Nigerian Research Journal of Engineering and Environmental Sciences 9(1) 2024 pp. 210-225
p ISSN: 2635-3342; e ISSN: 2635-3350

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Power System Security Assessment and Enhancement using Static Var Compensator

[*1]Amoo, A.Y., [1]Adebisi, O.I., [1]Amusa, K.A., [2]Ogunsola, O.J.

[1]Department of Electrical and Electronics Engineering, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.
[2]Department of Mathematics, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.

*adewaleyusufa@gmail.com

http://doi.org/10.5281/zenodo.12599644

ARTICLE INFORMATION

Article history:
Received 21 Mar. 2024
Revised 21 Apr. 2024
Accepted 09 May 2024
Available online 30 Jun. 2024

Keywords:
Bus voltage violation
Contingency
Line loading violation
Newton-Raphson load flow
Power system security
Severity index

ABSTRACT

Security of power system (SoPS) describes its compliance with the pre-defined operational limits when exposed to disturbances. This study analysed the SoPS of the Nigerian 30 bus Electricity grid and enhancement was done via static var compensator (SVC) application. The steady state response of power system was modelled with Newton-Raphson load flow equations. The system response was simulated in an electrical transient analyzer program (ETAP) environment, considering a test case of the Nigerian 30-bus power grid. The bus voltage magnitudes and line loadings were determined to examine their adherence to the specified limits. The N-1 contingency evaluation was carried out on all possible outage elements of the considered network without and with enhancement and the severity index (SI) was determined. The base case load flow analysis revealed six cases of bus voltage limit violations and two cases of branch overloads. Contingency analysis ranked Benin-Onitsha and Ikeja West-Aiyede as the most and least critical branches with SI of 80.75 and 3.56 respectively. Multi-SVC installation on the system with line improvement on the overloaded branches mitigated all the bus voltage limit violations and line overloads. Contingency analysis performed after enhancement produced an appreciable reduction in the SI of the outage elements compared to the no enhancement case. This study established that hybrid use of SVC and line expansion was a better power system security enhancement approach than an SVC deployed singly.

1. INTRODUCTION

The present-day power systems are dynamically complex and characterized by geographically dispersed components such as loads, generators, transformer, transmission lines among others. The topology of the system is frequently changing with increasing load demand. Persistent increase in demand has resulted in the networks being loaded close to stability limit, therefore, making them susceptible to contingencies under minor or major disturbances which affect their security and reliability (Khuntia and Rhueda, 2019; Belu, 2022; Kundur and Malik, 2022 and Sil and Maity, 2022)

Recently, most nations across the globe including Nigeria are liberalizing their power industry and this has left the systems functioning under extremely challenging and unpredictable conditions due to the competitive market environment. As a result, the networks have grown more vulnerable to contingencies due to high interconnectivity to provide adequate electricity to match the growing demand. Hence, there is a greater need to oversee the stages of the system security, which frequently force operators to make difficult decisions about whether or not to act, what to act on, and how much to act. (Jokojeje et al. (2015).

Impairment of power system security due to contingencies can lead to various challenges such as voltage instability, complete blackouts, inadequate compensation of reactive power, and significant transmission losses over long distances (Ezerugbo *et al.,* 2021; Adegoke and Sun, 2022; Wondie and Tella, 2022; Fawzy *et al.,* 2023 and Hailu *et al.,* 2023).

The use of capacitor banks, under-frequency relays, under-voltage relays, establishment of new transmission lines, construction of new power plants as well as upgrade of existing facilities are examples of the traditional techniques that have been thought to be effective in enhancing the power and voltage profiles of a power system network and, consequently, its security (Jokojeje *et al.,* 2015; Elmitwally and Ghanem, 2021 and Sheta *et al.,* 2023;). However, these techniques have been found to be unreliable due to wear and tear of mechanical components, delayed function responses, environmental and economic factors; all of which make their use unfavourable (Gur, 2018; Aghaei *et al.,* 2022 and Rojek *et al.,* 2023).

The adoption of quick-acting and cost-effective flexible alternating current transmission systems (FACTS), which are solid-state based devices, has been one of the feasible solutions to these conventional approaches in recent times. FACTS are static equipment that improves controllability and supply security on power system grids. As reported by Mohanty and Barik (2011); Ghosh *et al.,* 2015; Jokojeje *et al.* (2015); Gandoma *et al.,* (2018) and Adetokun and Muriiti, (2021), IEEE describes FACTS as power electronic based devices and other stationary equipment with potentials to control one or more parameters of the alternating current transmission systems to improve the power transfer efficiency.

FACTS technology is a novel method for strengthening the current power system infrastructures by taking advantage of advancements in the field of power electronics or solid state (Dragičević *et al.,* 2015; Jokojeje et al., 2015; Kumar *et al.*, 2017 and Wang *et al.,* 2017). Some of the popular FACTS devices usually employed for various power system applications include static synchronous compensator (STATCOM), unified power flow controller (UPFC), inter-line power flow controller (IPFC), thyristor-controlled series capacitor (TCSC), static synchronous series compensator (SSSC) and static var compensator (SVC) (Boucetta *et al.,* 2019; Khan *et al.,* 2021; Al Mashhadany *et al.,* 2022 and Kodeeswara *et al.,* 2023). Many investigations have been conducted to assess the benefits and prospective applications of these technologies since each device possesses a unique feature that can be utilized for various purposes (Divya and Ostegaard, 2009).

Therefore, the goal of this study was to assess and enhance the security of a power system network using SVC. SVC is one of the most important compensators frequently used in control system and it is operated for the regulation of other systems (Ibe and Onyema, 2013; Bajaj and Singh, 2020). The device is controlled by either the output or input to the system and the key elements which are responsible for the effectiveness of the compensator are thyristor-controlled capacitor (TCC) and thyristor-controlled reactor (TCR) (Ibe and Onyema, 2013; Hooshmand *et al*, 2015 and Bajaj and Singh, 2020).

2. METHODOLOGY

2.1. AC Power Flow Modelling

Load flow is an important tool used in the operation and planning stages of power systems. It provides useful information on the steady state conditions of the systems. Such information includes bus voltage magnitude, bus voltage angle, real and reactive line flows (Wang *et al.*, 2008). The formulation of the load flow model

A.Y. Amoo et al. / Nigerian Research Journal of Engineering and Environmental Sciences
9(1) 2024 pp. 210-225

for a typical n-bus power network in this study requires that the relationship between current, voltage, admittance, active and reactive powers of the system expressed by Equation (1) holds:

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{j=1}^{n} Y_{ij} V_j \; ; \qquad i, j = 1, 2, ..., n \tag{1}$$

where I_i, V_i^*, Y_{ij}, V_j, P_i and Q_i respectively represent current injected at bus i, complex conjugate of bus i voltage, admittance matrix element between bus i and j, bus j voltage, active power injected at bus i and reactive power injected at bus i.

