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The Effect of an Optimally Located Static VAR Compensator on Transmission System Parameters: A Case Study of Nigerian 330 KV Nine-Bus Power System

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Abstract*: This research presents the effect of an optimally located SVC on transmission system parameters using constant power, constant current and constant impedance, in which active and reactive powers vary with voltage in an exponential form. The Nigerian 330 kV, nine-bus system was used as a case study and simulated on NEPLAN. Calculated values of participation factor and voltage-reactive power (V-Q) sensitivity at least eigenvalue identified Aiyede Transmission Station (TS) as the optimal location of the SVC. The simulation results obtained show that for a constant power static load with SVC, the weak buses improved from 0.64348 to 1.00 pu at Aiyede TS, Oshogbo TS improved from 0.741988 to 0.95536 pu, Ikeja West TS improved from 0.94264 to 0.96498 pu and Ajaokuta TS improved from 0.9493 to 0.9659 pu, while the real power loss reduced from 74.218 to 47.521 MW. For a constant current static load, Aiyede TS improved from 0.8406 to 1.00 pu, Oshogbo TS from 0.8833 to 0.9738 pu, while the real power loss reduced from 31.84 to 27.625 MW. For a constant impedance static load, the voltage profile improved and the real power reduced from 18.81 to 17.742 MW. Hence, the power loss was compensated with SVC position at Aiyede TS.*

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I. Introduction

Load modeling in power system is the mathematical representation of the relation between the active or reactive power in a load bus and the complex voltage of the bus. The behavior of various electrical loads can be understood by load modeling, considered to be very important for power system analysis, grid operation and planning, and its accuracy enables electrical engineers to perform assessment of grid response to stability[1].Power system is a complex network that consists of synchronous generation, transmission line, load, etc. and its transfer through transmission line depends on the impedance of the line, bus voltages and phase angle. As demand for electricity increases, there is the need to either build new generation and transmission facilities or improve on the existing ones to match with the increased demand. Since building new generation and transmission facilities is expensive, the existing system can be improved by controlling the reactive power and voltage of the system using static var compensator (SVC), considered to be very effective in controlling voltage instability at rapidly varying loads.Modeling of SVC for the voltage control in power system, using the SVC circuit and IEEE 9 buses was designed and modelled in power world. Newton Raphson method was applied to compute the load flow solution. The simulation results showed that voltage improved when the reactive power was injected into SVC circuit[2]. Theused of SVC on weak grid lines for voltage support, compensation of reactive power and improvement of power factor usingMATLAB/Simulink and the result showed that the power factor improved with the used of SVC and reactive power of the system was compensated[3]. Minimization of active transmission loss in the Nigerian 330kV power network[4] was carried out using MATLAB/Simulink. The results showedthat the installation of SVC reducedthe total active transmission loss by 31.79 %. SVC was usedon an IEEE 14-bus system[5]to study power system stabilityand the simulation results showed an improvement in loadability and voltage stability. Abdou et. al[6] demonstrated the impact of SVC on a portion of the Egyptians national grid located in a new city in southern valley, which has 22 buses with 20 distribution transformers of 22/0.4 kV, various loads and two medium voltage feeders, forming a ring type power line. The system was simulated using NEPLAN and the results showed that the voltage profile improved and the total active power loss reduced with the use of SVC. Power flow control analysis of transmission lines[7] investigated the capability of SVC in stabilizing power system voltage through reactive power compensation. Power flow equations involving voltage drop with/without SVC and the modeling equations for SVC were developed and used to determine the system parameters. The Nigerian 330kV, 28-bus power system was modeled using MATLAB/Simulink software andthe buses, which hadweak voltage profile were identified and compensated. Malkar and Magdum[8] presented the recent trends in real and reactive power flow control with SVC and STATCOM controller for improvement of power flow in transmission line. Simulation was carried out using MATLAB/Simulink software and the results, in the case of FC-TCR compensation, show that reactive power flow improved proportionally with increasing capacitance up to certain value, after which the reactive power started decreasing. The work on minimizationof power loss and voltage deviation by SVC placement using continuous genetic algorithm[9]described the solution of a multi-objective optimization problem for finding the optimal location and size of SVC. Themethod was demonstrated on a standard IEEE 30-bus system and the results obtained revealedits effectiveness in handling multi-objective optimization problem.Shende et. al[10]investigated the optimal location and sizing of SVC by PSO technique for voltage stability enhancement and power loss minimization. The result obtained from the IEEE-14 bus system test shows that the PSO algorithm could easily find the optimal location and the size of the SVC, for which the voltage deviation and power loss is minimum. Stability enhancement of long transmission line system[11] showed how SVC was successfully applied to regulatethe power system voltage. To achieve this, shunt FACTS device-SVC was used in a two-machine system for improving the power system stability. Simulation was carried out using MATLAB/Simulink software and the results showed that transient stability and power oscillation damping improved.

