{imax} \tag{15}$$

$$Q_{imin} \leq Q_i \leq Q_{imax} \tag{16}$$

where V_{imin} and V_{imax} are bus i minimum and maximum voltages respectively and Q_{imin} and Q_{imax} are bus i minimum and maximum reactive power supplies respectively.

The bus i net real and reactive power inputs are expressed respectively by equations (17) and (18):

$$P_i = P_{gi} - P_{li} \tag{17}$$

$$Q_i = Q_{gi} - Q_{li} \tag{18}$$

where P_{gi} and Q_{gi} are bus i real and reactive power supplies respectively and P_{li} and Q_{li} are bus i real and reactive power demands respectively.

2.2. SSSC Power Flow Formulation

The equivalent circuit presented in Fig. 1 was considered for the formulation of SSSC power flow model. The voltage supplied by the SSSC is expressed by equation (19) while the constraint on the magnitude and phase of the voltage given by equation (20) and (21) respectively [26]:

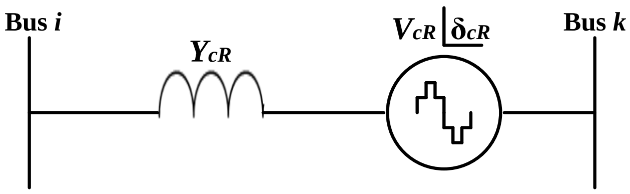

Fig. 1. A SSSC equivalent configuration [26]

$$E_{cR} = V_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \tag{19}$$

$$V_{cRmin} \leq V_{cR} \leq V_{cRmax} \tag{20}$$

$$0 \leq \delta_{cR} \leq 2\pi \tag{21}$$

where E_{cR}, V_{cR} and δ_{cR} respectively denote SSSC supplied voltage, voltage magnitude and voltage phase.

The existence of ac voltage source E_{cR} leads to the introduction of two new state variables V_{cR} and δ_{cR}. Hence, two new equations are required for the solution of the power flow [26]. The power flow model for the SSSC in Fig. 1 is described by equations (22) to (25) with Newton-Raphson based power flow equations resulting from its integration given by equation (26):

$$P_{cR} = V_{cR}^2 G_{kk} + V_{cR}V_k[G_{ik}\cos(\delta_{cR}-\delta_i) + B_{ik}\sin(\delta_{cR}-\delta_i)] + V_kV_{cR}[G_{kk}\cos(\delta_{cR}-\delta_k) + B_{kk}\sin(\delta_{cR}-\delta_k)] \tag{22}$$

$$Q_{cR} = -V_{cR}^2 G_{kk} + V_{cR}V_k[G_{ik}\sin(\delta_{cR}-\delta_i) + B_{ik}\cos(\delta_{cR}-\delta_i)] + V_kV_{cR}[G_{kk}\sin(\delta_{cR}-\delta_k) + B_{kk}\cos(\delta_{cR}-\delta_k)] \tag{23}$$

$$P_i = V_i^2 G_{ii} + V_i V_k [G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)] + V_i V_{cR} [G_{ik} \cos(\delta_i - \delta_{cR}) + B_{ik} \sin(\delta_i - \delta_{cR})] \quad (24)$$

$$Q_i = -V_i^2 B_{ii} + V_i V_k [G_{ik} \sin(\delta_i - \delta_k) + B_{ik} \cos(\delta_i - \delta_k)] + V_i V_{cR} [G_{ik} \sin(\delta_i - \delta_{cR}) + B_{ik} \cos(\delta_i - \delta_{cR})] \quad (25)$$

$$\begin{bmatrix} \Delta P_i \\ \Delta P_k \\ \Delta Q_i \\ \Delta Q_k \\ \Delta P_{ik} \\ \Delta Q_{ik} \end{bmatrix}^r = \begin{bmatrix} \frac{\partial P_i}{\partial \delta_i} & \frac{\partial P_i}{\partial \delta_k} & \frac{\partial P_i}{\partial V_i} V_i & \frac{\partial P_i}{\partial V_k} V_k & \frac{\partial P_i}{\partial \delta_{cR}} & \frac{\partial P_i}{\partial V_{cR}} V_{cR} \\ \frac{\partial P_k}{\partial \delta_i} & \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial V_i} V_i & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{cR}} & \frac{\partial P_i}{\partial V_{cR}} V_{cR} \\ \frac{\partial Q_i}{\partial \delta_i} & \frac{\partial Q_i}{\partial \delta_k} & \frac{\partial Q_i}{\partial V_i} V_i & \frac{\partial Q_i}{\partial V_k} V_k & \frac{\partial Q_i}{\partial \delta_{cR}} & \frac{\partial Q_i}{\partial V_{cR}} V_{cR} \\ \frac{\partial Q_k}{\partial \delta_i} & \frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial V_i} V_i & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{cR}} & \frac{\partial Q_k}{\partial V_{cR}} V_{cR} \\ \frac{\partial P_{ik}}{\partial \delta_i} & \frac{\partial P_{ik}}{\partial \delta_k} & \frac{\partial P_{ik}}{\partial V_i} V_i & \frac{\partial P_{ik}}{\partial V_k} V_k & \frac{\partial P_{ik}}{\partial \delta_{cR}} & \frac{\partial P_{ik}}{\partial V_{cR}} V_{cR} \\ \frac{\partial Q_{ik}}{\partial \delta_i} & \frac{\partial Q_{ik}}{\partial \delta_k} & \frac{\partial Q_{ik}}{\partial V_i} V_i & \frac{\partial Q_{ik}}{\partial V_k} V_k & \frac{\partial Q_{ik}}{\partial \delta_{cR}} & \frac{\partial Q_{ik}}{\partial V_{cR}} V_{cR} \end{bmatrix}^r \begin{bmatrix} \Delta \delta_i \\ \Delta \delta_k \\ \frac{\Delta V_i}{V_i} \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{cR} \\ \frac{\Delta V_{cR}}{V_{cR}} \end{bmatrix}^r \quad (26)$$

where P_{cR}, Q_{cR}, G_{ii}, B_{ii}, G_{kk}, B_{kk}, G_{ik}, B_{ik} respectively denote SSSC active power, SSSC reactive power, bus *i* self conductance, bus *i* self susceptance, bus *k* self conductance, bus *k* self susceptance, transfer conductance between buses *i* and *k* and transfer susceptance between buses *i* and *k*.