Equation (1) produces Equations (2) and (3) when separated into real and imaginary parts and these further yield Equations (4) and (5) respectively with the substitution of the polar form of V_i V_i^*, Y_{ij} and V_j in Equations (2) and (3):

$$P_i = \text{Re}\left\{ V_i^* \sum_{j=1}^{n} Y_{ij} V_j \right\} \tag{2}$$

$$Q_i = -\text{Im}\left\{ V_i^* \sum_{j=1}^{n} Y_{ij} V_j \right\} \tag{3}$$

$$P_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \cos(\theta_{ij} + \delta_j - \delta_i)$$

(4) $$Q_i = -V_i \sum_{j=1}^{n} Y_{ij} V_j \sin(\theta_{ij} + \delta_j - \delta_i) \tag{5}$$

where δ_i, δ_j and θ_{ij} respectively represent bus i voltage angle, bus j voltage angle and line i-j admittance angle.

The expressions of Equations (4) and (5) are together known as static load flow equations. They serve as important mathematical tool in describing the steady state response of power system networks. These equations are characteristically non-linear and are usually solved via numerical iterative procedure. Varieties of numerical iterative techniques are available for linearizing the expressions of the Equation (4) and (5), however, Newton-Raphson iterative method was employed for this study because of faster convergence rate, accuracy and suitability for large scale power networks (Kothari and Nagrath, 2008; Gupta, 2008 and Adebisi et al., 2017). The Newton-Raphson method application to Equations (4) and (5) produces a matrix expression of Equation (6) (Kothari and Nagrath, 2008; Gupta, 2008 and Adebisi et al., 2017):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{6}$$

Where ΔP, ΔQ, $\Delta\delta$ and ΔV denote changes in real power, reactive power, bus voltage angle and bus voltage magnitude respectively and J_1, J_2, J_3 and J_4 are the Jacobian matrix elements obtained partial differential manipulations of Equations (4) and (5).
ΔP, ΔQ, J_1, J_2, J_3, J_4, $\Delta\delta$ and ΔV in Equation (6) are expressed by Equations (7) to (14) respectively.

A.Y. Amoo et al. / Nigerian Research Journal of Engineering and Environmental Sciences
9(1) 2024 pp. 210-225

$$\Delta P = \begin{pmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \end{pmatrix} \tag{7}$$

$$\Delta Q = \begin{pmatrix} \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{pmatrix} \tag{8}$$

$$J_1 = \begin{pmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{pmatrix} \tag{9}$$

$$J_2 = \begin{pmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{pmatrix} \tag{10}$$

$$J_3 = \begin{pmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{pmatrix} \tag{11}$$

$$J_4 = \begin{pmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{pmatrix} \tag{12}$$

$$\Delta\delta = \begin{pmatrix} \Delta\delta_2^{(k)} \\ \vdots \\ \Delta\delta_n^{(k)} \end{pmatrix} \tag{13}$$

$$\Delta V = \begin{pmatrix} \Delta\left|V_2^{(k)}\right| \\ \vdots \\ \Delta\left|V_n^{(k)}\right| \end{pmatrix} \tag{14}$$

The system's real and reactive powers are computed from Equations (15) and (16) respectively while the new estimates of phase angle and magnitude of the bus voltage are determined from Equations (17) and (18) (Kothari and Nagrath, 2008; Gupta, 2008 and Adebisi *et al.*, 2017).

$$\Delta P_i^{(k)} = P_i^{sp} - P_i^{(k)} \tag{15}$$

$$\Delta Q_i^{(k)} = Q_i^{sp} - Q_i^{(k)} \tag{16}$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{17}$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \tag{18}$$

Where k is iteration count, P_i^{sp} and Q_i^{sp} are respective specified real and reactive powers, $\Delta P_i^{(k)}$, $\Delta Q_i^{(k)}$, $\Delta\delta_i^{(k)}$ and $\Delta\left|V_i^{(k)}\right|$ are respective discrepancy in real power, reactive power, bus voltage angle change and bus voltage magnitude at k^{th} iteration, $P_i^{(k)}$, $Q_i^{(k)}$, $\delta_i^{(k)}$ and $\left|V_i^{(k)}\right|$ are respective estimate of real power, reactive power, bus voltage angle and bus voltage magnitude at kth iteration and $\delta_i^{(k+1)}$ and $\left|V_i^{(k+1)}\right|$ are respective estimate of bus voltage angle and bus voltage magnitude at (k+1)th iteration.

The system voltage and reactive power constraints are defined by Equation (19) and (20) respectively.

A.Y. Amoo et al. / Nigerian Research Journal of Engineering and Environmental Sciences
9(1) 2024 pp. 210-225

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{19}$$

$$Q_i^{\min} \le Q_i \le Q_i^{\max} \tag{20}$$

Where V_i^{max} and V_i^{min} respectively denote maximum and minimum bus i voltage magnitudes and Q_i^{max} and Q_i^{min} respectively denote maximum and minimum reactive power injected at bus i.
The net real and reactive power inputs at bus i, P_i and Q_i, are defined by Equations (21) and (22) respectively.

$$P_i = P_{gi} + P_{li} \tag{21}$$

$$Q_i = Q_{gi} - Q_{li} \tag{22}$$

2.2. Violations of Tolerance Limits in Power System

The common forms of disturbances usually encountered during security assessment of power system network via contingency analysis are line and generator outages and these normally result in violations of bus voltage magnitude and line loading limits (Mohammed, 2012). Violation of bus voltage magnitude limit occurs when the buses in power system network are loaded beyond the acceptable voltage limit of operation. The tolerance limit for bus voltage magnitude is between 0.95 to 1.05 p.u.

Line loading limit violation is a condition that occurs when the MVA rating of the line exceeds the given rating. The lines are usually designed to be able to withstand 125% of their MVA limit in ideal condition. However, the usually practice by the utility companies is that a current flow above 80% of the MVA limit is declared a critical or alarm condition that requires urgent corrective measure (Mohammed, 2012; Abdul' Wafa et al., 2019 and NCC, 2023).