This research work is, therefore, focused on the effect of an optimally located SVC on voltage profile and power losses for the different static load types with the aim of solving the age long problem of power loss and voltage instability in the Nigerian transmission system that impedes the socio economic development and industrialization.

II. Materials and Method

Static load model: A static load model is a mathematical representation that relates the bus voltage (magnitude and angle) with the power (real and reactive) flowing into the bus. Traditionally static load models have been classified into constant power load, constant current load and constant impedance load. In this research, only the effect of an optimally located SVC on system voltage profile and power losses in transmission system having different static load models were considered.

i. Constant Impedance Load Model (Constant Z): The active and reactive powers are proportional to the square of the voltage magnitude.
ii. Constant Current Load Model (Constant I): The active and reactive powers are directly proportional to the voltage magnitude.
iii. Constant Power Load Model (Constant P): The active and reactive powers do not vary with changes in voltage magnitude[12]. The real and reactive power could be represented by exponential load models given by equations (1) and (2)

$$P = P_0 \left[\frac{V}{V_0}\right]^{\alpha} \tag{1}$$

$$Q = Q_0 \left[\frac{V}{V_0}\right]^{\beta} \tag{2}$$

Where

$V_0$is reference or rated voltage

P_0, Q_0 are active and reactive power consumed at rated voltage. Index α, β change according to different load types.

For constant impedance static load, $\alpha = \beta = 2$

Constant current static load, $\alpha = \beta = 1$

Constant power static load, $\alpha = \beta = 0$

P = actual active power

Q = actual reactive power

Modeling of static var compensator in power system:

The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The principle of SVC is to supply a varying amount of leading or lagging VAR to the lagging or leading system[13]. SVC provides effective solution to grid connected problem by making utility network more reliable, more controllable and more efficient. From Figure 3 SVC parameters were calculated using equations (14) to (17).

$$X_C = \frac{V^2{}_{bus}}{Q_{SVC}} \tag{14}$$

$$X_L = \frac{X_C}{2} \tag{15}$$

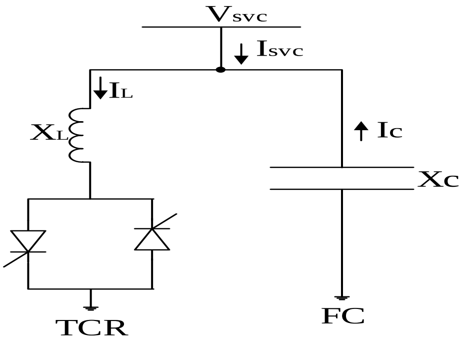

Figure no 1: Functional Diagram of a TCR-FC SVC[14].

$$C = \frac{1}{2\pi f X_C} \tag{16}$$

$$L = \frac{X_L}{2\pi f} \tag{17}$$

where Q_{SVC} = Reactive capacity of SVC
V_{bus} = Bus voltage, where SVC would be connected
X_C = Capacitive reactance
X_L= Inductive reactance
f = fundamental frequency

Optimal location of SVC: The optimal location of reactive power compensation for the improvement of voltage profile of a system was achieved by considering the identified "weakest bus" of the system using the V-Q sensitivity and participation factor. The bus with highest V-Q sensitivity value and participation factor, at the least eigenvalue, is the critical bus.

Newton Raphson power flow solution: Newton Raphson power flow method was used to analyze the nine-bus power system network. It is an iterative method, which approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to the first approximation. It is the iterative method used for most load flow because it converges faster. The number of iterations is independent of system size, more accurate and not sensitive to the factors such as slack bus selection and regulation transformer[15].

Data collection:

The nine-bus Nigerian 330 kV system was modelled in NEPLAN software version 5.52 environment using Newton Raphson power flow method as shown in Figure 2. The network in figure 3, comprising 9-bus, 8 transmission line, 3 generators and 6 loads is connected to an SVC. The model was achieved using elements arrangement. The data required for the simulation were obtained from the National Control Center (NCC) Oshogbo, Osun State, Nigeria. The per km values of the impedances were computed on the following base values S_{base} = 100 MVA, V_{base} = 330 kV