2.3. Power Flow Modelling of SVC

Let us consider an SVC installed at bus *i* in a typical n-bus power system model. This compensator will operate to inject or withdraw the reactive power Q_{SVCi} at bus *i*. The resultant bus *i* var is, therefore, determined from equation (27) [27], [28], [29]:

$$Q_i = Q_{gi} - Q_{SVCi} = Q_{li} \quad (27)$$

where Q_{gi}, Q_{li} and Q_{SVCi} respectively represent bus *i* reactive power generation, reactive power demand and SVC reactive power.

Considering further the SVC model in Fig. 2, when the susceptance or the firing angle of the compensator is appropriately constrained, the device acts as a variable susceptance. The current and the equivalent reactive power drawn by the SVC are respectively given by equations (28) and (29) [27], [28], [29]:

$$I_{SVC} = B_{SVC} V_i \quad (28)$$

$$Q_{SVC} = Q_i = -V_i^2 B_{SVC} \quad (29)$$

where I_{SVC}, B_{SVC} and Q_{SVC} represents SVC current, susceptance and reactive power respectively.

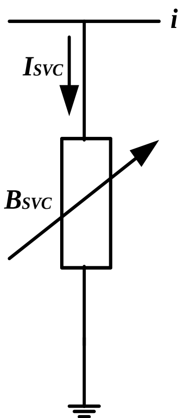

Fig. 2. A variable shunt susceptance representation of SVC

Equation (29) is the expression for the reactive power injected at bus *i* where the SVC is installed. The linearized power flow equations modeling the SVC at bus *i* with B_{SVC} considered as a state variable is given by the matrix of equation (30) [27], [28], [29]:

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^{(r)} = \begin{bmatrix} 0 & 0 \\ 0 & Q_i \end{bmatrix}^{(r)} \begin{bmatrix} \Delta\theta_i \\ \Delta B_{SVC}/B_{SVC} \end{bmatrix}^{(r)} \quad (30)$$

The updated B_{SVC} at the end of iteration *r* is expressed by equation (31) while the susceptance of the SVC, $B_{SVC,}$ is related to its firing angle α_{SVC} by equation (32):

$$B_{SVC}^{(r)} = B_{SVC}^{(r-1)} + \left(\frac{\Delta B_{SVC}}{B_{SVC}}\right)^{(r)} B_{SVC}^{(r-1)} \quad (31)$$

$$B_{SVC} = \frac{-V_i^2}{X_C X_L}\left\{X_L - \frac{X_C}{\pi}\left[2(\pi - \alpha_{SVC}) + \sin(2\alpha_{SVC})\right]\right\} \quad (32)$$

where X_L and X_C denote capacitive and inductive reactances of the SVC respectively.

The Newton-Raphson power flow equations with firing angle α as the new state variable is expressed as equation (33) [27], [28], [29]:

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^{(r)} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{\delta Q_i}{\delta \alpha} \end{bmatrix}^{(r)} \begin{bmatrix} \Delta\theta_i \\ \Delta\alpha_{SVC} \end{bmatrix}^{(r)} \quad (33)$$

$$\text{where } \frac{\delta Q_i}{\delta \alpha} = \frac{2V_i^2}{\pi X_L}\left[\cos(2\alpha_{SVC}) - 1\right] \quad (34)$$

The updated α_{SVC} after iteration r is given by equation (35):

$$\alpha_{SVC}^{(r)} = \alpha_{SVC}^{(r-1)} + \Delta\alpha_{SVC}^{(r)} \quad (35)$$

2.4. Test Case

The 28-bus model of the Nigerian 330 kV power network containing fifty-two transmission lines and nine generating stations was considered in this study as the test system to examine the effect of hybrid use of SSSC and SVC on the power flow control in an electricity grid. Fig. 3 shows the single-line diagram of system while its data are presented in Appendices I to III.

2.5. Simulation Software

MATLAB/Power System Analysis Toolbox (PSAT) was used as an implementation background in this study. PSAT is a comprehensive power flow software with capacity for robust one-line diagram and table-driven data manipulation. It can be deployed as a stand-alone power flow or data exchange application. The software is basically useful for development and analysis of power flow models and cases as well as harmonic, short circuit and contingency analyses. These benefits of the software made it the choice for the present study.

2.6. Economics of the System Useful Power Loss

In an attempt to quantify the useful power loss on the considered Nigerian electricity grid in monetary terms, the active power loss recorded during simulations without and with compensation via SSSC, SVC and hybrid SSSC-SVC were converted to cost equivalent and the savings in revenue arising from the application of compensation determined. The cost equivalent of the useful power loss on the system was determined using the current power transmission charge recommended in the minor tariff review of Transmission Company of Nigeria multi-year tariff order [30]. A statutory ₦6.20 per kilowatt-hour (kWh) energy transported on the Nigerian grid was recommended with an additional inflation rate cost of 20.77% of the statutory charge, leading to an overall cost of ₦7.49 per kWh. The economics of the useful power loss is detailed as follows:

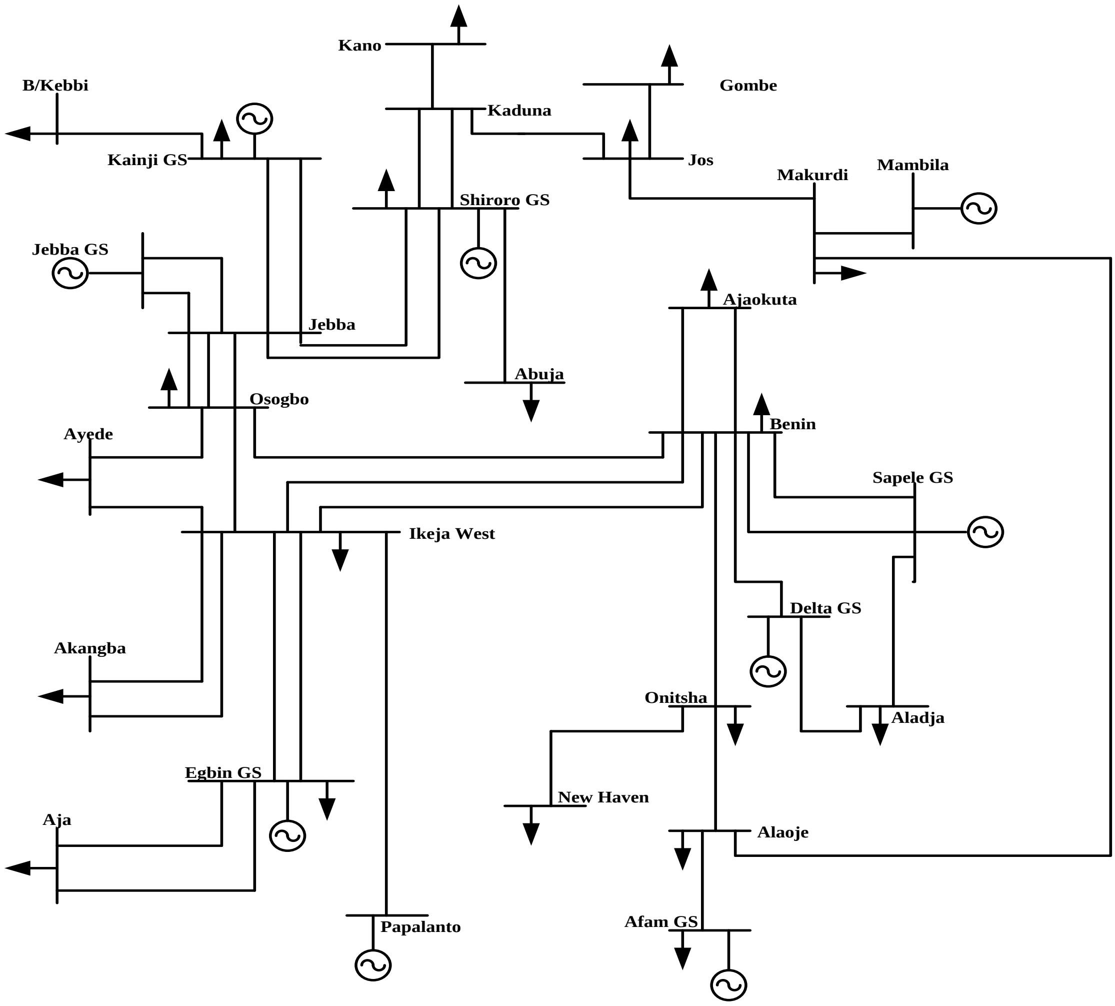

Fig. 3. The single-line diagram of the 28-bus model of the Nigerian 330 kV power grid [31]

Let us consider that P_{nc} and P_c are the system useful power losses when no compensation was applied and with compensation applied respectively while C_{nc} and C_c are the yearly costs of useful power losses when no compensation was applied and with compensation applied respectively.

The relationships between C_{nc} and P_{nc} and C_c and P_c are expressed by equations (36) and (36) respectively:

$$C_{nc} = P_{nc} \times ₦7.49 \times 24 \times 365 \tag{36}$$

$$C_c = P_c \times ₦7.49 \times 24 \times 365 \tag{37}$$

The yearly saving in cost due to the reduction in useful power losses from the compensation applied is expressed by equations (38) and (40):

$$C_{s(SSSC)} = C_{nc} - C_{c(SSSC)} = ₦7.45 \times 24 \times 365 \times (P_{nc} - P_{c(SSSC)}) \tag{38}$$

$$C_{s(SVC)} = C_{nc} - C_{c(SVC)} = ₦7.45 \times 24 \times 365 \times (P_{nc} - P_{c(SVC)}) \tag{39}$$

$$C_{s(SSSC-SVC)} = C_{nc} - C_{c(SSSC-SVC)} = ₦7.45 \times 24 \times 365 \times (P_{nc} - P_{c(SSSC-SVC)}) \tag{40}$$

where $C_{s(SSSC)}$, $C_{s(SVC)}$ and $C_{s(SSSC-SVC)}$ respectively represent yearly savings in cost due to application of SSSC, SVC and hybrid SSSC-SVC on the test network, $C_{c(SSSC)}$, $C_{c(SVC)}$ and $C_{c(SSSC-SVC)}$ respectively represent costs of useful power loss due to application of SSSC, SVC and hybrid SSSC-SVC on the test network and $P_{c(SSSC)}$, $P_{c(SVC)}$ and $P_{c(SSSC-SVC)}$ represent useful power losses due to application of SSSC, SVC and hybrid SSSC-SVC on the test network respectively.

III. RESULTS AND DISCUSSION

3.1. The Results of the Nigerian 28-Bus System Steady State Behaviour without Enhancement

The obtained results of the steady state behaviour of the considered Nigerian electricity grid from the implementation of the PSAT model in Fig. 4 with no enhancement are presented in Figs. 5 and 6 which show the voltage profile and the power losses of the system respectively. Examination of the voltage profile in Fig. 5 revealed that before enhancement seven buses violated the statutory bus voltage magnitude limit of 0.95 to 1.05 p.u. for effective system operation. These buses which include Ayede (9), New Haven (13), Onitsha (14), Gombe (16), Jos (19), Kano (22) and Makurdi (26) had voltage magnitudes of 0.9333, 0.8853, 0.9281, 0.8353, 0.8658, 0.8712 and 0.8897 respectively. Similarly, an observation from Fig. 6 revealed that the grid had total active power loss of 1.8876 p.u. (188.76 MW on a base MVA 100) and total reactive power loss of 13.7165 p.u. (1,371.65 MVAr on a base MVA 100) without enhancement.