2.3. Performance Index Evaluation

Performance or severity index is an important measure usually applied for selection and ranking of contingencies. It is of two types which are the active power performance index and the voltage performance index. Voltage performance index (PI_V) gives a measure of the bus voltage limit violation and it is mathematically expressed as in Equation (29) (Roy, 2011; Vinodiya and Titare, 2015 Abdul Wafa et al., 20 and Sirisha et al., 2020).

$$PI_V = \sum_{i=1}^{N-1}\left(2\left(\frac{V_i - V_{isp}}{V_{i\max} - V_{i\min}}\right)^2\right) \tag{29}$$

Where N is the difference between the total number of buses and voltage-controlled buses, V_i is the post load flow voltage of bus i, V_{isp} is the specified voltage at bus i assumed as 1 p.u., $V_{i\max}$ is the maximum voltage limit taken as 1.05 of V_{isp} and $V_{i\min}$ is the minimum voltage limit, generally assumed as 0.95 of V_{isp} .

Active power index or Line MVA performance index $\left(PI_p\right)$ on the other hand describes the degree of line, generator or transformer overloads and it is mathematically expressed by Equation (30) (Roy, 2011 and Vinodiya and Titare, 2015):

$$PI_P = \sum_{i=1}^{L} \frac{1}{2}\left(\frac{P_i}{P_{i\max}}\right)^2 \tag{30}$$

Where L is the total number of transmission lines present in the system, P_i is the active power flow in line i and $P_{i\max}$ is the maximum active power flow in line *i* expressed by Equation (31).

$$P_{i\max} = \frac{V_i V_j}{X} \tag{31}$$

Where V_i is the voltage at bus *i*, V_j is the voltage at bus *j*, and X is the reactance between buses I and *j*.

2.4. Power Flow Model of SVC

Corrective action is one of the key processes in the power system security assessment. For this study, SVC was the device employed for the implementation of the corrective action undertaken. The choice of an SVC was due to its capability to provide rapid compensation of reactive power for bus voltage stabilization within acceptable limit of operation, loss reduction and make better use of the available equipment.

The equivalent circuit representation of the variable shunt susceptance model of the device shown in Figure 1 was taken into consideration to formulate its power flow model. Referring to Figure 1, the current and reactive power drawn by the SVC, I_{SVC} and Q_{SVC}, are given by Equations (32) and (33) respectively:

$$I_{SVC} = jB_{SVC}V_i \tag{32}$$

$$Q_{SVC} = Q_i = -V_i^2 B_{SVC} \tag{33}$$

Where B_{SVC} and Q_i respectively denote SVC susceptance and bus *j* reactive power.

The linearized power flow model of the SVC with B_{SVC} as a state variable is expressed by Equation (34) while B_{SVC} is updated based on Equation (35) at the end of the kth iteration:

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^{(k)} = \begin{bmatrix} 0 & 0 \\ 0 & Q_i \end{bmatrix}^{(k)} \begin{bmatrix} \Delta\theta_i \\ \dfrac{\Delta B_{SVC}}{B_{SVC}} \end{bmatrix}^{(k)} \tag{34}$$

$$B_{SVC}^{(k)} = B_{SVC}^{(k-1)} + \left(\frac{\Delta B_{SVC}}{B_{SVC}}\right)^{(k)} B_{SVC}^{(k-1)} \tag{35}$$

The SVC susceptance is the fluctuating susceptance needed to regulate the voltage magnitudes of buses the desired level and after the compensation level computation; the required firing angle for the compensation can be established (Ambriz-Perez *et al.*, 2000). Q_i and B_{SVC} are related to the firing angle, α_{SVC}, by Equation (36) (Ugdir *et al.,* 2011):

$$Q_i = -V_i^2 B_{SVC} = -\frac{V_i^2}{X_C L_L}\left\{X_L - \frac{X_C}{\pi}\left[2\left(\pi - \alpha_{SVC}\right) + \sin\left(2\alpha_{SVC}\right)\right]\right\} \tag{36}$$

Where X_C and X_L are respectively the SVC capacitive and inductive reactances.

A.Y. Amoo et al. / Nigerian Research Journal of Engineering and Environmental Sciences
9(1) 2024 pp. 210-225

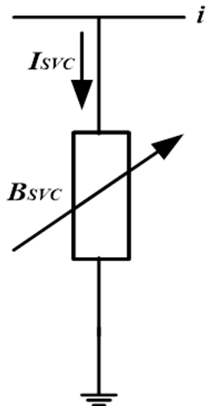

Figure 1 : SVC variable susceptance equivalent circuit représentation (Lakshmi *et al.*, 2022)

The linearized set of power flow model for SVC arising from Equation (36) is given by Equation (37) which is further modified as Equation (38) with Equation (39) as the updated α_{SVC} at the end of kth iteration.

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^{(k)} = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{\delta Q_i}{\delta \alpha} \end{bmatrix}^{(k)} \begin{bmatrix} \Delta \theta_k \\ \Delta \alpha_{SVC} \end{bmatrix}^{(k)} \quad (37)$$

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^{(k)} = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{2V^2_i}{\pi X_L}\left[\cos(2\alpha_{SVC}) - 1\right] \end{bmatrix}^{(k)} \begin{bmatrix} \Delta \theta_k \\ \Delta \alpha_{SVC} \end{bmatrix}^{(k)} \quad (38)$$

$$\alpha_{SVC}^{(k)} = \alpha_{SVC}^{(k-1)} + \Delta \alpha_{SVC}^{(k)} \quad (39)$$

The new estimate of B_{SVC} is obtained from Equation (40) (Ambriz-Perez et al., 2000).

$$B_{SVC} = -\frac{X_L - \dfrac{X_C\left[2\left(\pi - \alpha_{SVC}\right) + \sin\left(2\alpha_{SVC}\right)\right]}{\pi}}{X_C X_L} \quad (40)$$

Expressing B_{SVC} as a function of α_{SVC} does not depict the discontinuities as B_{SVC} varies continuously in both capacitive and inductive operating regions. Therefore, SVC power flow linearization based on α_{SVC} offers a better numerical behavior in comparison to B_{SVC} (Ambriz-Perez *et al.*, 2000).

2.5. Test Network

This study considered the Nigerian 330 kV, 30-bus electricity grid comprising 11 generating stations, 19 load buses and 53 transmission lines was considered as a case. Figure 2 shows the on-line diagram of the network while its data are presented in Appendices I and II. The current and equivalent MVA rating of the system are 1,360 A and 777.34 MVA respectively (TCN, 2012).