III. Results

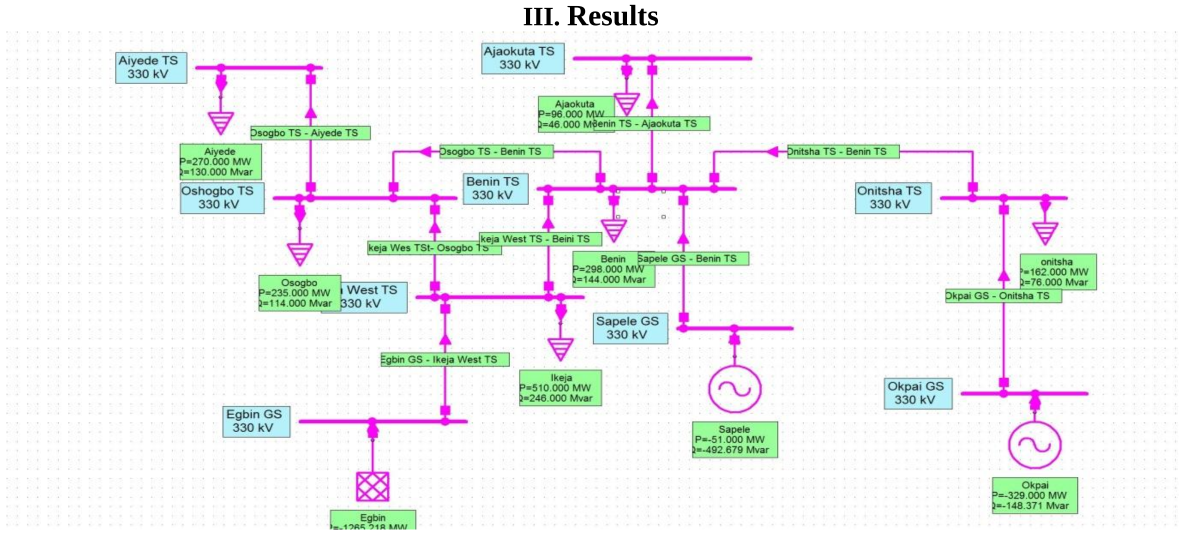

Figure no 2: The 330kV 9-bus Nigeria Power System without SVC

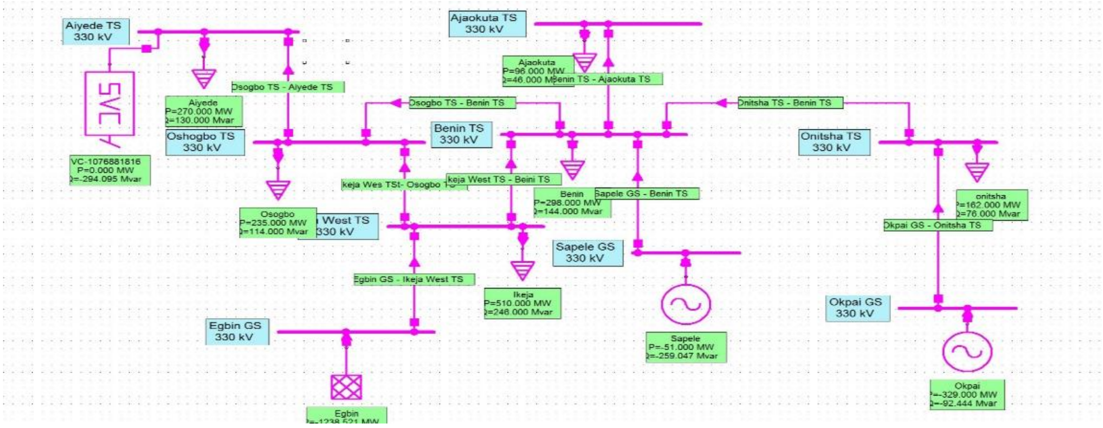

Figure no 3: The 330kV 9-bus Nigeria Power System with SVC

Table no 1: Voltage profile of constant power static load buses

Bus Name	Voltage Magnitude Without SVC (pu)	Voltage Angle without SVC (rad)	Voltage Magnitude with SVC (pu)	Voltage Angle with SVC (rad)
Oshogbo TS	0.741988	- 0.4573	0.95536	- 0.39786
Aiyede TS	0.64348	- 0.64565	1.00	- 0.5043
Ikeja West TS	0.94264	- 0.10818	0.96498	- 0.1064
Egbin GS	1.00	0	1.00	0
Benin TS	0.96498	- 0.2792	0.9813	- 0.25826
Sapele GS	1.00	- 0.28095	1.00	- 0.2600
Ajaokuta TS	0.9493	- 0.308865	0.9659	- 0.286
Onitsha TS	0.9842	- 0.2443	0.98883	- 0.22336
Okpai GS	1.00	- 0.218	1.00	- 0.1972

Table no 2: Constant power static load buses with weak voltages profile

Bus Name	Voltage (pu)
Aiyede TS	0.64348
Oshogbo TS	0.741988
Ikeja West TS	0.94264
Ajaokuta TS	0.9493

