Multi-Type FACTS Controllers for Power System Compensation: A Case Study of the Nigerian 48-Bus, 330 kV System

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ABSTRACT: Flexible alternating current transmission system (FACTS) devices have provided proficient answers to power system instabilities faced in the systems operations today with very little infrastructural investment fund. This paper investigates the effects of the installation of the combination of two kinds of FACTS controllers; static VAR compensator (SVC) and thyristor controlled series compensator (TCSC) compared with the installation of SVC or TCSC alone in the system. Voltage magnitude profile, active and reactive power losses of the three scenarios were achieved in the Nigerian 48-bus power system network using power system analysis toolbox (PSAT) in MATLAB environment. Simulation results obtained without and with FACTS devices optimally placed using voltage stability sensitivity factor (VSSF), revealed that the percentage decrease of the net real and reactive power losses of the combined SVC and TCSC was the highest at 31.917% whereas that of the standalone SVC and TCSC stood at 19.769% and 30.863% respectively. This shows that in addition to their capabilities to maintain acceptable voltage profile, the combination of SVC and TCSC has better compensating effect as they mitigate against power losses which was observed in their high percentage decrease in power losses compared to the standalone FACTS devices.

KEYWORDS: FACTS, optimum location, PSAT, SVC, TCSC, VSSF

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I. INTRODUCTION

The ever growing population of electric energy consumers necessitates the expansion of electrical power systems as is the case in Nigeria (Nkan *et al*, 2019a). With the ongoing expansions and growth of the electric utility industry, including deregulation in Nigeria, numerous changes characterized by additional generating stations, increase in transmission lines and loads are experienced thereby pushing the transmission systems closer to their stability and thermal limits and hence, causing the transfer of reactive power during steady state operating conditions to constitute a major problem of voltage instability (Nkan *et al*, 2019b). The application of flexible alternating current transmission system (FACTS) devices to power system stability has been an attractive ongoing area of research (Archana, 2016), and in most of the reported studies, attention has been focused on the ability of these devices to improve voltage magnitude profiles (Tripathi and Pandiya, 2017), improve system security by damping system oscillations, enhancement of power system performance like transfer stability, secure voltage profile and reduce the system losses (Shishir *et al*, 2014). Minimal attempts have been made to investigate the effect of multiple FACTS installations in power system for reliability purpose. With the increasing need for higher exchange of electrical energy through existing transmission lines, grid companies are more interested in raising and controlling the power-flow through the main transmission lines without losing system reliability. Hence, transmission lines are expected to be operated at maximum capacity close to thermal limits (Lumpur, 2000). This results to some parts of the transmission line experiencing low and high power flow.

In (Pasala *et al*, 2012), shunt FACTS devices; SVC and Static Synchronous Compensator (STATCOM) were located on the transmission line to improve transient stability with predefined direction of real power flow using Simulink. The results show that the FACTS devices, when placed slightly off-centre towards sending-end, give better performance in improving system stability. However, these FACTS controllers were not optimally placed as the midpoint was only a guess work. Attia and Sharaf, (2020) in their work presented a FACTS based dynamic stabilization scheme using modified series–parallel switched filter compensation (MSPFC). The proposed dynamic scheme was controlled by an Incremental Fuzzy Logic controller (MIFLC) to ensure fast response dynamic voltage stabilization and efficient energy utilization. In enhancement of power system voltage stability with the aid of reactive/capacitive power switching mechanism, Folorunso *et al*, (2014) placed SVC in Owerri transmission station and the result showed the dynamic nature of the SVC in absorbing reactive power in period of high voltage and supplying reactive power when low voltage occurs. (Kavitha and Neela, 2017; Raj