2.6. Choice of Simulation Software

In this study, ETAP software was used for the simulation of AC power flow and power index computations during contingency analysis. The key benefits of ETAP software are that it is very suitable for network modelling and analysis of generation, transmission, distribution, and industrial system and permits functions integration. The ETAP model of the Nigerian 30 – bus power network is showed in Figure 3.

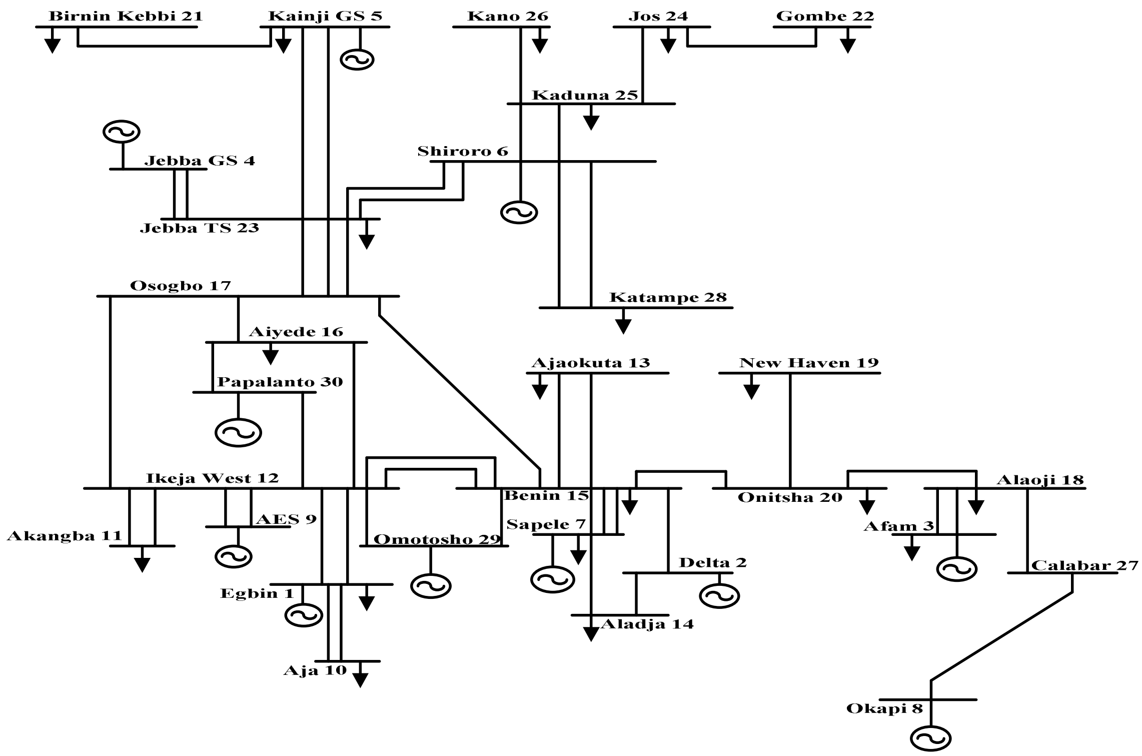

Figure 2: The 30-bus model of the Nigerian electricity grid

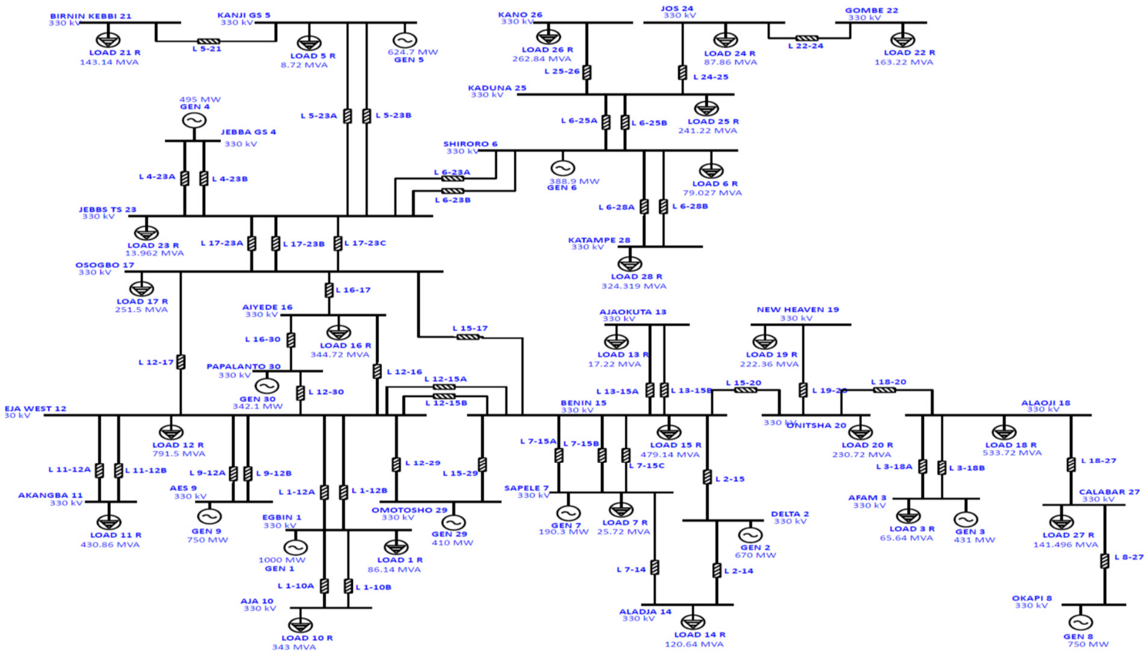

Figure 3: ETAP model of the 30-bus of the Nigerian electricity grid

3. RESULTS AND DISCUSSION

3.1. The Results of the Nigerian 30-Bus Power Grid before and after Compensation

The results of pre and post compensation of the Nigerian 30 – bus power network on ETAP environment is showed in Figure 4 are shown respectively in Figures 3 and 4. The results in Figure 4 revealed that six buses namely New Haven, Onitsha, Gombe, Jos, Kano and Calabar with voltage magnitudes of 0.9003, 0.9468, 0.6608, 0.8141, 0.8138 and 0.9319 p.u. respectively violated the statutory voltage tolerance limit of 0.95 to 1.05 p.u. for a secured operation. In addition to the system total active power loss was 218.76 MW, two branches L8 – 27 (Okapi-Calabar) and L18 – 27 (Alaoji-Calabar) with respective loadings of 101.6 and 84.19% exceeded the acceptable MVA limit of 80% for optimum system operation.