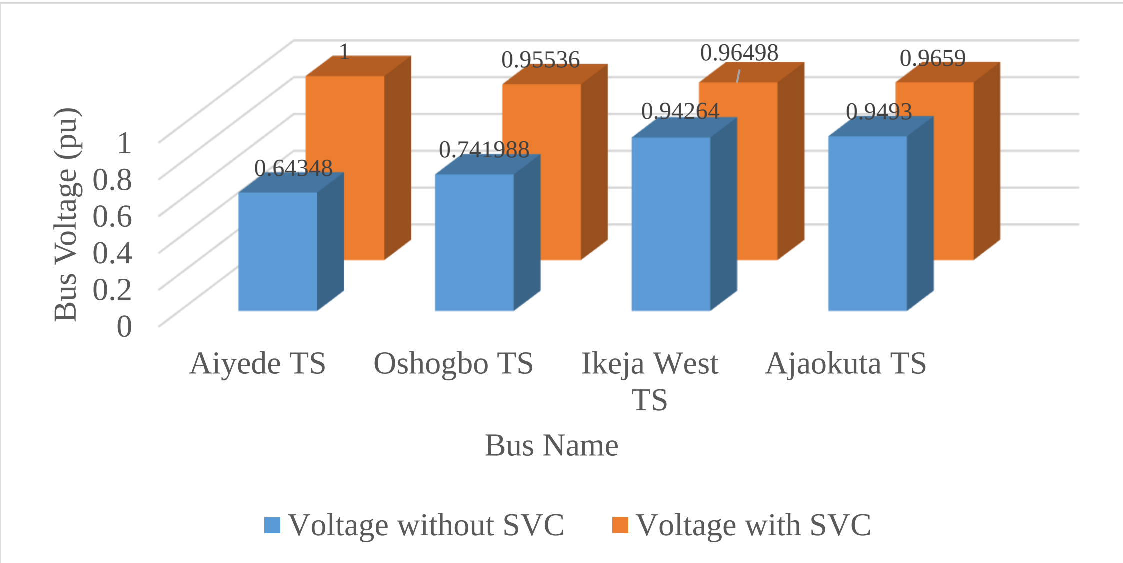

Figure no 4: Constant power static load weak bus voltage compensation representation

Table no 3: Eigenvalues for different static load type

No	Constant Power Static Load (Mvar/%)	Constant Current Static Load (Mvar/%)	Constant Impedance Static Load (Mvar/%)
1	2.4142	6.4365	7.7110
2	26.1978	26.7301	26.9605
3	46.8231	59.7450	64.3756
4	132.3213	136.4140	138.0183
5	151.4259	153.5857	154.6909
6	280.0706	283.9026	285.4618

Table no 4: V-Q sensitivity indices for constant power static load

Bus Name	Sensitivity % MVAr
Aiyede TS	0.2982
Oshogbo TS	0.1347
Ajaokuta TS	0.0378
Ikeja West TS	0.0086
Onitsha TS	0.0065
Benin TS	0.0056

