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Original Research Article

Enhancement of the Nigerian National Grid Performance with a FACT Compensator

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ABSTRACT

The Nigerian grid is faced with loss of lines and system collapse due to overloads, under-loads, and inadequate reactive power at the buses. Analysis of the power flow supported by static voltage stability condition of the system can provide an insight to the system performance indicators like voltage profile, power flows and losses. Voltage control and power loss reduction strategies are still based on mechanical methods such as synchronous generators/condensers, tap changing of transformers, switching of shunt reactors and capacitor banks, switching of transmission lines, generating unit scheduling, and manual load shedding. However, flexible alternating current transmission system (FACT) such as static VAR compensator offers flexible and fast control of power system operations unlike the mechanically switched devices which are restricted by wear and tears and slow response. Hence this work demonstrates the use of static voltage analysis in seeking the optimal placement of static volt-ampere reactance (VAR) compensator called (SVC) on the power system. This idea was tested on Transmission Company of Nigeria (TCN) 330 kV-bus system which was modelled and analyzed using NEPLAN software and the results showed substantial improvement in the voltage profiles and loss reduction. Simulations of the peak condition showed that 9 stations violated the set limits. It is recommended that FACTS devices be optimally located at Sakete (6°44'11"N 2°39'29"E) bus bars for effective transmission of electric power on the grid.

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1. INTRODUCTION

The Nigerian national grid has recorded about two hundred and thirteen power system collapses between 2010 and 2021 (Adegboye and Dawal, 2012; TCN-NCC, 2021; Nnodim and Akintayo, 2022). The attendant consequences are both economic and technical. Most of the system collapses have been attributed to loss of critical transmission lines/generators due to faults or overloads which compromises the system security and stability. Voltage instability, voltage collapse, high power losses and losses of generator synchronism occur prior to system collapse (Nkan et al., 2021; Dzirutwe, 2022). Hence the need to determine areas in the network where voltage stability is lowered, and overloaded elements which limit transmission capabilities and offer fast and corrective action (Gupta et al., 2020; Nadeem et al., 2020; Salam, 2020; Nkan et al., 2021).

Voltage instability is one of the major causes of voltage collapse. It is concerned with the ability of a power system to maintain voltage at all buses under normal conditions and after being subjected to a disturbance. Voltage instability is basically due to the lack of ability of a power system to maintain steady state voltages at all buses following a disturbance while voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a black-out or abnormally low voltages in a considerable part of a power system (Munoz-Hernandez et al., 2013; Kundur, 2022).

The causes of voltage collapse may be faulted or heavily loaded transmission lines as well as insufficient supply and/or shortage of reactive power (Zarkani et al., 2021; Adesina, 2022). Voltage limits are set in a power system to provide upper and lower voltage boundaries for operating equipment and overall power system. The purpose of voltage limits is to maintain voltage levels on both transmission and customer connections. Exceeding the upper-voltage limit may lead to overheating and over-excitation of the power equipment while operating the equipment below the lower voltage limit may cause motor loads to stall and may lead to voltage collapse (Simpson-Porco et al., 2016).

Controlling the power flows in the transmission network could be achieved through conventional and mechanical methods as well as by deployment of flexible alternating current transmission system (FACTS) devices. Conventional devices can be used but with some restrictions. Mechanical components have a setback due to wear and tear and very slow response. FACTS devices can successfully control the power flow in the electric power network, reduce power flow in heavily loaded lines, thus ensuring increased loadability, reduced system losses, improve system stability and bus voltage profile as well as reduce cost of production (Ge et al., 1998; El-Arini and Ahmed, 2012).

The concept of FACTS was developed originally for transmission network, but it has been extended to include power quality in distribution systems operating at low or medium voltages. In the early days, the power quality referred primarily to the continuity of power supply at acceptable voltage and frequency. However, the prolific increase in the use of computers, microprocessors and power electronic systems has resulted in power quality issues involving transient disturbances in voltage magnitude (Singh, 2006; Sankar et al., 2019). Many approaches have been used to improve bus voltage profile and prevent voltage instability such as placement of FACTS, placement of series and parallel capacitors, rescheduling of the generation, and under-voltage load shedding (Padiyar, 2007).

FACTS device in general and SVC is used in this research over other FACTS devices for several reasons. SVC is the most widely used shunt FACTS devices within power networks due to its low cost and efficiency in power system enhancement (Das et al., 2018). It is more conventional and available. SVC can control voltage with high level of accuracy. It is a shunt connected static volt-ampere reactive (VAR) generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to provide voltage support and when installed in a proper location, it can also reduce power loses, enhances stability and security of the electric power network (Zarkani et al., 2021).

The specific problem addressed in this work is the identification of bus voltages that violates upper and lower voltages boundaries (weak nodes) and power system losses, and the provision of most economic and effective compensation techniques. Achieving this will involve the development of a model the 330 kV TCN grid network system, power flow analysis of the network based on the Newton Raphson solution method and an extensive static voltage stability analysis, leading to the identification of the bus voltages that violates the operational and statutory limits of the grid. The control part takes into consideration the selection of the best fit bus for the installation of the SVC such as to restore the system voltage to the acceptable limit and analysis of the effect of the SVC compensator in ensuring voltage improvement and power loss reduction.