3.2. The Nigerian 30 – Bus Power Grid Contingency Analysis Results Before and After Enhancement

The results of N-1 contingency analysis on all the possible outage elements of the considered grid before and after the introduction of SVC are presented in Figures 5 and 6 which respectively delineate the combined performance index and ranking of the severity of each of the outage elements. The simulation results in Figure 5 identified branch 38 (L15-20) which is Benin-Onitsha with a severity index of 80.75 as the most critical branch and branch 31 (L12-16) which is Ikeja West-Aiyede with a severity index of 3.56 as the least critical branch in the system. As observed during the simulation, an outage on Benin-Onitsha branch resulted into nine buses violating the 0.95 to 1.05 p.u. acceptable voltage limit whereas an outage on Ikeja West-Aiyede led to two branches exceeding the recommended 80% of MVA limit and six buses violating the statutory voltage limit. The implication of the high severity index observed on Benin-Onitsha branch is that an outage on this branch at any point in time requires prompt remedial measure before resulting into multiple catastrophic effects on the overall system, although this does not mean the impact of an outage on Ikeja-Aiyede and other branches should be ignored as this also has negative influence on the system performance.

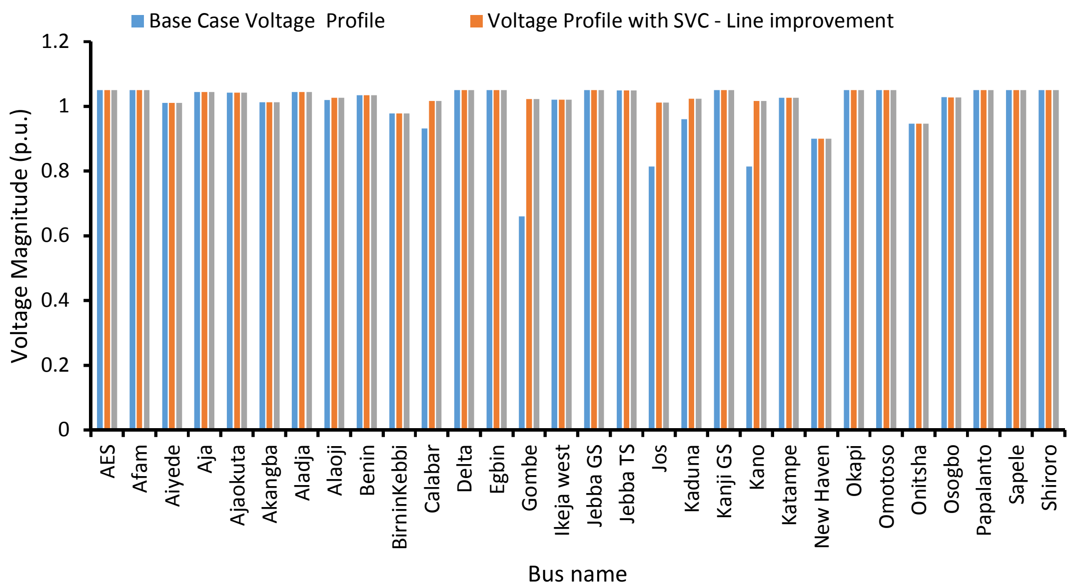

Figure 4: The Nigerian 30 – bus power grid voltage profile

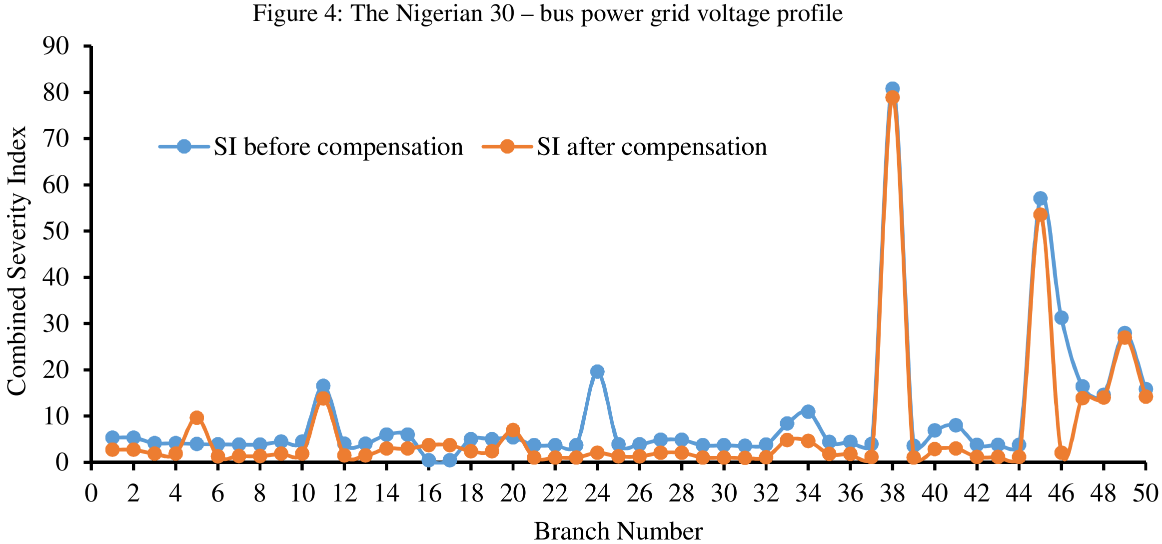

Figure 5: Combined performance index of the outage elements during contingency analysis

It was also observed from Figure 5 that the corrective action implemented impacted positively on the severity indices of every outage element due to the appreciable improvement recorded compared to when no compensation was applied. Benin-Onitsha branch still remained the most vulnerable branch with a performance index of 78.88 while Ikeja West-Aiyede with the severity index of 0.59 remains the least critical branch as indicated by both Figure 5 and 6. Two cases of over compensations were however observed from

Figure 5 where branches 5 and 20 (Delta-Aladja and Sapele-Aladja) had higher performance indices of 9.66 and 6.95 respectively after compensation as compared to 3.97 and 5.37 that was obtained before compensation. Moreover, branches L6-25A and L6-25B (Kanji-Kaduna) which exhibited non-convergence without corrective action; have now converged, with five cases of violations obtained each. These findings are indications that that the implemented corrective action improved the voltage profile, reduced the line losses and enhanced the security level of the Nigerian 30-bus power system.