3.2. The Results of the Nigerian 28-Bus System Steady State Behaviour with Enhancement

The obtained results of the steady state behaviour of the Nigerian electricity grid considered from the implementation of the PSAT models in Figs. 7 to 9 where SSSC, SVC and hybrid SSSC-SVC were respectively installed are presented in Figs. 10 to 12 which respectively depict comparison of the system bus voltage magnitudes, total real power loss and total reactive power loss before and after compensation.

The results in Fig. 10 revealed that the application of SSSC, SVC and hybrid SSSC-SVC respectively on the Nigeria 28-bus power network aside enhancing Ayede, New Haven, Onitsha, Gombe, Jos, Kano and Makurdi voltage magnitudes which were constrained before compensation to an acceptable level for effective operation, had positive impacts on the overall system voltage profile. While the SSSC inclusion improved the voltage magnitudes of the constrained buses to 0.9730, 1.0000, 0.9846, 1.0000, 0.9917, 0.9663 and 1.0331 p.u., SVC installation enhanced the values to 0.9581, 1.0000, 0.9853, 1.0000, 0.9907, 0.9613 and 0.9877 p.u. respectively. Hybrid SSSC-SVC installation on the other hand improved the constrained buses' voltage magnitudes to respective 0.9859, 1.0000, 0.9856, 1.0000, 0.9911, 0.9918 and 1.0330 p.u.

The overall comparison of the system bus voltage magnitudes as delineated in Fig. 10 indicated that the hybrid SSSC-SVC had a better impact on the voltage profile compared to either SSSC or SVC. Hybrid SSSC-SVC generally increased the voltage magnitudes of eight buses which include Ajaokuta (6), Benin (8), Ayede, Oshogbo (10), Alaoji (12), Onitsha (14), B. Kebbi (15) and Kano to 1.0121, 1.0155, 0.9859, 0.9812, 1.0066, 0.9856, 0.9872 and 0.9918 respectively. This was followed by SSSC which increased the voltage magnitudes of Akangba (4), Jos, Kaduna (20) and Makurdi to 0.9861, 0.9917, 1.0163 and 1.0331 p.u. respectively. SVC performed least of the three enhancement schemes. The improvement in voltage profile offered by SSSC, SVC and hybrid SSSC-SVC impacted positively on the system's power losses as depicted in Figs. 11 and 12.

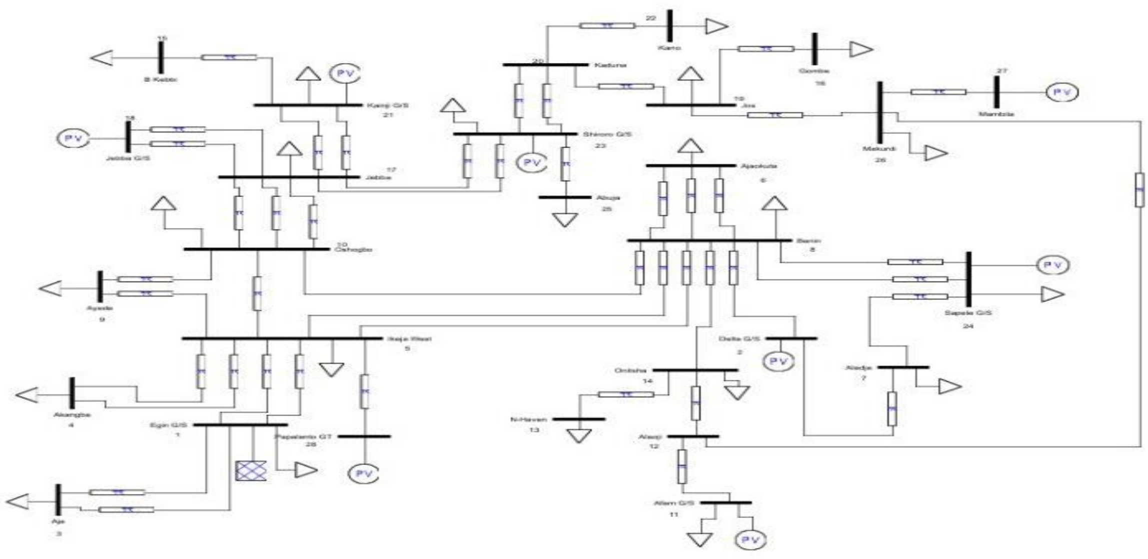

Fig. 4. PSAT model of the Nigerian 28-bus electricity grid before enhancement

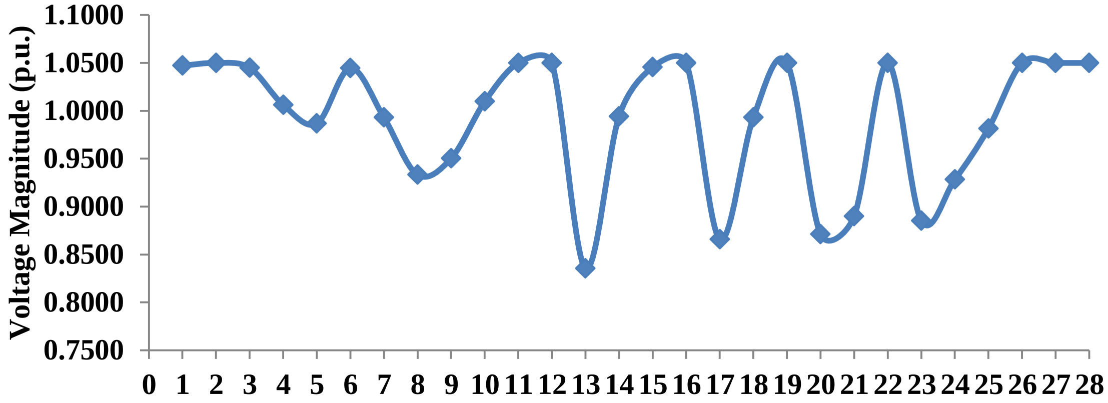

Fig. 5. The Nigerian 28-bus electricity grid voltage magnitudes before enhancement