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and Bhattacharyya, 2017) examined the effectiveness of the optimal installation of TCSC, SVC, combined TCSC-SVC and UPFC in upgrading the security of power systems, in terms of minimizing the line loading and load voltage deviations. In (Bhattacharyya and Kumar, 2016; Kumar *et al*, 2019), the authors applied gravitational search algorithm (GSA) based optimization technique for the optimal allocation of FACTS devices in IEEE 30 and 57 test bus systems. Both active and reactive loading of the power system was considered and the effect of FACTS devices on the power transfer capacity of the individual generator was investigated. (Dixit *et al*, 2015; Agrawal *et al*, 2018; Ahmad and Sirjani, 2020) presented the employment of different optimization techniques to optimally placed TCSC in the power system. Their findings resulted in the reduction of active power and transmission line losses. Hemeida *et al*, (2020) employed two-area system to examine the feasibility of TCSC, with auxiliary control to improve the grid voltage profile, and network performance. The simulation results proved the effectiveness of the proposed method for voltage profile improvement and network performance.

In this paper, effect of the multiple FACTS devices on voltage stability and power losses will be investigated in the Nigerian 330 kV, 48-bus system. SVC and TCSC will be optimally placed in the system using PSAT. The compensating effect when both devices are placed together in the system will be compared with the effect of the FACTS devices placed individually in the system.

II. METHODOLOGY

In this section, the models of the FACTS controllers under study are briefly reviewed and presented. Modeling of the Nigerian 330 kV, 48-bus power system network with the FACTS controllers is also achieved and presentation of the power system bus and transmission line data is made.

A. Modeling of SVC AND TCSC

Figure 1 demonstrates the SVC regulator model used in this study taking into consideration the firing angle α, assuming a balanced basic frequency operation.

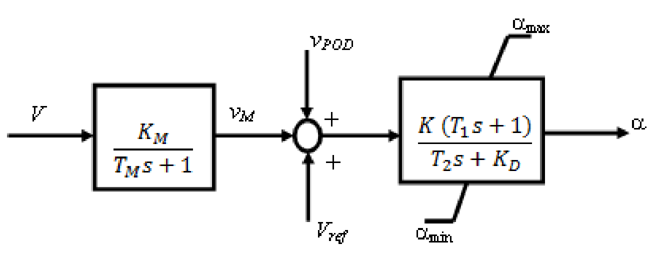

Figure. 1: SVC Regulator (Federico, 2008).

The algebraic and differential equations (2.1 – 2.3), according to Federico, (2008) are as follows:

$$\dot{V}M = (K_m V - vm)/T_m \tag{1}$$

$$\dot{\alpha} = (-K_{D\alpha} + K\frac{T_1}{T_2 T_m}(vm - K_m V) + K\big(V_{ref} + vPOD - vm\big))/T_2 \tag{2}$$

$$Q = \frac{2\alpha - \sin 2\alpha - \pi(2 - \frac{X_C}{X_L})}{\pi X_L} V^2 = b_{svc}(\alpha)V^2 \tag{3}$$

where:
$\dot{V}$M is the measure voltage rating, K_m is the measured gain, V is the voltage rating, v_m is the measured voltage, T_m is the measured time delay, $\dot{\alpha}$ is the firing angle, $K_{D\alpha}$ is the integral deviation of the firing angle, K is the regulator gain, T_1 is the transient regulator time constant, T_2 is the regulator time constant, V_{ref} is the reference voltage, vPOD is the power oscillation damping voltage, Q is the reactive power injected at the SVC node, X_L is the inductive reactance, X_C is the capacitive reactance and b_{SVC} is the total susceptance of the SVC.

The functional model of TCSC is represented in Figure 2 with the terminals of the controller at T_K and T_M. The fundamental frequency operation can be represented by the following set of equations (4 - 15). These equations include the control system and sinusoidal currents equations in the controller (Hingorani and Gyugyi, 2000).