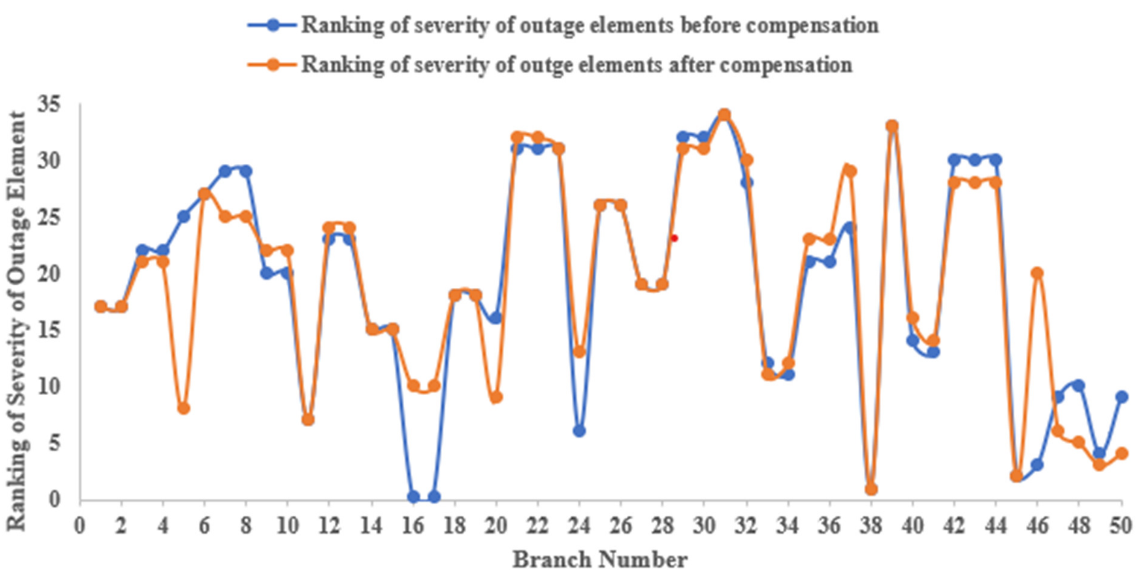

Figure 6: Ranking of severity of the outage elements during contingency analysis

4. CONCLUSION

In this study, power system security assessment and enhancement using SVC were carried out considering the Nigerian 330 kV, 30-bus power network. The system steady state was modelled using Newton-Raphson based load flow equations which were simulated to obtain the voltage profile and real and reactive power flows of the network. New Haven, Onitsha, Gombe, Jos, Kano, and Calabar violated the statutory voltage tolerance limit of 0.95 to 1.05 p.u. and two lines Okapi-Calabar and Alaoji-Calabar exceeded the recommended MVA limit of 80% in addition to the overall actual power loss recorded on the system being 218.76 MW. The N-1 contingency analysis on the fifty outage elements in the system identified Benin-Onitsha with highest performance index of 80.73 as the most vulnerable branch with an outage on this element resulting into Afam, Okapi, Alaoji, New Haven, Onitsha, Gombe, Jos, Kano and Calabar violating the voltage statutory limit. This is an indication that an outage on this branch requires prompt attention before impacting negatively on the system overall performance. The hybrid corrective strategy incorporating the use of multi-SVC and line improvement was found to be the most feasible remedial plan among those considered by the study. There were no bus voltage or line loading problems as a result of the plan. The contingency analysis conducted subsequent to the corrective action's execution resulted in fewer bus voltage magnitude and line loadings violations compared with no corrective action case. The Benin-Onitsha branch maintained its position as the most critical line with a severity index of 78.88, but the severity index of each outage element with corrective measure implemented was found to be much lower than when no remedial action was done. The Nigerian 30-bus power grid voltage profile, power losses and level of security were improved with hybrid SVC and line expansion application.

5. ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and contributions of the transmission company of Nigeria toward the success of this work.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Ambriz-Perez H., Acha E. and Fuerte-Esquivel C. R. (2000). Advanced SVC Models for Newton-Raphson Load Flow and Newton Optimal Power Flow Studies. *IEEE Publications on Power Systems.* 15(1), pp. 129-136.

Adegoke S.A. and Sun X. (2022). Power System Optimization Approach to Mitigate Voltage Instability Issues. *Journal of Cogent Engineering*. 10(21), pp. 1-40.

Abul'Wafa, A.R., El'Garably, A. and Nasser, S. 2019. Power System Security Assessment under N-1 and N-1-1 Contingency Conditions. International Journal of Engineering Research and Technology. 12(11), pp. 1854-1863.

Aghaei M., Fairbrother A., Gok, A., Ahmad S., Kazim S., Lobato K., Oreski G., Reinders A., Schmitz J., Theelen M., Yilmaz P. and Kettle J. (2022). Review of Degradation and Failure Phenomena in Photovoltaic Modules. *Renewable and Sustainable Energy Reviews*. 159(4), pp. 1364-0321.

Akram Elmitwally and Abdelhady Ghanem, (2021). Local current-based method for fault identification and location on series capacitor-compensated transmission line with different configurations. *International Journal of Electrical Power and Energy Systems*. 133, pp. 107283

Adetokun, B. B. and Muriithi, C. M. (2021). Application and Control of Flexible Alternating Current Transmission System Devices for Voltage Stability Enhancement of Renewable-Integrated Power Grid: A Comprehensive Review. *Journal of Heliyon*, 7(3), pp. 173-184.

Al Mashhadany, Y., Abbas, A. K. and Algburi, S. (2022). Study and Analysis of Power System Stability Based on FACT Controller System. *Indonesian Journal of Electrical Engineering and Informatics*. 10(2), pp. 317-332.

Amit Kumar Roy and Sanjay Kumar Jain. (2013). Improved Transmission Line Contingency Analysis in Power System using Fast Decoupled Load Flow. *International Journal of Advances in Engineering and Technology*. 6(5), pp. 2159-2170.

Adebisi, O.I., Adejumobi, I. A., Ogunbowale, P. E. Ade-Ikuesan, O.O. (2017). Compensator for Voltage Stability Enhancement and Power Loss Reduction in Power Systems Network. *LAUTECH Journal of Engineering and Technology*. 11(2), pp. 110-122.

Belu, R. (2022). Smart Grid Fundamentals: Energy Generation, Transmission and Distribution. CRC Press.

Boucetta, I., Djemai, N., Ahmed, S. and Laid, Z. (2019). Enhancement of Power System Transient Stability with a Large Penetration of Solar Photovoltaic using FACTS. *In International Conference on Electrical Engineering and Control Applications*. 3(10), pp. 533-547.