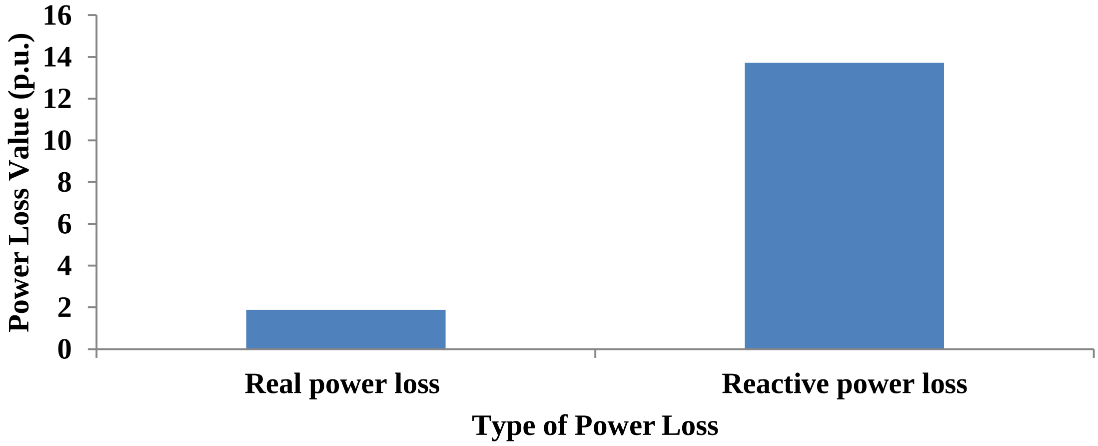

Fig. 6. The Nigerian 28-bus electricity grid total real and reactive power losses before enhancement