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2. MATERIALS AND METHODS

2.1. Network Structure

The methodology adopted in this work involves data collection and parameter estimation mean method, power flow formulation and analysis using Newton-Raphson method, voltage stability analysis using sensitivity/modal technique and modeling/simulation of the system in NEPLAN software. Two scenarios were considered for this work, they are Scenario 1 – Load flow and stability analyses at peak condition under base case without and with SVC: Scenario 2 – Load flow at off-peak condition under base case without and with SVC.

The structure of Nigerian 330 kV grid system network was modeled in NEPLAN. It consists of thirteen generating stations (GS): Kainji G.S, Jebba G.S, Shiroro G.S, Odukpani G.S, Geregu Gas and Geregu NIPP, Okpai G.S, Olorunsogo Gas and Olorunsogo NIPP, Egin G.S, Omotosho Gas and Omotosho NIPP, Azura-Edo IPP and Ihovbor NIPP, Delta G.S, Afam IV & VI and Alaoji NIPP. It is also characterized by sixty bus bars made up of fifteen 16 kV generator buses, one 16 kV slack bus and Forty-seven 330 kV load buses; Eighty-five 330 kV transmission lines; thirteen 16/330 kV unit power transformers and Forty-three load points (TCN-NCC, 2021). The combine total output of generators on bar capability for peak generation and utilization are:

$$P_{Gen} = 5{,}840.914\, MW,\ Q_{Gen} = 2{,}148.368\, MVAR$$

$$P_{Load} = 5{,}563\, MW,\ and\ Q_{Load} = 2{,}793.1\, MVAR$$

Off-peak generation and utilization are as follows:

$$P_{Gen} = 5{,}595.885\, MW,\ Q_{Gen} = 779.742\, MVAR$$

$$P_{Load} = 5{,}305{,}265\, MW, Q_{Load} = 1{,}332.114\, MVAR$$

The network was divided into three areas: Area 1 (West), Area 2 (East) and Area 3 (North). The North is connected to the west through double circuit line between Jebba and Osogbo, single circuit between Osogbo and Ganmo. The North is tied to the East via double circuit line between Makurdi and Ugwuaji, double circuit line from Ajaokuta to Benin and from Benin to Onitsha while the West is linked to the East through single circuit transmission line between Osogbo and Ihovbor, Benin, Omotosho and Ikeja West. Also, the South-East is connected to South-South through quadruple transmission line between Ugwuaji and Ikot-Ekpene and double circuit from Alaoji to Afam. As at the time of this work, the national peak demand forecast was estimated around 24,900 MW, total installed generation capacity estimated at 12,910.40 MW, and generation capacity was estimated at 7,652.6 MW, while the transmission wheeling capacity was 8,100 MW.

The empirical system data obtained from the Transmission Company of Nigeria (TCN) include:

i. Transmission line parameters such as the length of the lines in km, shunt admittance (resistance and reactance in Ω/km respectively) and line capacitance in μF/km.

ii. Generator/synchronous machine parameters obtained include the generator type, the rated power (S_r) in MVA; the rated voltage (V_r) in kV, the power factor (cos ϕ), the Synchronous reactance, load flow type (PV or SL), generated active power (P_{Gen}) in MW, generated reactive power (Q_{Gen}) in MVAR and the inertial constant of the machine (H) in seconds

iii. Busbar parameters obtain included the rated bus voltages in kV, the frequency in Hz and the bus type (generator bus, slack bus or load bus).

iv. The load parameters such as load flow type (PQ), active power (P) in MW, reactive power (Q) in MVAR, apparent power (S) in MVA, load current (I) in A, the power factor (PF) and the dynamic model (constant Z) were obtained.

2.2. Model of Load Flow

A detailed information on power flow analysis can be obtained in previous work (Saadat, 1999; Eltamaly et al., 2018; Salam, 2020; Dai *et al.*, 2022). Power flow study is a steady-state analysis whose target is to determine the voltages, currents, real and reactive power flows in a system under a given condition. For this research, the procedure began by:

i. obtaining the system architecture and network data.

ii. solve base case power flow; do contingency analysis and ranking.

iii. apply SVC; form full Jacobian matrix J.

iv. determine J^{-1}.

v. compute the reduced Jacobian matrix; calculate the eigenvalue and eigenvectors.

vi. compute the deviation in voltage; $\Delta V = \xi \Lambda^{-1} \eta \Delta Q$

vii. plot p-v and q-v curves.

viii. check for violation of voltage limit; ıf non, plot P-V and Q-V Curves; output P-V and Q-V curves. If there is violation of voltage limit; determine weaker voltage areas.

ix. perform participation factor analysis.

x. output P-V and Q-V curves (Kulkarni and Ghawghawe, 2013; Gupta et al., 2020).

2.3. Algorithm for Solving the Power Flow Problem using N-R Method (Rectangular Form)

The numerical solution of power flow using the Newton Raphson (N-R) method follow the algorithm below.

Step 1: Given that a bus i of the system is characterized by the active power P_i, reactive power Q_i, the bus voltage magnitude V_i and the voltage phase angle δ_i. Y_{ik} represents the admittance between bus i and bus k while V_k represents the voltage magnitude at bus k.