Bajaj M. and Singh A. K. 2020. Grid integrated renewable DG systems: A review of power quality Challenges and State-of-the-Art Mitigation Techniques. International Journal of Energy Research. 44(1), pp. 26-69.

Dragičević, T. Lu, X., Vasquez J. C. and Guerrero, J. M. (2015). DC Microgrids—Part II: A Review of Power Architectures, Applications, and Standardization Issues. *IEEE Transactions on Power Electronics*. 31(5), pp. 3528-3549.

Divya, K. C., and Østergaard, J. (2009). Battery energy storage technology for power systems—An overview. Electric power systems research, 79(4), pp. 511-520.

Elmitwally, A., Eladl, A. & Morrow, J. (2015). Long-Term Economic Model for Allocation of FACTS Devices in Restructured Power Systems Integrating Wind Generation. *Journal of IET Generation, Transmission and Distribution*. **9**(16), pp. 2653–2663.

Ezerugbo E.N., Ekwue A.O. and Anih L.U., (202)1. Voltage Stability Analysis of Nigeria 330kv Power Grid using P-V Plots. *Nigeria Journal of Technology*. 40(1), pp. 70 – 80.

Fawzy, S. Abd-Raboh, Elhossaini E. and Eladl, A. A. (2023). Optimal Allocation of Multi-Type FACTS Devices for Mitigating Wind Power Spillage with Enhancing Voltage Stability and Social Welfare. *Journal of Scientific Reports*. 13(1), pp. 2045-2322.

Gupta, J.B. (2008). Power System Analysis. S.K. Kataria and Son, India. 350pp.

Gandoman, F. H., Ahmadi, A., Sharaf, A. M., Siano, P., Pou, J., Hredzak, B. and Agelidis, V. G. (2018). Review of FACTS Technologies and Applications for Power Quality in Smart Grids with Renewable Energy Systems. *Journal of Renewable and Sustainable Energy*. 82(9), pp. 502-514.

Gür, T. M. 2018. Review of Electrical Energy Storage Technologies, Materials and Systems: Challenges and Prospects for Large-Scale Grid Storage. Journal of Energy and Environmental Science. 11(10), pp. 2696-2767.

Hailu, E. A. Nyakoe, G. N. and Muriithi, C. M. (2023). Techniques of power system static security assessment and improvement: A literature survey. Journal of Heliyon. 9(3), pp. 2405-8440.

Hooshmand, R. A., Morshed, M. J., and Parastegari, M. 2015. Congestion Management by Determining Optimal Location of Series FACTS Devices using Hybrid Bacterial Foraging and Nelder–Mead Algorithm. *Journal of Applied Soft Computing*. 28(2), pp. 57-68.

Ibe, O. G. and Onyema, A. I. (2013). Concepts of Reactive Power Control and Voltage Stability Methods in Power System Network. *Journal of Computer Engineering*. 11(2), pp. 15-25.

Jokojeje, R. A., Adejumobi, I. A., Mustapha, A.O. and Adebisi, O.I. 2015. Application of Static Synchronous Compensator (STATCOM) In Improving Power System Performance: A Case Study of the Nigeria 330 kV Electricity Grid. *Nigerian Journal of Technology*, 34(3), pp. 564-572.

Kumar, D., Zare, F. and Ghosh, A. (2017). DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects. *Journal IEEE Access*. 5(13), pp. 12230-12256.

Kundur, P. (2007). Power system stability. *Power system stability and control. 10*, pp. 7-1.

Kothari, D.P. and Nagrath, I.J. (2008). Modern Power System Analysis. Tata McGraw-Hill, New Delhi, India.

Khuntia, S. R., Rueda, J. L. and Van der Meijden, M. A. (2019). Risk-Based Security Assessment of Transmission Line Overloading Considering Spatio-Temporal Dependence of Load And Wind Power Using Vine Copula. *IET Renewable Power Generation.* 13(10), pp. 1770-1779.

Kodeeswara K. G., Rajesh, P., Kumaravel, S. and Irusapparajan, G. (2023). Two-Area Power System Stability Analysis by Frequency Controller with UPFC Synchronization and Energy Storage Systems by Optimization Approach. *International. Review of Applied Sciences and Engineering.* 14(2), pp. 270-284.

Khan, A. N., Imran, K., Nadeem, M., Pal, A., Khattak, A., Ullah, K. and Younis, M. S. 2021. Ensuring Reliable Operation of Electricity Grid by Placement of FACTS Devices for Developing Countries. *Journal of Energies*, 14(8), pp. 2283-2295.

Mohanty A.K. and Barik A.K. 2011. Power System Stability Improvement using FACTS Devices. *International Journal of Modern Engineering Research.* 1(2), pp. 666-672.

Lakshmi, K. D., Panigrahi, P. K., and Kumar Goli, R. (2022). Machine Learning Assessment of IoT Managed Microgrid Protection in Existence of SVC using Wavelet Methodology. AIMS Electronics and Electrical Engineering, 6(4), pp.370-384.

Mohammed, S.E.G., Mohammed, A.Y. and Abdelrahim, Y.H. 2012. Power System Contingency Analysis to Detect Network Weaknesses. *Zaytoonah University International Engineering Conference of Design and Innovation in Infrastructure.* 18(20), pp. 1-13.

Rojek, I.; Jasiulewicz-Kaczmarek, M.; Piechowski, M. and Mikołajewski, D. (2023). An Artificial Intelligence Approach for Improving Maintenance to Supervise Machine Failures and Support. *Journal of* Applied Science. 13(8), pp. 4971.

Roy, A.K. (2011). Contingency Analysis in Power Systems. Unpublished Master Dissertation. Thapar University, Patiala, India, 84pp.

Sil, A. and Maity, S. (2022). Industrial Power Systems: Evolutionary Aspects. CRC Press.

Sheta, A.N., Abdulsalam, G.M. and Sedhom, B.E. (2023). Comparative Framework for AC-Microgrid Protection Schemes: Challenges, Solutions, Real Applications and Future Trends. *Journal of Protection and Control of Power System.* **8**(24), 1 – 40

Udgir, S., Varshney, S., and Srivastava, L. (2011). Optimal Placement and Sizing of SVC for Voltage Security Enhancement. *International Journal of Computer Applications*, *32*(6), pp. 44-51.

Vinodiya, P. and Titare, L.S. (2015). Power System Contingency Ranking using Fast Decoupled Load Flow Method. *International Journal of Recent Research in Electrical and Electronics Engineering*. 2(3), pp. 153-160.