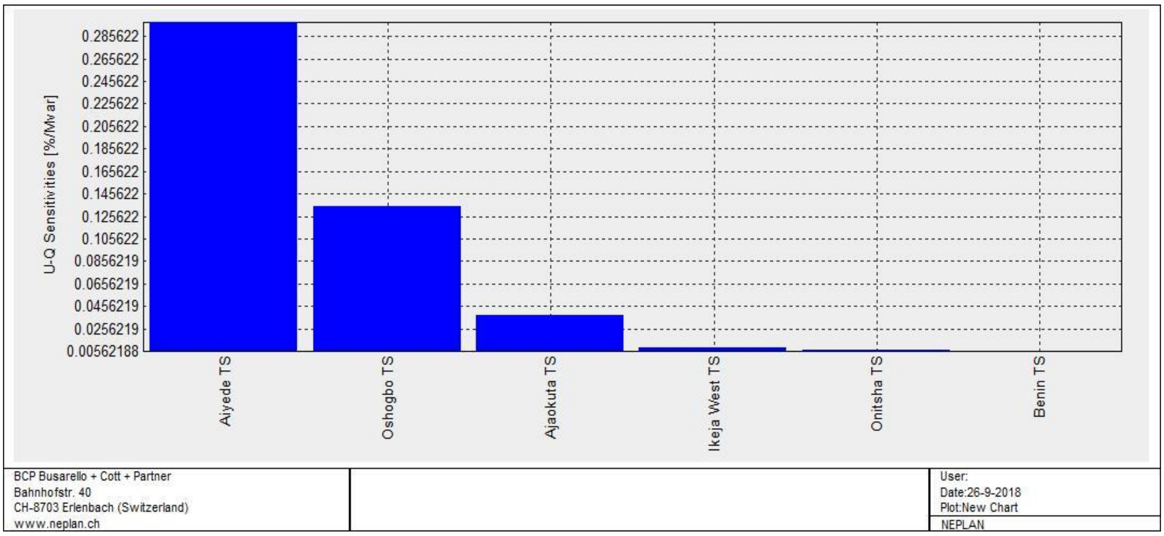

Figure no 5: Constant power static load V-Q sensitivities

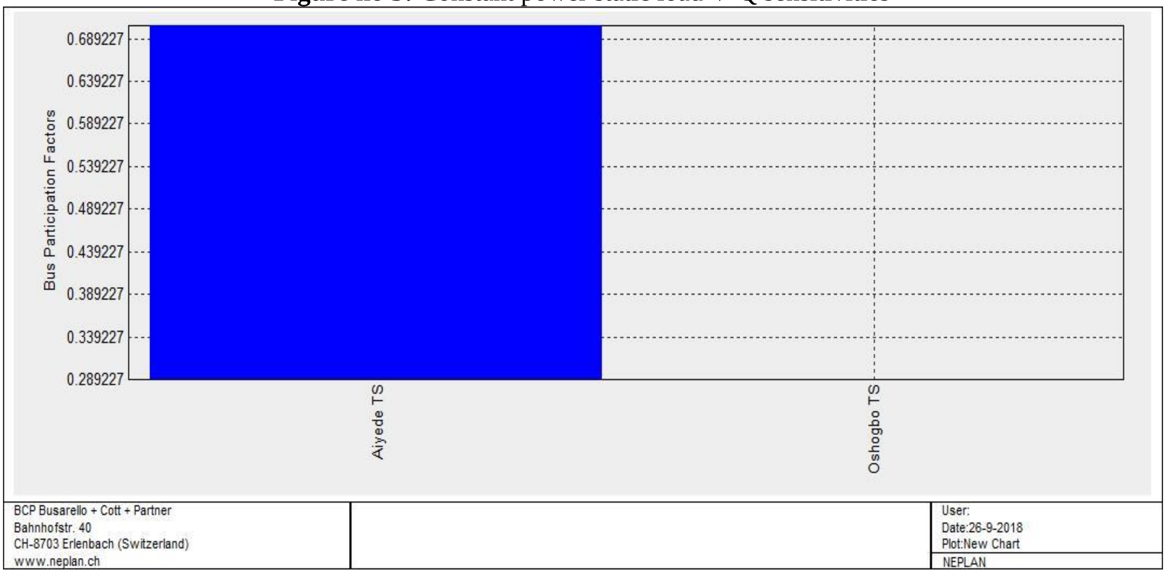

Figure no 6: Bus participation factor at the least eigenvalue of 2.4142 for constant current static load

Table no 5: Voltage profile of constant current static load buses

Bus Name	Voltage Magnitude Without SVC (pu)	Voltage Angle without SVC (rad)	Voltage Magnitude with SVC (pu)	Voltage Angle with SVC (rad)
Oshogbo TS	0.8833	-0.2967	0.9738	- 0.28798
Aiyede TS	0.8406	- 0.3735	1.00	- 0.3543
Ikeja West TS	0.96351	- 0.0873	0.97257	- 0.0873

Egbin GS	1.00	0	1.00	0
Benin TS	0.97805	- 0.2059	0.98476	- 0.2007
Sapele GS	1.00	- 0.2059	1.00	- 0.19897
Ajaokuta TS	0.9636	- 0.2339	0.97045	- 0.2286
Onitsha TS	0.987991	-0.1710	0.9899	- 0.1658
Okpai GS	1.00	-0.1449	1.00	- 0.1309

Table no 6: Constant current static load buses with weak voltage profile

Bus Name	Voltage (pu)
Aiyede TS	0.8406
Oshogbo TS	0.8833

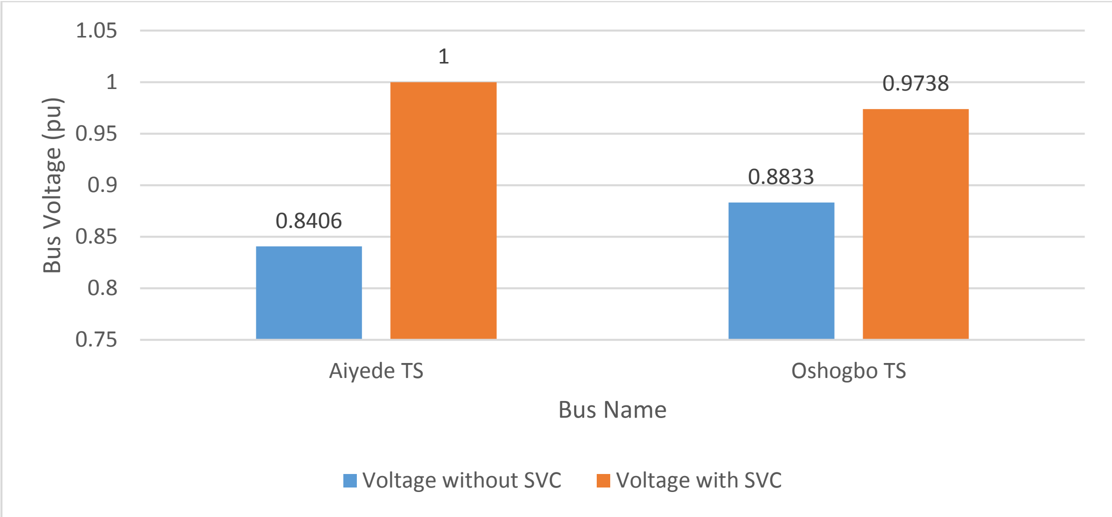

Figure no 7: Constant current static load weak bus voltage compensation representation