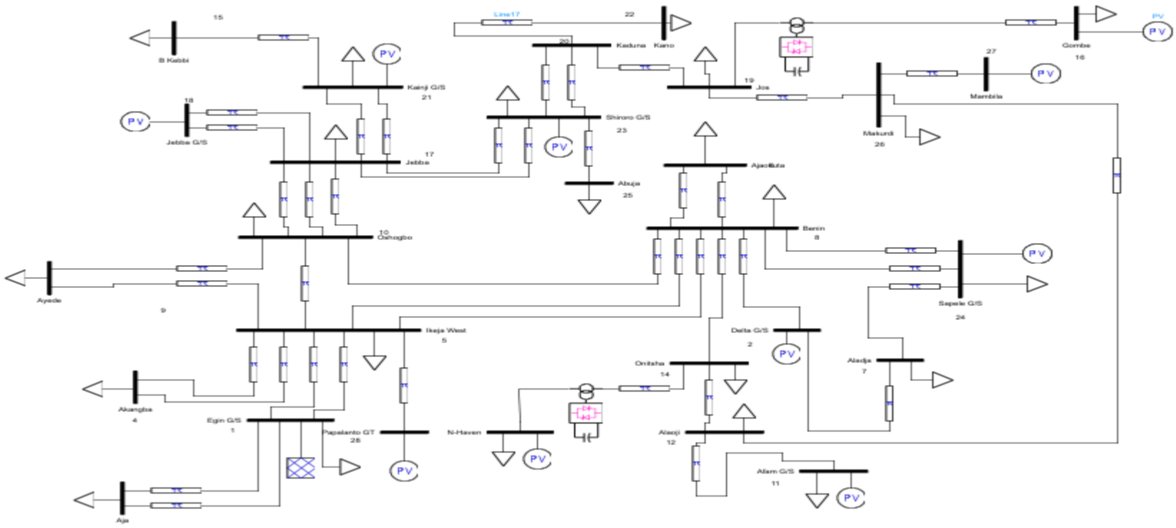

Fig. 7. PSAT model of the Nigerian 28-bus network with SSSC

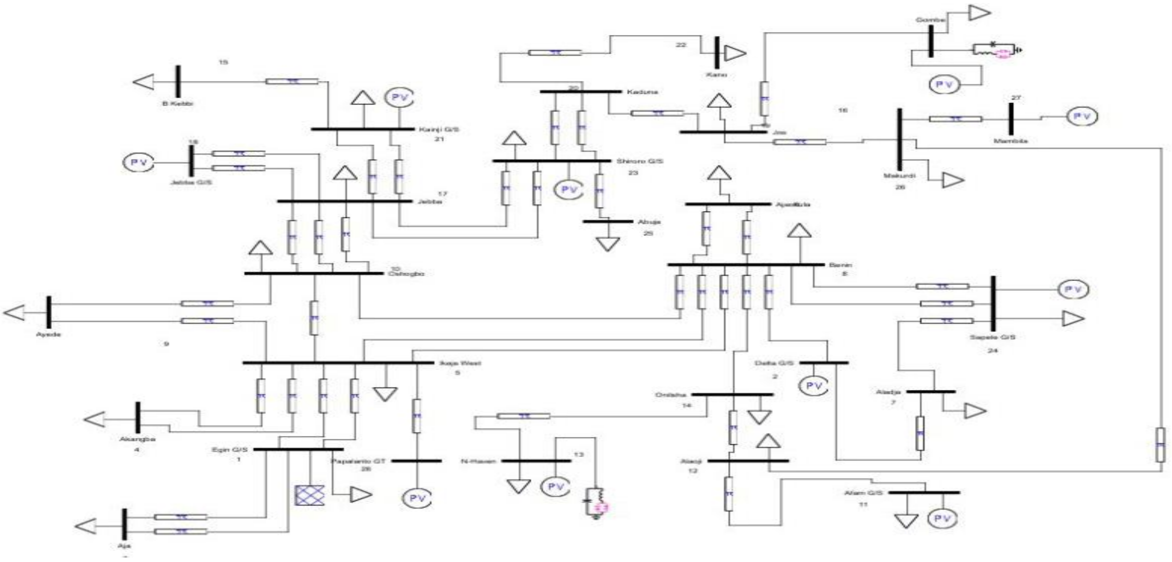

Fig. 8. PSAT model of the Nigerian 28-bus network with SVC

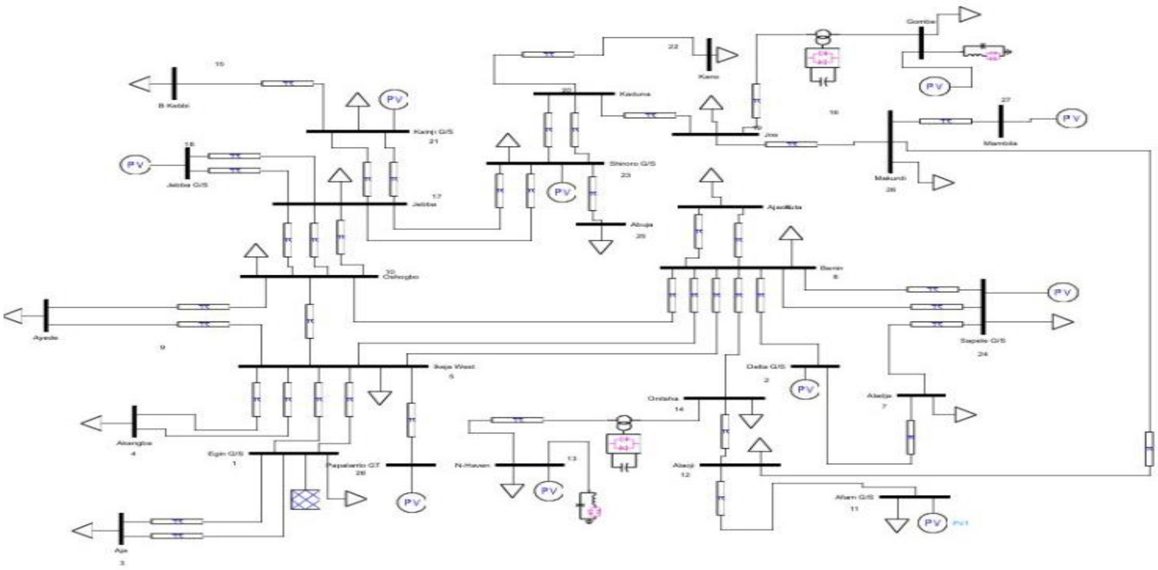

Fig. 9. PSAT model of the Nigerian 28-bus network with hybrid SSSC-SVC

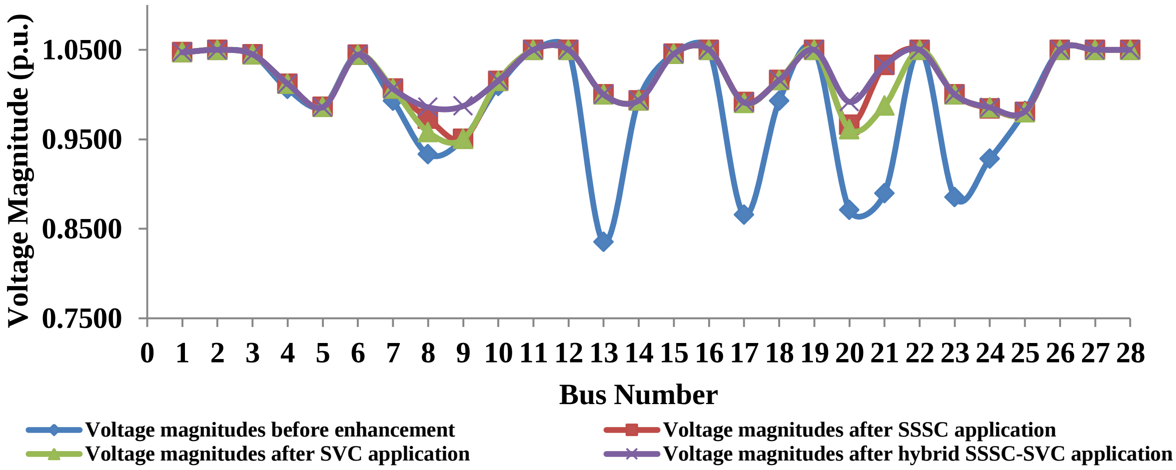

Fig. 10. Comparison of the voltage profile of the Nigerian 28-bus power network before and after SSSC, SVC and hybrid SSSC-SVC application

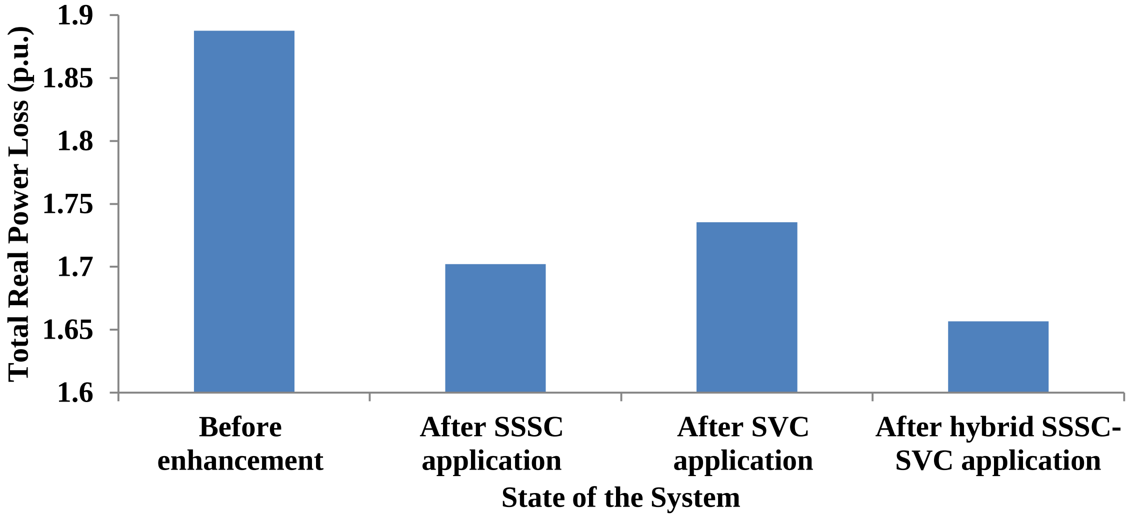

Fig. 11: Comparison of the Nigerian 28-bus electricity grid total real power loss before and after SSSC, SVC and hybrid SSSC-SVC application