Step 2: Read all network data such that the system admittance matrix, initial bus voltages and angles are formed

Step 3: Calculate the real and reactive power:

The injected current into i^{th} bus of the total *n* bus is given by Equation (1).

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k \quad (1)$$

Where Y_{ik} represents the admittance between bus i and bus k while V_k represents the voltage magnitude at bus k.

Apparent power S_i^* at the i^{th} bus is represented by Equation (2).

$$S_i^* = P_i - jQ_i = V_i^* I_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k \quad (2)$$

Where P_i is the active power and Q_i reactive power.

The voltage and admittance can be represented as follows:

$$V_i = (e_i + jf_i) \quad (3)$$

$$Y_{ik} = (G_{ik} + jB_{ik}) \quad (4)$$

Where e_i and f_i real and imaginary part of V_i while G_{ik} and B_{ik} are the conductance and susceptance of Y_{ik}.

Hence:

$$P_i - jQ_i = (e_i - jf_i) \sum_{k=1}^{n} \{(G_{ik} + jB_{ik})(e_k + jf_k)\} \quad (5)$$

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If the real and imaginary part are separated:

$$P_i = \sum_{k=1}^{n}\{e_i(e_k G_{ik} - f_k B_{ik}) + f_i(f_k G_{ik} + e_k B_{ik})\} \quad (6)$$

$$Q_i = \sum_{k=1}^{n}\{f_i(e_k G_{ik} - f_k B_{ik}) - e_i(f_k G_{ik} + e_k B_{ik})\} \quad (7)$$

Step 4: Determine the real and reactive power mismatch as the difference between the scheduled and calculated value at each p iteration step $i = 1,2,3, \ldots, (N-1)$.

$$\Delta P_i^p = P_{i(scheduled)} - P_i^p \quad (8)$$

$$\Delta Q_i^p = P_{i(scheduled)} - Q_i^p \quad (9)$$

Step 5: Determine the residual bus voltage

$$\Delta V_i[\Delta|V_i| = |V_{scheduled}| - |V_i^p|] \quad (10)$$

Step 6: Confirm if ΔP_i^p, ΔQ_i^p and ΔV_i are less than the tolerance specified. If yes, jump to step 10, else proceed to step 7.

Step 7: Estimate the element of the Jacobian matrix using the bus voltages determined earlier.

Step 8: Using the direct iterative method, solve linear equation formed to determine Δe_i and Δf_i

Step 9: Update the bus voltages and angles as in Equations (11) and (12)

$$e_i^{p+1} = e_i^p + \Delta e_i^p \quad (11)$$

$$f_i^{p+1} = f_i^p + \Delta f_i^p \quad (12)$$

Step 10: With the updated voltages, return to step 4 to recompute P_i, Q_i, $P\Delta_i$, and ΔQ_i

Step 11: Step 10 is repeated until the tolerance is reached then output the results.

2.4. Determination of Voltage Stability by Q-V Modal Analysis

The Jacobian matrix used to compute bus voltages in Newton-Raphson load flow method is given by:

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2 \\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta \\ \Delta|V|\end{bmatrix} \quad (13)$$

The t-th diagonal element of the matrix $[J_4]_{ii}$ is the $Q - V$ sensitivity analysis of the load bus $-i$.

$$\frac{dQ_i}{dV_i} = [J_4]_{ii} \quad (14)$$

Considering change in both real and reactive bus power with:

$$\Delta P = 0$$

$$[\Delta Q] = [J_R][\Delta|V|] \quad (15)$$

Where the reduced Jacobian is expressed as:

$$[J_R] = [J_4] - [J_3][J_1]^{-1}[J_2] \quad (16)$$

$$[\Delta|V|] = [J_R]^{-1}[\Delta Q]$$

The V-Q sensitivity at load bus represents the slope of the V-Q curve at the given operating point. A positive V-Q sensitivity is an indicator of stable operation, the smaller the sensitivity, the more stable the bus. As the system craws in the vicinity of vulnerable voltage collapse, the sensitivity increases and at the voltage stability limit, it becomes infinite.

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The voltage stability characteristics of the load buses in a power system can be assessed by computing a set of eigenvalues and the corresponding eigenvectors of the reduced Jacobian Matrix $[J_R]$. Let $[\xi]$ be the right eigenvector of $[J_R]$, $[\eta]$ is left eigenvector and $[\lambda]$ is the diagonal eigenvalue matrix of $[J_R]$, then:

$$[J_R] = |\xi|[\lambda][\eta] \tag{17}$$

$$[\Delta|V|] = [\xi][\lambda]^{-1}[\eta][\Delta Q] \tag{18}$$

$$[\Delta|V|] = [\sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q] \tag{19}$$

From the above, the V-Q sensitivity at load bus m is computed as equation (20).

$$\frac{\partial|V_k|}{\partial Q_m} = \sum_i \frac{\xi_{ki}\eta_{ik}}{\lambda_i} \tag{20}$$

Finally, the bus participation factor (P_{ki}) can expressed as Equation (21). This will determine the weak bus that can cause voltage collapse. The higher the value of P_{ki}, the weaker is the load bus and its tendency to cause voltage instability.

$$P_{ki} = \xi_{ki}\eta_{ik} \tag{21}$$

2.5. Compensation with SVC

The SVC is an important type of shunt controllers, it is a member of the FACT technology. Its model is like a static synchronous generator with zero active power but with limits on reactive power. The bus with SVC act like a PV bus. Hence, in power flow, the look like a variable shunt susceptance. The magnitude of the shunt susceptance represents the required value to regulate the bus voltage at specified value.