Table no 7: V-Q Sensitivity indices for constant current static load

Bus Name	Sensitivity % MVAr
Aiyede TS	0.1127
Oshogbo TS	0.0582
Ikeja West TS	0.0076
Ajaokuta TS	0.0368
Onitsha TS	0.0065
Benin TS	0.0052

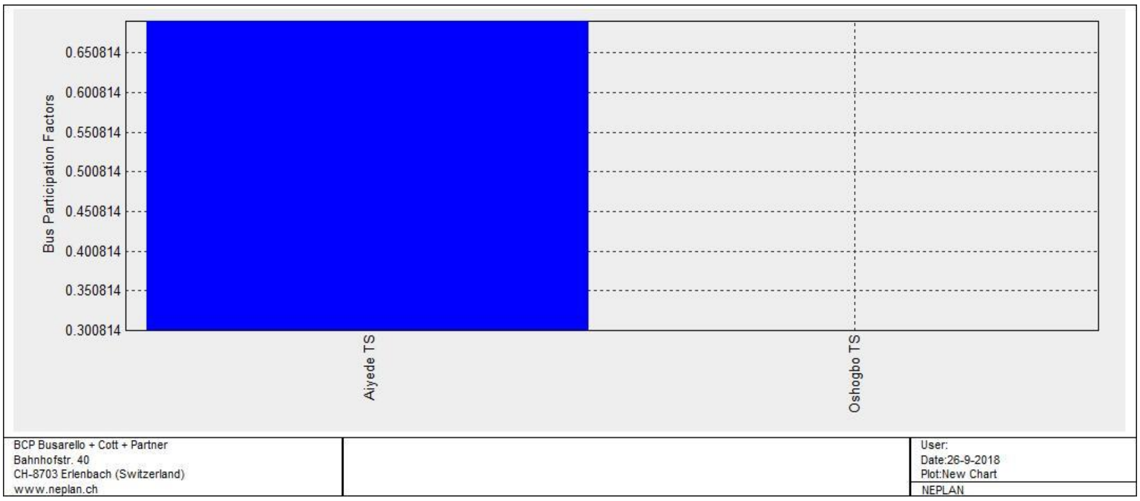

Figure no 8: Bus participation factor at the least eigenvalue of 6.4365 for constant current static load

Table no 8: Constant impedance static load bus voltage

Bus Name	Voltage Magnitude Without SVC (p.u)	Voltage Angle without SVC (rad)	Voltage Magnitude with SVC (p.u)	Voltage Angle with SVC (rad)
Oshogbo TS	0.93508	- 0.2164	0.98428	- 0.2147
Aiyede GS	0.91199	- 0.2600	1.00	- 0.2566
Ikeja West TS	0.9723	- 0.0733	0.9772	- 0.0733
Egbin GS	1.00	0	1.00	0
Benin TS	0.98326	- 0.1641	0.98688	- 0.1623
Sapele GS	1.00	- 0.1623	1.00	- 0.1588
Ajaokuta TS	0.9698	- 0.1885	0.9735	- 0.1763
Onitsha TS	0.9896	- 0.1274	0.9906	- 0.1257
Okpai GS	1.00	- 0.0995	1.00	- 0.09774