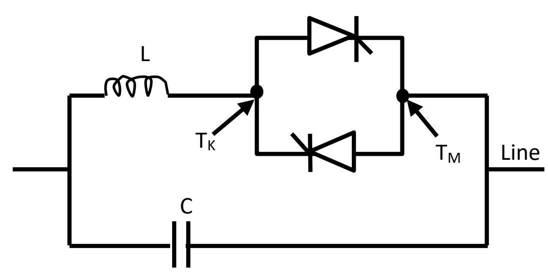

Figure 2: Thyristor Controlled Series Capacitor (Hingorani and Gyugyi, 2000).

$$[x_c', \alpha']^T = f(x_c, \alpha, I, I_{ref}) \tag{4}$$

$$P + V_k V_m B_e \sin(\delta_k - \delta_m) = 0 \tag{5}$$

$$-V_k^2 B_e + V_k V_m B_e \cos(\delta_k - \delta_m) - Q_k = 0 \tag{6}$$

$$-V_m^2 B_e + V_k V_m B_e \cos(\delta_k - \delta_m) - Q_m = 0 \tag{7}$$

$$B_e - B_e(\alpha) = 0 \tag{8}$$

$$(P^2 + Q_k^2)^{\frac{1}{2}} - IV_k = 0 \tag{9}$$

where x_c' and f (x_c,α,I,I_{ref}) stand for the internal control system variables and equations. x_c is the constant reactance of the TCSC model, α is the firing angle, B_e is the series susceptance, B_{ref} is the reference susceptance, V_k and V_m are the terminal voltages of controller, δ_k and δ_m are the magnitudes of the angles at the controller terminals, Q_k and Q_m are the reactive power injections at both controller terminals, P and I are the active power and current flowing through the controller respectively, and I is the reference current of the controller (Hingorani and Gyugyi, 2000). B_e is given as presented in Eq. (10).

$$B_e(\alpha) = \pi(K_x^4 - 2K_x^2 + 1)\cos K_x(\pi - \alpha) + [X_C(\pi K_x^4 \cos K_x(\pi - \alpha) - \pi\cos(K_x - \alpha) - 2K_x^4 \alpha \cos K_x(\pi - \alpha) \quad (10)$$

where

$k_x(Percentage\ of\ compensation\ of\ TCSC) = \left(\frac{X_C}{X_L}\right)^{\frac{1}{2}}$

For an impedance control model with no droop, which yields the simplest set of steady state equations from the numerical point of view, the power flow equations for the TCSC are

$$B_e - B_{ref} = 0 \quad (11)$$

$$P + V_k V_m B_e \sin(\delta_k - \delta_m) = 0 \quad (12)$$

$$-V_k^2 B_e + V_k V_m B_e \cos(\delta_k - \delta_m) - Q_k = 0 \quad (13)$$

$$B_e - B_e(\alpha) = 0 \quad (14)$$

$$(P^2 + Q_k^2)^{\frac{1}{2}} - IV_k = 0 \quad (15)$$

B. Modeling of Nigerian 48-bus System

Modeling of the Nigerian 48-bus system derived from the bus and transmission line data, comprises 16 PV generators for load flow studies, 79 transmission lines and 32 load buses was achieved using PSAT software in MATLAB as shown in Figure 3. The bus data and transmission line input data of the Nigerian power system network were picked from (Umoh, 2018) but not displayed here due to space constraint.

III. SIMULATION

A. Newton-Raphson Power Flow without FACTS Controllers

The result of the power flow solution of network of Figure 3 without FACTS devices using Newton Raphson iteration method for power flow computation is as presented in Table 1. The simulation was completed in 0.156s after 4 iterations with a maximum convergence error of 2.9437×10^{-9} p.u. with active and reactive maximum power mismatches of 2.12×10^{-13} p.u. and 4.01×10^{-13} p.u. respectively. According to Ayodele *et al* (2016), acceptable voltage profile should be within ±5% of the normal 330 kV voltage magnitude profile equivalent to 1.0 p.u. Hence from Table 1, it is noticed that the voltage profile for the unfortified system shows that the following buses have voltages below this acceptable range: 3(Kaduna) – 0.94822, 4(Kano) – 0.93852, 6(Makurdi) – 0.94047, 9(Jos) – 0.9381, 28(Ayede) – 0.94829 and 31(Sakete) – 0.94689.