3. RESULTS AND DISCUSSION

The needed data for the power system under study was entered into the model, thus enhancing the implementation and simulation in NEPLAN software. The base case and the network condition with SVC installed at both peak and off-peak conditions were simulated and the results compared. Accuracy or convergence mismatch (ϵ) was specified as 0.001. The load flow solution converged after five iterations.

The upper voltages limit of 346.5 kV (+5%) and lower voltage limit of 280.5 kV (-15%) have been set as working standard in TCN grid operation and control for all 330 kV buses: Minimum Voltage = 85% and Maximum Voltage = 105%. The buses outside the voltage limits are identified from the Newton-Raphson Load flow solution and corrective measures applied by incorporating SVC at optimal location.

The obtained results for the load flow analysis of the power system under consideration for the first scenario are presented in Figure 1. This figure presents the results of the computational iterative load flow model for the TCN 60-bus, 330kV power system using Newton-Raphson method. In Figure 1, 9 bus bars associated with 9 Stations violated the set limits. These are: Olorunsogo, Egbin, Ikeja-West, Oke-Aro, Akungba, Ajao, Lekki, Alagbon and Sakete. With this information, the identified bus bars where SVC is to be placed for effective transmissions are filtered to only nine. These bus bars violated the lower voltage limit and therefore under voltage condition were experienced around Lagos Complex (Area 1). The average percentage voltage profile of load flow at peak condition without SVC is 80.967%, these are presented in Figure 2.

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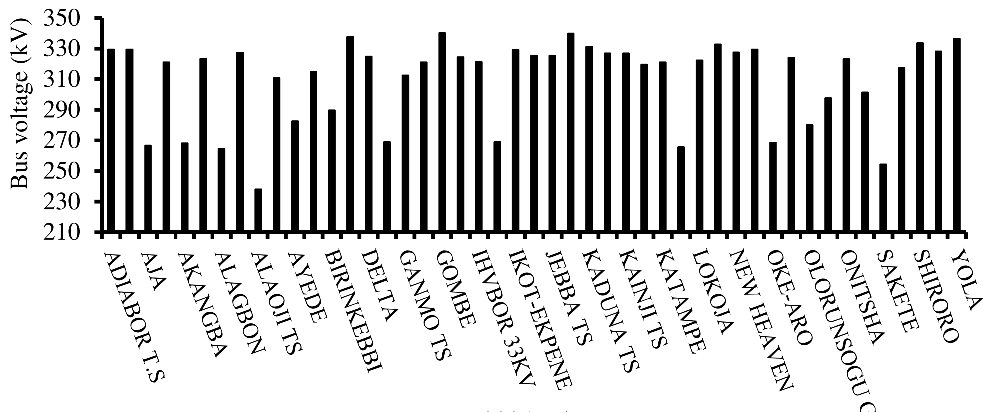


Figure 1: Load flow at peak without SVC

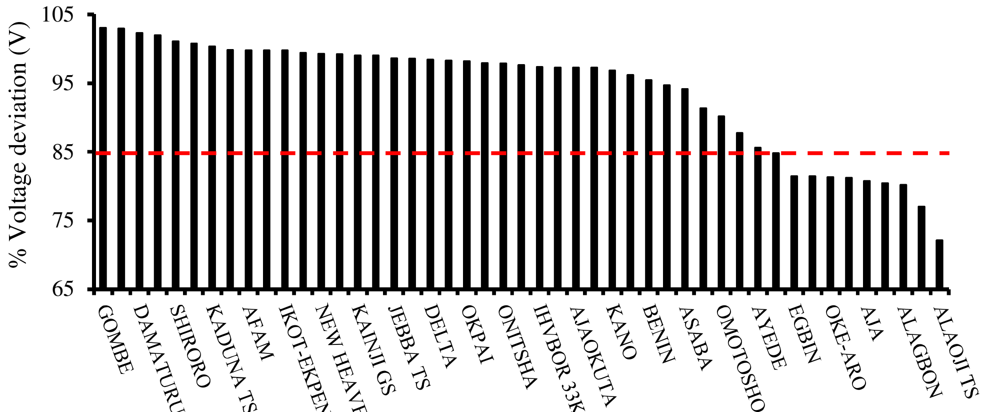


Figure 2: Voltage deviation of load flow at peak without SVC

When SVC was located at each of these candidate buses one after the other, the resultant voltage profiles are as shown in Table 1. The percentage average voltage of the bus voltages calculated as shown in Table 1 shows that the load flow without SVC at peak condition had aggregate mean percentage bus voltage of 80.967%. SVCs at Olorunsogo, Egbin, Ikeja West, Oke-Aro, Akangba, Aja, Lekki, Alagbon and Sakete gave aggregate percentage bus voltages of 87.360%, 88.640%, 88.377%, 88.564%, 88.604%, 89.040%, 89.267%, 89.414% and 90.468% respectively. Therefore, the optimal location for SVC for maximum impact on the network is Sakete and the load flow result with SVC placed at Sakete is shown in Figure 3, with voltage deviation shown in Figure 4. System active and reactive power loss at peak condition with and without SVC are presented in Figures 6 and 7 respectively.