Table no 9: Constant impedance static load buses with weak voltage profile

Bus Name	Voltage (pu)
Aiyede TS	0.91199
Oshogbo TS	0.93508

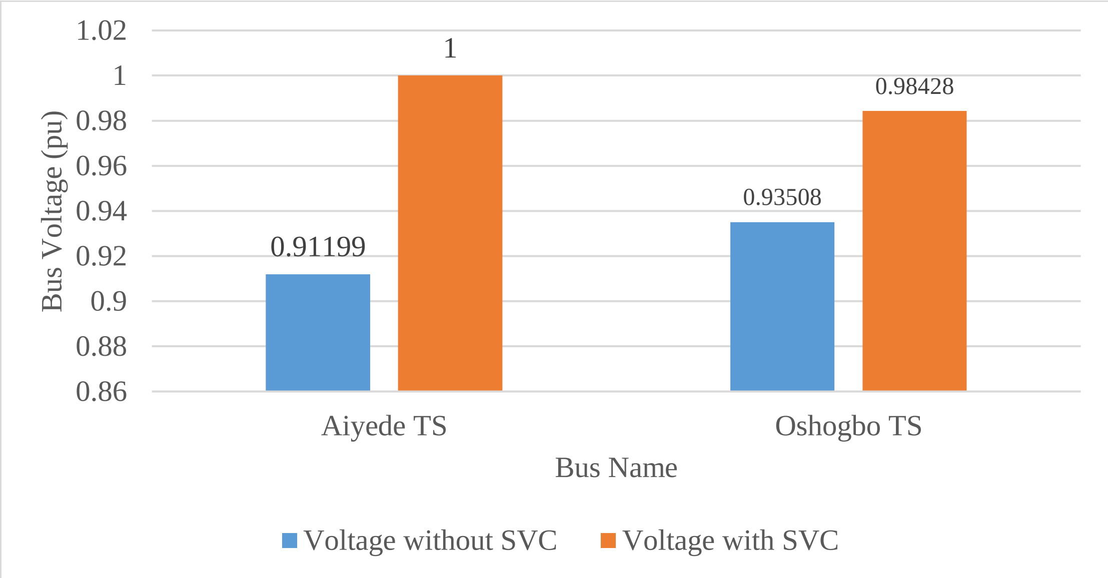

Figure no 9: Constant impedance static load weak bus voltage compensation representation

Table no 10: V-Q sensitivity indices for constant impedance static load

Bus Name	Sensitivity % MVAr
Aiyede TS	0.0940
Oshogbo TS	0.0500
Ikeja West TS	0.0074
Ajaokuta TS	0.0365
Onitsha TS	0.0065
Benin TS	0.0051

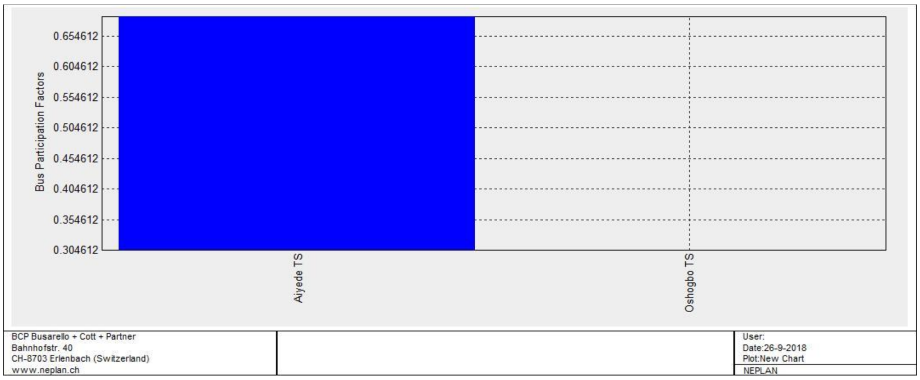

Figure no 10: Bus participation factor at the least eigenvalue of 7.7110 for constant impedance static load

Table no 11: Static load power loss without SVC

Name	Constant Power Static Load	Constant Current Static Load	Constant Impedance Static Load
Real (MW)	74.218	31.84	18.81
Reactive (MVAr)	448.849	81.045	-32.662

Table no 12: Static load power loss with SVC

Name	Constant Power Static Load	Constant Current Static Load	Constant Impedance Static Load
Real (MW)	47.521	27.625	17.742
Reactive (MVAr)	196.124	31.866	-49.49