B. Optimal Placement of FACTS Devices

Table 2 shows the simulation result of the continuation power flow (CPF) which was completed in 2.0922 seconds with maximum loading parameter (λ_{max}) yielding 3.1887. It is observed that buses 3(Kaduna), 4(Kano), 6(Makurdi), 9(Jos), 13(Osogbo), 22(Ugwuaji) and 28(Ayede) are found to be very weak buses with voltages well below 0.800 p.u.

Validating the above result, voltage stability sensitivity factor (VSSF) was computed for all the load buses as shown in

Table 1: Power flow results of Nigerian 48-bus system without FACTS devices.

Bus No	Bus Name	Voltage (pu)	Phase Angle (rad)	Real Power (pu)	Reactive Power (pu)
1	Birnin Kebbi	0.98989	0.12733	-1	-0.62
2	Kainji GS	1.0	0.14101	4.92	0.50156
3	**Kaduna**	**0.94822**	**-0.00196**	**-1.2**	**-0.9**
4	**Kano**	**0.93852**	**-0.0149**	**-0.41**	**-0.26**
5	Asaba	0.97449	0.03685	-0.8	-0.59
6	**Makurdi**	**0.94047**	**-0.01068**	**-1.0**	**-0.6**
7	Alagbon	1.0225	-0.01134	-0.7	-0.43
8	Lekki	1.0146	-0.01596	-1.1	-0.78
9	**Jos**	**0.9381**	**-0.01536**	**-1.6**	**-0.7**
10	Shiroro GS	1.0	0.04631	5.0	6.3177
11	Jebba	0.99552	0.09226	-2.6	-1.95
12	Jebba GS	1.0	0.09623	4.03	3.77
13	Oshogbo	0.9716	0.04773	-1.27	-0.95
14	Ganmo	0.97467	0.06552	-1.0	-0.75
15	Katampe	0.969	0.0382	-3.03	-2.27
16	Gwagwalada	0.97132	0.03834	-2.2	-1.65
17	Lokoja	0.97999	0.04126	-1.2	-0.9
18	Ajaokuta	0.99934	0.08191	-1.2	-0.9
19	Geregu GS	1.0	0.08321	5.31	2.0461
20	Odukpani GS	1.0	0.08415	2.6	0.98022
21	New heaven	0.97093	0.03608	-1.96	-1.47
22	Ugwuaji	0.96702	0.031	-1.75	-1.31
23	Onitsha	0.97343	0.03741	-1.0	-0.75
24	Benin	0.99563	0.05622	-1.44	-1.08
25	Ihovbor GS	1,0	0.06294	1.166	0.81105
26	Adiabor	0.99378	0.07192	-0.9	-0.48
27	Omotosho GS	1.006	0.04124	1.65	0.9512
28	**Ayede**	**0.94829**	**0.00364**	**-1.9**	**-1.51**
29	Ikot Ekpene	0.98185	0.04068	-1.65	-0.74
30	Olorunsogo GS	0.97	0.01475	1.96	-0.15072
31	**Sakete**	**0.94689**	**-0.06526**	**-2.25**	**-1.9**
32	Akangba	0.99231	-0.02395	-2.03	-1.52
33	Ikeja West	0.99657	-0.01956	-8.47	-6.35
34	Okearo	1.0133	-0.01106	-1.2	-0.9
35	Aja	1.0278	-0.00552	-1.2	-0.9
36	Egbin GS	1.033	0.0	9.2005	17.6746
37	AES GS	1.0	0.07664	2.452	-1.2759
38	Okpai GS	1.0	0.07442	4.66	2.6555
39	Sapele GS	1.0	0.06584	1.78	0.92912
40	PH Main	0.98741	0.0306	-2.8	-1.4
41	Delta GS	1.003	0.07619	3.41	1.5599
42	Aladja	0.99	0.06026	-2.1	-1.58
43	Itu	0.98783	0.0109	-1.99	-0.91
44	Eket	0.99188	-0.0019	-2.0	-1.47
45	Ibom GS	1.0	-0.00188	0.305	2.2952
46	Alaoji	0.99243	0.03697	-2.4	-1.0
47	Alaoji GS	1.0	0.0895	2.5	0.1307
48	Afam GS	1.0	0.04905	7.0	4.0565