In order to validate the results as obtained by load flow solution, voltage stability analysis using sensitivity/modal analysis method, P-V and Q-V curves methods of voltage stability prediction was implemented and the chart results of the first scenario shown in Figures 7 to 12. From the results shown, when the power system network was not compensated in the first scenario, the aggregate mean percentage voltage was 80.967% which violated the lower voltage limit of 85% with nine bus bars within Lagos complex affected. Whereas when the network was compensated, it was discovered that SVC installed at Sakete bus bar improved the system voltage significantly within the weak bus zones to 90.468%. This is well within the acceptable voltage limit (i.e., 85%≤V≤105%) set for the system. Hence, no voltage violation occurred when

SVC is located at Sakete bus. Also, the transmission real power loss reduced from 277.914 MW to 251.922 MW when SVC was located at Sakete.

Looking at the results in Figures 6 (a) and (b), it is obvious that as the active power increases, the corresponding bus voltages will decrease and as the reactive power is increasing, the bus voltages will also increase. However, in the P-V curve shown in Figure 8, Sakete experienced voltage collapse at about 5,910.688 MW (106.25%) load power. The Q-V curve as shown in Figure 9 shows that Sakete is the least stable of the buses being reactive power deficient. At 100% nominal voltage, reactive power at Sakete bus was 552.914 MVAR. Hence it needs to be compensated to increase its VAR margin and hence mitigate voltage instability and voltage collapse. Immediately SVC was optimally placed at Sakete, the reactive power margin increased, and all the hitherto weak buses became highly voltage stable as can be seen in Figures 11 and 12.

At peak load with attendant low voltages at Lagos area, SVC installed at Sakete increased the affected bus voltages to acceptable limit and no under voltage violation occurred.

Table 1: Resultant voltage profile with SVC at each of the candidate buses

Lower limit voltage violation (%kV)	Load flow without SVC	SVC @ Olorunsogo	SVC @ Egbin	SVC @ Ikeja-West	SVC @Oke-Aro	SVC @ Akangba	SVC @Aja	SVC @ Lekki	SVC @Alagbon	SVC @ Sakete
Olorunsogo	84.79	96.10	89.74	90.27	90.11	90.34	89.79	89.87	89.88	90.93
Egbin	81.48	86.90	89.98	88.66	89.12	88.75	90.06	90.14	90.21	89.52
Ikeja-West	81.45	87.46	88.64	89.42	89.18	89.52	88.72	88.78	88.84	90.38
Oke-Aro	81.30	87.16	88.98	89.05	89.74	89.15	89.06	89.13	89.19	89.99
Akangba	81.22	87.25	88.44	89.21	88.98	90.49	88.51	88.57	88.63	90.18
Aja	80.77	86.24	89.35	88.02	88.49	88.11	90.40	90.49	90.57	88.89
Lekki	80.47	85.96	89.08	87.74	88.21	87.84	90.14	91.04	90.85	88.62
Alagbon	80.19	85.71	88.83	87.49	87.96	87.59	89.89	90.53	91.64	88.37
Sakete	77.04	83.46	84.72	85.54	85.29	85.65	84.79	84.86	84.92	97.34
Average voltage	80.97	87.36	88.64	88.38	88.56	88.60	89.04	89.27	89.41	90.47