IV. Discussion

The data required for the simulation of the different static load types using NEPLAN Software were obtained from the National Control Center (NCC) Oshogbo, Osun State, Nigeria. Figure 2 shows the 330kV Nigerian nine bus power system used for the simulation without SVC. Similarly, the 330kV Nigeria nine-bus power system used for the simulation with SVC is shown in Figure 3. The voltage profile obtained from the simulation of constant power static load with and without SVC were recorded as shown in Table 1. It was observed that all the bus voltages were within the statutory limit of 0.95 or 313.5 to 1.05 or 346.5 except buses in Table 2. The weak buses were Aiyede TS with value 0.64348, Oshogbo TS with value 0.741988, Ikeja West TS with value 0.94264 and Ajaokuta TS with value 0.9493. Figure 4 represents the constant power static load weak bus voltage compensation. The eigenvalues, V-Q sensitivity and participation factor at the various least eigenvalues were calculated using NEPLAN software to confirm that Aiyede TS was the most vulnerable to initiate voltage collapse. Since there were nine buses among which three generator buses, the total number of eigenvalues of the reduced Jacobian matrix J_R was six as shown in Table 3. It was observed that the minimum eigenvalue for constant power static load was 2.4142 and it was most critical mode. The V-Q sensitivity for the constant power static load was calculated to determine the most critical bus as shown in Table 4. Aiyede TS was the most critical with sensitivity of 0.2982. Figure 5 shows V-Q sensitivity graph representation. The bus participation factors were calculated, the result shows that Aiyede TS has the highest bus participation factor at the least eigenvalue of 2.4142 as shown in Figure 6 and showed the highest contribution of Aiyede TS to voltage collapse. When the SVC was connected to Aiyede TS bus (see Table 1) near to the peak load condition, in order to keep the voltage at that bus at 1.00 pu, the SVC injects 294.09501 MVAr to Aiyede TS bus. With the incorporation of SVC however, the output of the weak buses improved (see Table 2) from 0.64348 pu to 1.00 pu, Oshogbo TS improved from 0.741988 pu to 0.95536 pu, Ikeja West TS improved from 0.94264 pu to 0.96498 pu and Ajaokuta TS improved from 0.9493 pu to 0.9659 pu. While the power loss before compensation is shown in Table 11, that after compensation is shown in Table 12. The real power loss reduced from 74.218 MW to 47.521 MW, while the reactive power loss also reduced from 448.849 MVAr to 196.124 MVAr with the incorporation of SVC. For constant current static load, the voltage profile obtained from the simulation with and without SVC were recorded in Table 5. It was observed that all the bus voltages were within the statutory limit except buses in Table 6; the weak buses of Aiyede TS with the value of 0.8406 and Oshogbo TS with the value of 0.8833 while Figure 7 represents the constant current static load weak bus voltage compensation. Table 3 shows the calculated eigenvalues for the constant current static load with a minimum eigenvalue of 6.4365, considered to be the most critical mode. The V-Q sensitivity calculated to determine the most critical bus (Table 7) shows that Aiyede TS was the most critical with sensitivity of 0.1127. The bus participation factor was also calculated and the result shows that Aiyede TS with the highest bus participation factor at the least eigenvalue of 6.4365, presented in Figure 8, shows the highest contribution of Aiyede TS to voltage collapse. The SVC injects 174.38356 MVAr to Aiyede TS bus in order to keep the voltage magnitude at 1.00 pu (see Table 5) as the voltage profile of the weak buses improved, as shown in Table 6: Aiyede TS improved from 0.8406 to 1.00 pu and Oshogbo TS improved from 0.8833 to 0.9738 pu, real power loss reduced from 31.84 to 27.625 MW while reactive power loss reduced from 81.045 to 31.866 MVAr, as shown in Tables 11 and 12. For constant impedance static load, the voltage profile obtained from the simulation with and without SVC were recorded as shown in Table 8. It was observed that all the bus voltages were within the statutory limit except buses in Table 9; of Aiyede TS, with voltage value of 0.91199 and Oshogbo TS with value of 0.93508 while Figure 9 represents the constant impedance static load weak bus voltage compensation. Table 3 also shows the calculated eigenvalues for the constant impedance static load with the minimum eigenvalue of 7.7110 considered to be the most critical mode. The V-Q sensitivity calculated to determine the most critical bus shows that Aiyede TS was the most critical with sensitivity of 0.0940 (see Table 10). The calculated bus participation factor also shows that Aiyede TS has the highest value at a least eigenvalue of 7.7110, shown in Figure 10, indicating the highest contribution of Aiyede TS to voltage collapse. The device however, injected 103.55917 to Aiyede TS bus to keep the voltage magnitude at 1.00 pu as the voltage profile of the weak buses improved as shown in Table 13. The real power loss reduced from 18.81 to 17.742 MW.

V. Conclusion

This research presents the effect of optimal location of SVC on voltage profile and power losses for the different static load types. Nigeria 330 kV, nine bus system was modelled using NEPLAN software, simulation was carried out for the different static load types and the voltage profiles for each bus with and without SVC were obtained and recorded. It was observed that some of the load buses have weak voltage profile, attributed to their distance from the generating station or the nature of load connected to them. Not all the buses would require compensation, but only the ones with voltage profile below statutory limit (need the connection of SVC).

The following conclusions were made:

1. The load flow for the different static load types, with and without SVC simulated using the NEPLAN software, gives improved voltage profile of the weak buses with the incorporation of SVC. For constant power static load, Aiyede TS improved from 0.64348 to 1.00 pu, Oshogbo TS improved from 0.741988 to 0.95536 pu, Ikeja West TS improved from 0.94264 to 0.96498 pu and Ajaokuta TS improved from 0.9493 to 0.9659 pu. For constant current static load, Aiyede TS improved from 0.8406 to 1.00 pu and Oshogbo TS improved from 0.8833 to 0.9738 pu. For constant impedance static load, Aiyede TS improved from 0.91199 to 1.00 pu and Oshogbo TS improved from 0.93508 to 0.98428 pu.
2. The weakest bus (Aiyede TS) was identified for the placement of SVC. The eigenvalues, V-Q sensitivity and participation factor at the various least eigenvalues calculated using NEPLAN confirm that Aiyede TS was the most vulnerable to initiate voltage collapse.
3. The total power loss for the different static load types reduced with the incorporation of SVC. For constant power static load, the real power loss reduced from 74.218 to 47.521 MW while the reactive power loss reduced from 448.849 to 196.124 MVAr. For constant current static load, real power loss reduced from 31.84 to 27.625 MW while reactive power loss reduced from 81.045 to 31.866 MVAr. For constant power static load, the real power loss reduced from 18.81 to 17.742 MW.

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