Table 3. VSSF is represented by $|dV_i/dP_{total}|$ where dP_{total} and dV_i are the total active load change and per unit voltage change in the i^{th} bus in the system. The change in the total active load is always the same for the buses; hence, it can be taken to be the differential change in the bus voltages. The bus with the highest voltage sensitivity factor is always taken as the weakest bus in the system. The term weakest bus stems from the fact that the load that is connected to this bus will be more affected than other loads when there is an unexpected load increase (Keskin, 2007). It is noticed that bus 4 (Kano) has the highest sensitivity factor of 0.57724 closely followed by bus 3(Kaduna) with 0.49777. They are therefore adjudged the weakest buses for the installation of the two FACTS devices.

Table 2: Continuation power flow results of the Nigerian 48-bus system.

Bus No	Bus Name	Voltage (pu)	Phase Angle (rad)	Real Power (pu)	Reactive Power (pu)
1	Birnin Kebbi	0.96707	1.4136	-3.1179	-1.9331
2	Kainji GS	1.0	1.4573	15.3402	3.9795
3	**Kaduna**	**0.45045**	**0.91556**	**-3.7415**	**-2.8061**
4	**Kano**	**0.36128**	**0.69314**	**-1.2784**	**-0.81066**
5	Asaba	0.82442	1.0825	0.0	0.0
6	**Makurdi**	**0.4527**	**0.84401**	**-3.1179**	**-1.8708**
7	Alagbon	0.99535	-0.04016	-2.1826	-1.3407
8	Lekki	0.96922	-0.05571	-3.4297	-2.432
9	**Jos**	**0.45069**	**0.88936**	**0.0**	**0.0**
10	Shiroro GS	1.0	1.3216	15.5896	20.4486
11	Jebba	0.95326	1.1445	-8.1066	-6.08
12	Jebba GS	1.0	1.168	12.5652	19.449
13	**Oshogbo**	**0.76656**	**0.73986**	**-3.9598**	**-2.962**
14	Ganmo	0.82974	0.97765	0.0	0.0
15	Katampe	0.9435	1.3103	-9.4473	-7.0777
16	Gwagwalada	0.9562	1.3069	0.0	0.0
17	Lokoja	0.97631	1.3106	0.0	0.0
18	Ajaokuta	0.99566	1.3673	-3.7415	-2.8061
19	Geregu GS	1.0	1.3754	16.5562	6.8176
20	Odukpani GS	1.0	1.618	8.1066	3.8203
21	New heaven	0.8002	1.2215	-6.1111	-4.5834
22	**Ugwuaji**	**0.79321**	**1.2334**	**0.0**	**0.0**
23	Onitsha	0.80527	1.2203	-3.1179	-2.3384
24	Benin	0.89796	0.85171	-4.4898	-3.3674
25	Ihovbor GS	1.0	0.85656	3.6355	16.0759
26	Adiabor	0.97735	1.5797	0.0	0.0
27	Omotosho GS	0.8155	0.52741	0.0	0.0
28	**Ayede**	**0.78631**	**0.25526**	**-5.9241**	**-4.7081**
29	Ikot Ekpene	0.9059	1.4184	-5.1446	-2.3073
30	Olorunsogo GS	0.97	0.19153	6.1111	13.4839
31	Sakete	0.88227	-0.00628	0.0	0.0
32	Akangba	0.85077	-0.04229	-6.3294	-4.7392
33	Ikeja West	0.88226	-0.00628	-26.4088	-19.7988
34	Okearo	0.95763	-0.00289	0.0	0.0
35	Aja	1.0129	-0.02119	0.0	0.0
36	Egbin GS	1.033	0.0	1.7733	54.9283
37	AES GS	1.033	0.0	0.0	0.0
38	Okpai GS	1.0	1.4938	14.5295	11.5664
39	Sapele GS	0.93133	0.88685	0.0	0.0
40	PH Main	0.95832	1.4402	-8.7302	-4.3651
41	Delta GS	1.003	0.95292	10.6321	10.1301
42	Aladja	0.9784	0.93175	0.0	0.0
43	Itu	0.93086	1.3507	-6.2047	-2.8373
44	Eket	0.94511	1.3057	-6.2359	-4.5834
45	Ibom GS	1.0	1.3052	0.95097	7.7669
46	Alaoji	0.94872	1.4417	0.0	0.0
47	Alaoji GS	1.0	1.7846	7.7948	1.6201
48	Afam GS	1.0	1.4995	21.8255	16.0121