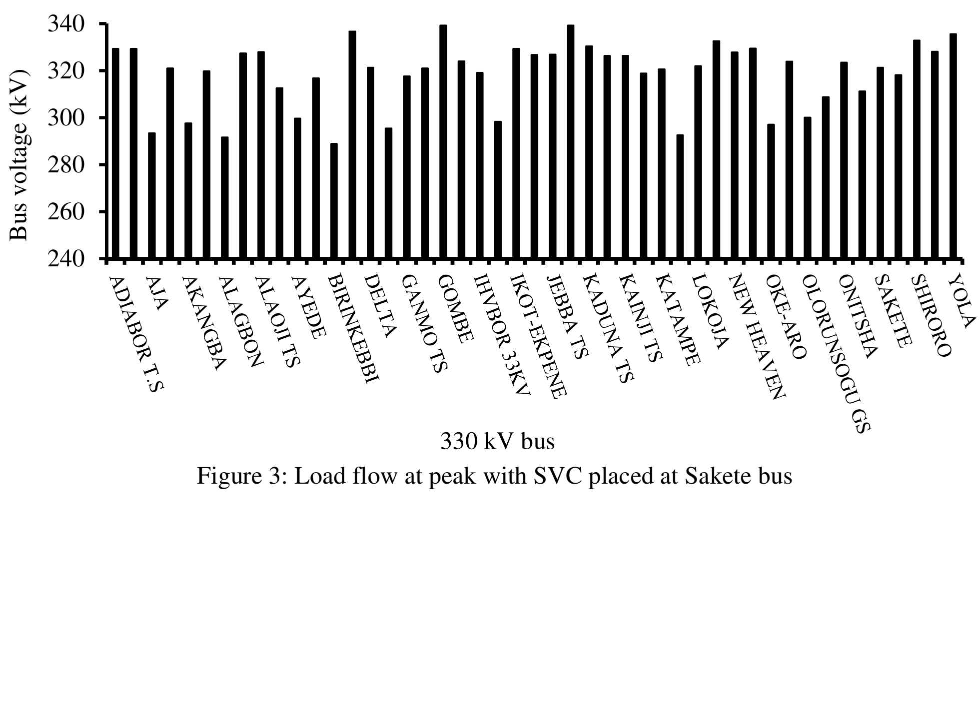


Figure 3: Load flow at peak with SVC placed at Sakete bus

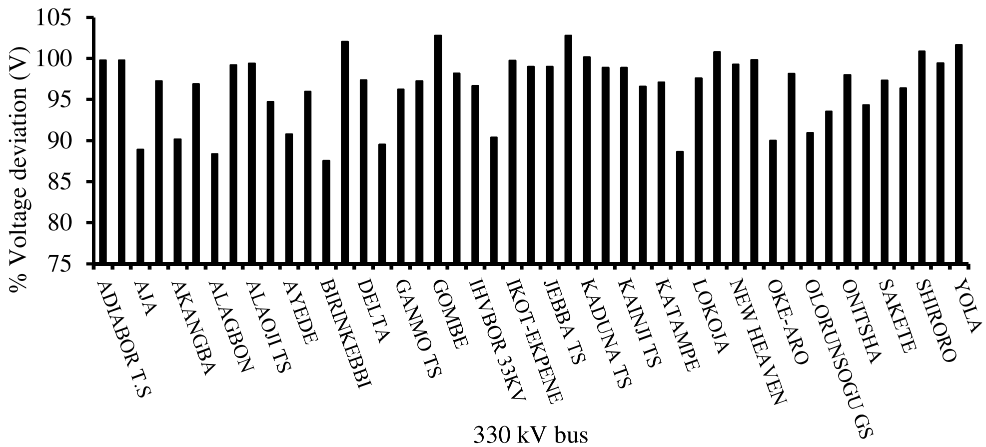


Figure 4: Voltage deviation with SVC placed at Sakete bus

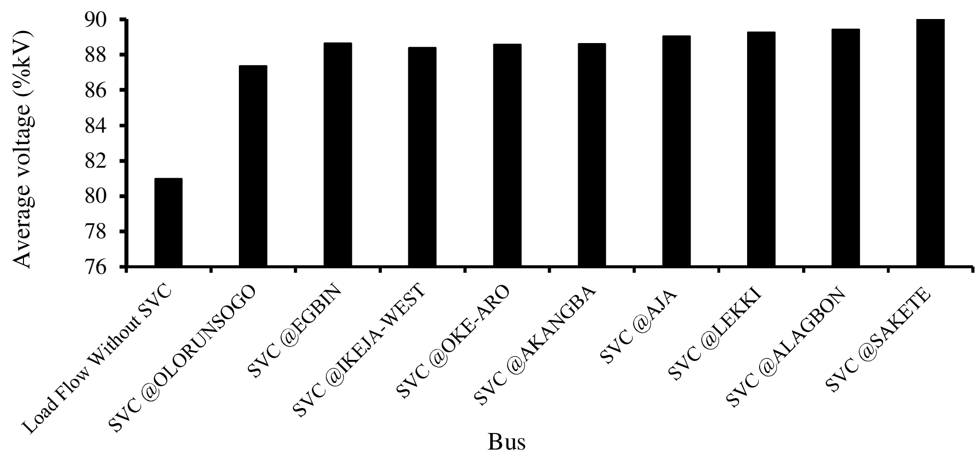
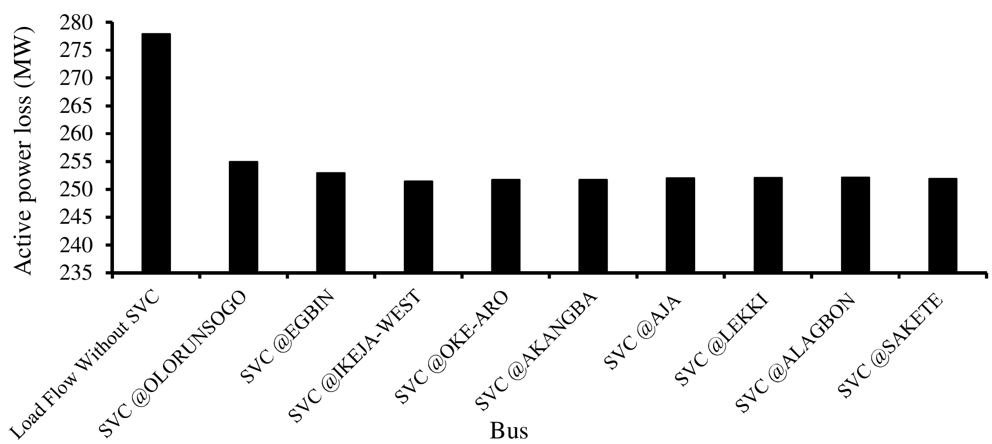


Figure 5: Average percentage voltage profile with and without SVC at peak condition



(a)