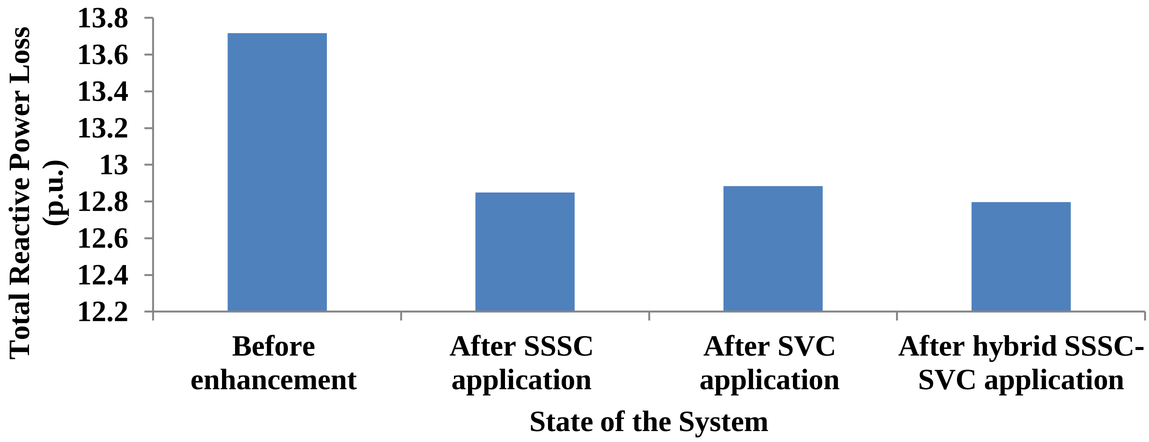

Fig. 12. Comparison of the Nigerian 28-bus electricity grid total reactive power loss before and after SSSC, SVC and hybrid SSSC-SVC application

The SSSC, SVC and hybrid SSSC-SVC application respectively reduced the system's real power loss by 9.83, 8.06 and 12.24% from 188.76 MW to 170.21, 173.55 and 165.66 MW. The compensators equally decreased the system total reactive power loss from 1371.65 MVAr to 1284.91, 1288.39 and 1279.72 MVAr, leading to improvement of 6.32, 6.07 and 6.70% respectively in the reactive line flow of the network. Observing from Figs. 11 and 12, hybrid SSSC-SVC was found to be the most effective compensator of the three enhancement schemes considered since it produced the least real and reactive power losses of the three controllers in addition to the best enhanced voltage profile.

3.3. Results of Cost Analysis of the System Useful Power Loss

The cost analysis of the useful power loss on the considered Nigerian electricity grid revealed that 188.76 MW loss in active power when no enhancement was applied on the system is equivalent to yearly loss of ₦12,384,996,624.00 in the transmission of electric power over the grid. The total power losses of 170.21, 173.55 and 165.66 MW, however, produced by the use of SSSC, SVC and hybrid STATCOM-SSSC on the grid resulted in yearly loss of ₦11,167,886,604.00, ₦11,387,032,020.00 and ₦10,869,350,184 respectively in the export of electric power on the grid. Comparison of these cost values showed that compensation via SSSC, SVC and hybrid SSSC-SVC produced cost savings of ₦1,217,110,020.00, ₦997,964,604.00 and ₦1,515,646,440.00 respectively. This is an indication that hybrid SSSC-SVC offered the best cost saving for transmission of electric power of the three enhancement options considered in the study.

3.4. Discussion of the Results

The steady state response analysis of the considered Nigerian electric power transmission grid before enhancement revealed that Ayede, New Haven, Onitsha, Gombe, Jos, Kano and Makurdi violated the statutory voltage limit of 0.95 to 1.05 p.u required for smooth and effective system operation since their voltage magnitudes were 0.9333, 0.8853, 0.9281, 0.8353, 0.8658, 0.8712 and 0.8897 respectively. Total real power loss of 188.76 MW and total reactive power loss of 1,371.65 MVAr respectively were also recorded on the system under no enhancement condition.

The infringement of the voltage tolerance limit observed on the constrained buses when no compensation was applied suggested that the considered grid was not operating satisfactorily and the instability imposed on the network due to out-of-tolerance voltage condition could serve as a potential source of threat to the system's security, leading to series of operational issues such as blackouts, equipment damage, high power losses and cascaded failures. The high losses characteristically decrease the amount of useful electric power transmitted over the grid; the energy that could have been to meet more demands of the customers.

Therefore, enhancement in a multi-compensation mode was applied to the grid to boost its performance. The reason for this action was because satisfactory steady state response of the network was unattainable when SSSC, SVC and hybrid SSSC-SVC were deployed individually in sequence on the seven constrained buses from the no enhancement condition as a result of bus voltage magnitude violation cases recorded. Enhancement was introduced into the grid via two buses Gombe and Jos for SVC and hybrid SSSC-SVC and two branches Gombe-Jos and Onitsha-New Haven for SSSC and hybrid SSSC-SVC. Under these conditions, desired performance was achieved from the grid where no bus voltage magnitude violations occurred. A 100 MVA rating of each controller used during the implementation was observed to positively influence the voltage profile and the power losses of the system, however, to a varying degree. SSSC improved the voltage magnitudes of the seven constrained buses to 0.9730, 1.0000, 0.9846, 1.0000, 0.9917, 0.9663 and 1.0331 p.u. respectively; the values which were within tolerance range while SVC enhanced the values to 0.9581, 1.0000, 0.9853, 1.0000, 0.9907, 0.9613 and 0.9877 p.u. respectively. Hybrid SSSC-SVC improved the values to 0.9859, 1.0000, 0.9856, 1.0000, 0.9911, 0.9918 and 1.0330 p.u. respectively.