Wondie T.T., Tella T.G. and Li Y. (2022). Voltage Stability Assessment and their Improvement using Optimal Placed Static Synchronous Compensator (STATCOM). *Journal of Electrical and Computer Engineering*. 2022, pp. 2071454

Wang, K., Yu, J., Yu, Y., Qian, Y., Zeng, D., Guo, S. and Wu. J. (2017). A survey on energy internet: Architecture, approach, and emerging technologies. *IEEE systems journal*. 12(3), pp. 2403-2416.

APPENDICES

I: The Nigerian 30-bus grid system node data

Bus name	Bus number	V (p.u.)	Phase (º)	P_G (MW)	Q_G (MVAr)	P_D (MW)	Q_D (MVAr)
Egbin	1	1.05	0	0	0	68.9	51.7
Delta	2	1.05	0	670	0	0	0
Afam	3	1.05	0	431	0	52.5	39.4
Jebba GS	4	1.05	0	495	0	0	0
Kanji GS	5	1.05	0	624.7	0	7	5.2
Shiroro	6	1.05	0	388.9	0	70.3	36.1
Sapele	7	1.05	0	190.3	0	20.6	15.4
Okapi	8	1.05	0	750	0	0	0
AES	9	1.05	0	750	0	0	0
Aja	10	1	0	0	0	274.4	205.8
Akangba	11	1	0	0	0	344.7	258.5
Ikeja est	12	1	0	0	0	633.2	474.9
Ajaokuta	13	1	0	0	0	13.8	10.3
Aladja	14	1	0	0	0	96.5	72.4
Benin	15	1	0	0	0	383.3	287.5
Aiyede	16	1	0	0	0	275.8	206.8
Osogbo	17	1	0	0	0	201.2	150.9
Alaoji	18	1	0	0	0	427	320.2
New haven	19	1	0	0	0	177.9	133.4
Onitsha	20	1	0	0	0	184.6	138.4
BirninKebbi	21	1	0	0	0	114.5	85.9
Gombe	22	1	0	0	0	130.6	97.9
Jebba TS	23	1	0	0	0	11.3	8.2
Jos	24	1	0	0	0	70.3	52.7
Kaduna	25	1	0	0	0	193	144.7
Kano	26	1	0	0	0	220.6	142.9
Calabar	27	1	0	0	0	110	89
Katampe	28	1	0	0	0	290.1	145
Omotoso	29	1.05	0	410	0	0	0
Papalanto	30	1.05	0	342.10	0	0	0

A.Y. Amoo et al. / Nigerian Research Journal of Engineering and Environmental Sciences
9(1) 2024 pp. 210-225

II: The Nigerian 30-bus grid system branch data

From Bus	To Bus	R(p.u.)	X(p.u.)	B(p.u.)
Aja 10	Egbin 1	0.0006	0.0044	0.0295
Aja 10	Egbin 1	0.0006	0.0044	0.0295
Akangba 11	Ikeja west 12	0.0007	0.005	0.0333
Akangba 11	Ikeja west 12	0.0007	0.005	0.0333
Egbin 1	Ikeja west 12	0.0023	0.0176	0.1176
Egbin 1	Ikeja west 12	0.0023	0.0176	0.1176
Ikeja west 12	Benin 15	0.011	0.0828	0.55
Ikeja west 12	Benin 15	0.011	0.0828	0.55
Ikeja west 12	Aiyede 16	0.0054	0.0405	0.2669
Ikeja west 12	Osogbo 17	0.0099	0.0745	0.4949
Ajaokuta 13	Benin 15	0.0077	0.0576	0.383
Ajaokuta 13	Benin 15	0.0077	0.0576	0.383
Delta 2	Benin 15	0.0043	0.0317	0.2101
Delta 2	Aladja 14	0.0012	0.0089	0.0589
Aladja 14	Sapele 7	0.0025	0.0186	0.1237
Benin 15	Onitsha 20	0.0054	0.0405	0.2691
Benin 15	Osogbo 17	0.0098	0.0742	0.493
Benin 15	Sapele 7	0.002	0.0148	0.0982
Benin 15	Sapele 7	0.002	0.0148	0.0982
Benin 15	Sapele 7	0.002	0.0148	0.0982
Aiyede 16	Osogbo 17	0.0045	0.034	0.2257
BirninKebbi 21	Kanji GS 5	0.0122	0.0916	0.6098
Osogbo 17	Jebba TS 23	0.0061	0.0461	0.3064
Osogbo 17	Jebba TS 23	0.0061	0.0461	0.3064
Osogbo 17	Jebba TS 23	0.0061	0.0461	0.3064
Afam 3	Alaoji 18	0.001	0.0074	0.0491
Afam 3	Alaoji 18	0.001	0.0074	0.0491
Alaoji 18	Onitsha 20	0.006	0.0455	0.3045
New heaven 19	Onitsha 20	0.0036	0.0272	0.1807
Gombe 22	Jos 24	0.0118	0.0887	0.5892
Jebba TS 23	Jebba GS 4	0.0002	0.002	0.0098
Jebba TS 23	Jebba GS 4	0.0002	0.002	0.0098
Jebba TS 23	Shiroro 6	0.0096	0.0721	0.4793
Jebba TS 23	Shiroro 6	0.0096	0.0721	0.4793
Jebba TS 23	Kanji GS 5	0.0032	0.0239	0.1589
Jebba TS 23	Kanji GS 5	0.0032	0.0239	0.1589
Jos 24	Kaduna 25	0.0081	0.0609	0.4046
Kaduna 25	Kano 26	0.009	0.068	0.4516
Kaduna 25	Shiroro 6	0.0038	0.0284	0.1886
Kaduna 25	Shiroro 6	0.0038	0.0284	0.1886
Shiroro 6	Katampe 28	0.0038	0.0284	0.1886
Shiroro 6	Katampe 28	0.0038	0.0284	0.1886
Alaoji 18	Calabar 27	0.0071	0.0532	0.38
Calabar 27	Okapi 8	0.0079	0.0591	0.39
Ikeja west 12	AES 9	0.0061	0.0118	0.0932
Ikeja west 12	AES 9	0.0061	0.0118	0.0932
Omotoso 29	Benin12	0.0024	0.0177	0.0325
Omotoso 29	Ikeja-West	0.00314	0.0236	0.0324
Papalanto 29	Ikeja-West	0.0032	0.0242	0.0475
Papalanto 30	Aiyede 16	0.0038	0.0284	0.0475