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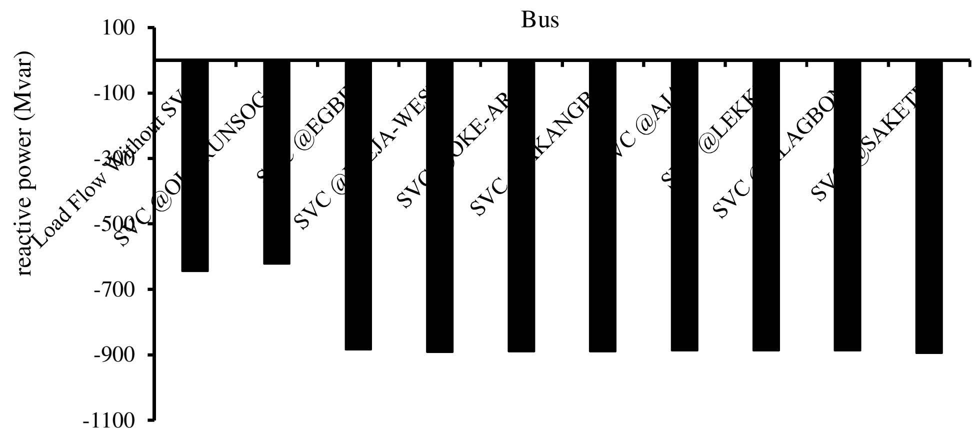

(b)

Figure 6: (a) System active power loss at peak condition with and without SVC (b) System reactive power loss at peak condition with and without SVC