The system voltage profile improvement observed was due to compensation offered by the controllers. SVC, SSSC and hybrid SSSC-SVC through shunt, series and series-shunt compensations respectively were able to mitigate reactive power deficiencies on the affected buses and lines and on the overall were able to enhance the buses' voltage magnitudes to the range acceptable for a stabilized operation of the system. Hybrid SSSC-SVC exhibited superiority over SSSC and SVC by generally improving the voltage magnitudes of eight buses which are Ajaokuta, Benin, Ayede, Oshogbo, Alaoji, Onitsha, B. Kebbi and Kano to 1.0121, 1.0155, 0.9859, 0.9812, 1.0066, 0.9856, 0.9872 and 0.9918 respectively. This was followed by SSSC which increased the voltage magnitudes of Akangba, Jos, Kaduna and Makurdi to 0.9861, 0.9917, 1.0163 and 1.0331 p.u. respectively. SVC showed least effectiveness of the three enhancement schemes by producing voltage magnitudes which were intermediate to those of SSSC and hybrid SSSC-SVC.

The impact of SSSC, SVC and hybrid SSSC-SVC on the voltage magnitudes resulted into a pronounced positive effective on the system real and reactive power flows. The system total real power loss decreased by 9.83, 8.06 and 12.24% from 188.76 MW to 170.21, 173.55 and 165.66 MW respectively when SSSC, SVC and hybrid SSSC-SVC were applied in sequence. The total reactive power loss equally decreased from 1371.65 MVAr to 1284.91, 1288.39 and 1279.72 MVAr, leading to improvement of 6.32, 6.07 and 6.70% respectively in the reactive line flow of the system.

Judging from the performance of the three enhancement schemes considered in the study, hybrid SSSC-SVC outclassed SSSC and SVC through its impact on voltage profile and power flow on the considered grid. Analysis of the cost implication of the compensation rendered by SSSC, SVC and hybrid SSSC-SVC revealed that the use of hybrid SSSC-SVC produced the highest yearly cost saving of ₦1,515,646,440.00 in the export of electric power over the Nigerian power grid compared to the yearly cost savings of ₦1,217,110,020.00 and ₦997,964,604.00, respectively offered by SSSC and SVC.

This study's results are in tandem with the findings of authors in [32], [33], [34] where hybrid use of SSSC and SVC was found to exhibit excellent performance in enhancing power flow on the considered networks through real power minimization. The results from this study also align with the submission of the works of authors [35], [36], [37], [38], [39], [40], [41]. Although steady state stability was the focal point of these works, hybrid SSSC-SVC, however, still proved itself as a more potent means of actualizing a rapid steady state stability of the considered networks.

IV. CONCLUSION

One of the main power system goals is to ensure adequate and regular electricity supply to the customers. This can only be made possible when technical issues such as high power losses and poor voltage profile which often characterize most power networks especially from developing nations including Nigeria are sufficiently and promptly addressed. FACTS devices which are economic and fast-acting solutions play a leading role in this respect. Therefore, in this study, the effect of hybrid configured SSSC and SVC on power flow control in the Nigerian electric power transmission grid was assessed.

Load flow equations which give description of steady state behaviour of power system network were formulated. The system's steady state response before and after enhancement with SSSC, SVC and hybrid SSSC-SVC were simulated. The voltage profile and power losses of the system were determined and analyzed. Analysis of the overall results indicated that hybrid SSSC-SVC exhibited superiority over SSSC and SVC deployed singly by producing the most improved bus voltage magnitudes, highest power flows accompanied by the most reduced losses and highest cost saving on the considered Nigerian power network. Hence, hybrid use of SSSC and SVC improved power flow in the Nigerian 28-bus electricity grid better than either SSSC or SVC with a reduced revenue loss.

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APPENDICES

Appendix I: The Nigerian 28-bus electricity grid bus data

Bus Identification		**Bus Loads**	
Name	**No**	**MW**	**MVAr**
Egbin	1	68.90	51.70
Delta	2	0.00	0.00
Aja	3	274.40	205.80
Akangba	4	244.70	258.50
Ikeja-West	5	633.20	474.90
Ajaokuta	6	13.80	10.30
Aladja	7	96.50	72.40
Benin	8	383.30	287.50
Ayede	9	275.80	206.8
Osogbo	10	201.20	150.90
Afam	11	52.50	39.40
Alaoji	12	427.00	320.20
New-Heaven	13	177.90	133.40
Onitsha	14	184.60	138.40
B/Kebbi	15	114.50	85.90
Gombe	16	130.60	97.90
Jebba	17	11.00	8.20
Jebba G	18	0.00	0.00
Jos	19	70.30	52.70
Kaduna	20	193.00	144.70
Kanji	21	7.00	5.20
Kano	22	220.60	142.90
Shiroro	23	70.30	36.10
Sapele	24	20.60	15.40
Abuja	25	110.00	89.00
Makurdi	26	290.10	145.00

Mambila	27	0.00	0.00
Papalanto	28	0.00	0.00

Appendix II: The Nigerian 28-bus electricity grid branch datat

Transmission Lines Data			
Bus		Resistance R(pu)	Reactance X(pu)
From	To		
1	3	0.0006	0.0044
4	5	0.0007	0.0050
1	5	0.0023	0.0176
5	8	0.0110	0.0828
5	9	0.0054	0.0405
5	10	0.0099	0.0745
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
9	10	0.0045	0.0340
15	21	0.0122	0.0916
10	17	0.0061	0.0461
11	12	0.0010	0.0074
12	14	0.0060	0.0455
13	14	0.0036	0.0272
16	19	0.0118	0.0887
17	18	0.0002	0.0020
17	23	0.0096	0.0271
17	21	0.0032	0.0239
19	20	0.0081	0.0609
20	22	0.0090	0.0680
20	23	0.0038	0.0284
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

Appendix III: The Nigerian 28-bus electricity grid generator data

Bus Identification		Voltage	Generator		Reactive Limits	
Name	No	Magnitude	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
Kainji	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