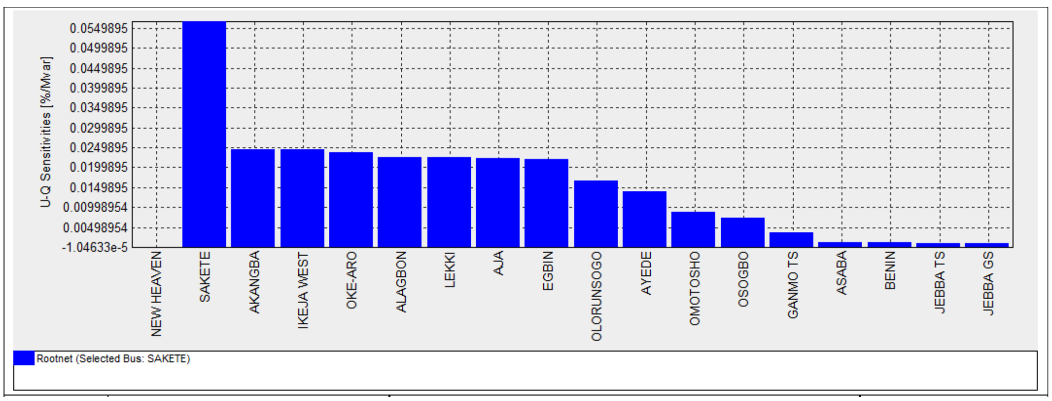

Figure 7: Sensitivity analysis without SVC

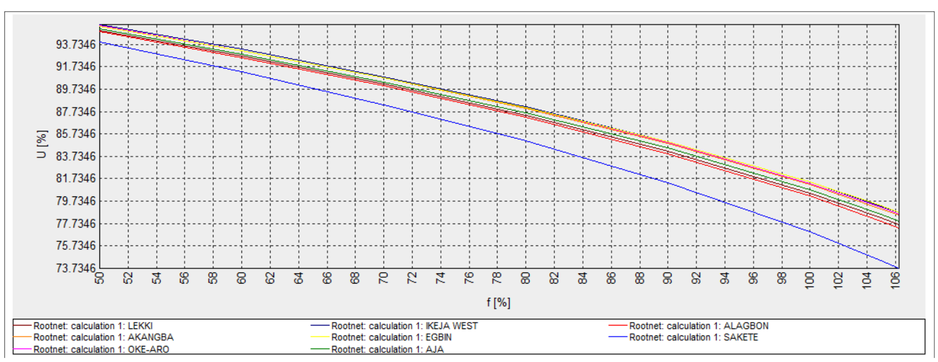

Figure 8: P-V curves without SVC

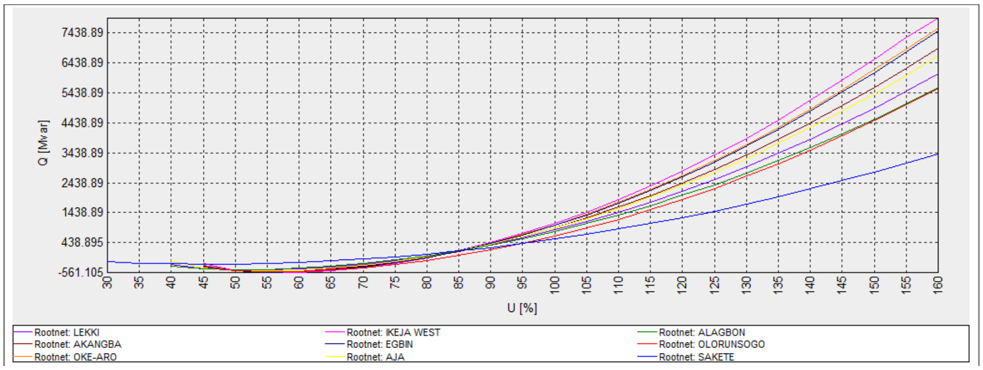

Figure 9: Q-V curves without SVC

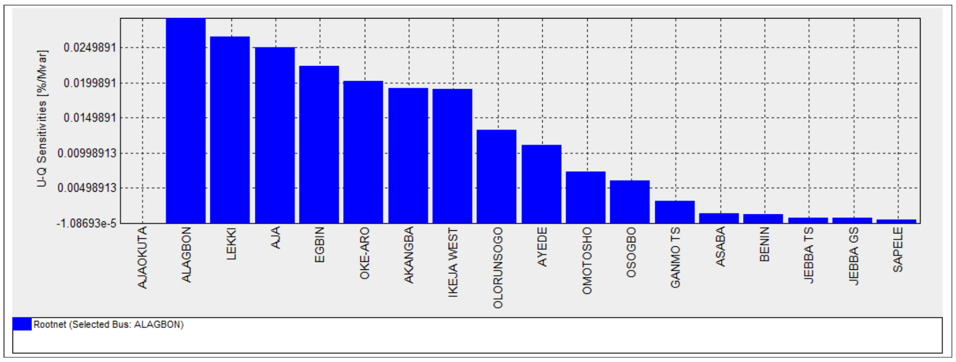

Figure 10: Sensitivity analysis with SVC at Sakete

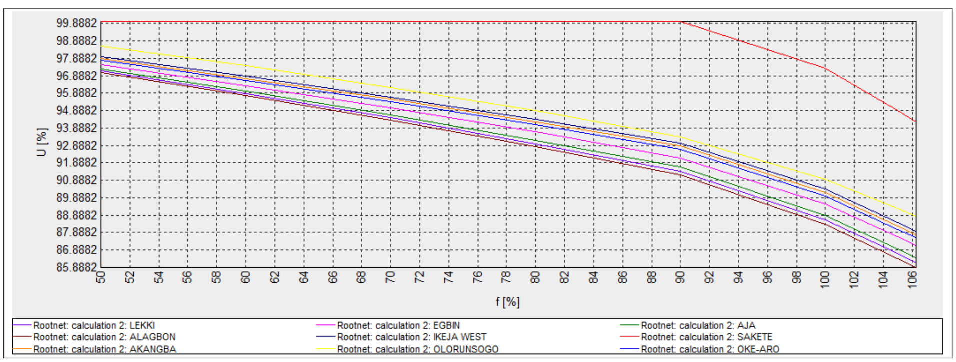

Figure 11: P-V curves with SVC at Sakete

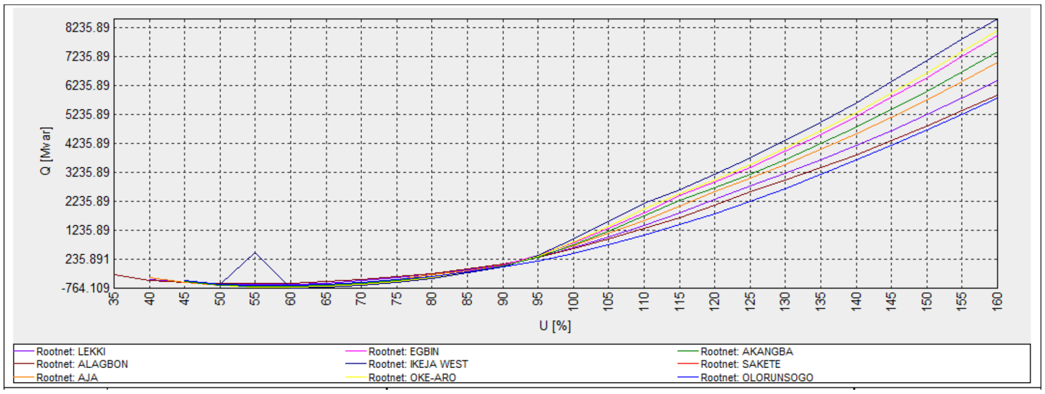

Figure 12: Q-V curves with SVC at Sakete

4. CONCLUSION

This work investigated the effects or impacts of locating SVC on a power transmission system in terms of voltage profile improvement, enhancement of voltage stability, power transmission loss reduction and overall system performance improvement. The achievement of these goals was facilitated by running load flow solutions and voltage stability studies using NEPLAN software. The TCN 60-bus, 330 kV power transmission system was used as a case study. Relating to the set objectives, the values from the results obtained after modeling and simulation are coherent with the theoretical background. SVC injects VAR in capacitive mode during low voltages and absorbs VAR (inductive mode) at high bus voltages thereby keeping bus voltages constant within the acceptable limits. This has been achieved as demonstrated by SVC installation at Sakete and Damaturu in this project. P-V and Q-V curves theoretical characteristics also validate the test case characteristic experiencing voltage collapse after exceeding the load margin and being unstable at left hand side of the minima and stable operation at the right-hand side of the minima. Sakete bus bars have been found to have exhibited voltage instability and when appropriately compensated, the bus voltage profiles improved drastically, and transmission losses were reduced. Therefore, it can be inferred that improvement of VAR margin of the transmission network by optimally locating SVC is therefore an alternative to reducing flows in heavily loaded lines, resulting in reduced transmission losses, increased loadability, enhanced voltage profile, improved stability of the network and reduction in the cost of producing power.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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