The P-V nose curves for the seven weak buses illustrated in Figure 4 affirms bus 4(Kano) and bus 3(Kaduna) as the weakest buses hence, most suitable for the placement of FACTS devices. This is because the reactive powers are insufficient at these load buses when the loading parameter reaches its critical point at 3.1887, causing an unstable power system and near-voltage collapse.

C. Power Flow Simulation with FACTS Controllers

With SVC installed at the weak buses 4(Kano), and 3(Kaduna) of the case study system, the power flow simulation converges at 1.1727×10^{-10} p.u. in 0.172s after 4 iterations. Maximum real and reactive power mismatches are 1.94×10^{-13} p.u. and 2.14250 p.u. respectively. With the placement

Table 3 Voltage stability sensitivity factors of the Nigerian 48-bus system.

Bus No	Bus Name	Voltage Stability Sensitivity Factor	Bus No	Bus Name	Voltage Stability Sensitivity Factor
1	Birnin Kebbi	0.02282	25	Ihovbor GS	0.00000
2	Kainji GS	0.00000	26	Adiabor	0.01643
3	**Kaduna**	**0.49777**	27	Omotosho GS	0.00000
4	**Kano**	**0.57724**	28	Ayede	0.16198
5	Asaba	0.15007	29	Ikot Ekpene	0.07595
6	Makurdi	0.48777	30	Olorunsogo GS	0.00000
7	Alagbon	0.02715	31	Sakete	0.06462
8	Lekki	0.04538	32	Akangba	0.14154
9	Jos	0.48741	33	Ikeja West	0.11431
10	Shiroro GS	0.00000	34	Okearo	0.05367
11	Jebba	0.04226	35	Aja	0.01490
12	Jebba GS	0.00000	36	Egbin GS	0.00000
13	Oshogbo	0.20504	37	AES GS	0.00000
14	Ganmo	0.14493	38	Okpai GS	0.00000
15	Katampe	0.02550	39	Sapele GS	0.00000
16	Gwagwalada	0.01512	40	PH Main	0.02909
17	Lokoja	0.00368	41	Delta GS	0.00000
18	Ajaokuta	0.00368	42	Aladja	0.01160
19	Geregu GS	0.00000	43	Itu	0.05697
20	Odukpani GS	0.00000	44	Eket	0.04677
21	New heaven	0.17073	45	Ibom GS	0.00000
22	Ugwuaji	0.17381	46	Alaoji	0.04371
23	Onitsha	0.16816	47	Alaoji GS	0.00000
24	Benin	0.09767	48	Afam GS	0.00000

of TCSC on line 3 - 4 and on line 3 - 9 closer to the weakest bus, simulation is completed in 0.1715 after 4 iterations with a maximum convergence error of 9.6232×10^{-11} with active and reactive maximum power mismatches of 1.07678 p.u. and 1.06881 p.u. respectively.

Lastly, SVC and TCSC are placed in the case study network for effective enhancement of power system stability. The series FACTS device (TCSC) is placed on line 3-9 closer to bus 3 while the shunt FACTS device (SVC) is placed on bus 4. Performance of power flow on the system shows that in 0.281s, the simulation reaches its convergence after 4 iteration at 8.4746×10^{-11} p.u., with maximum real and reactive power mismatches of 1.25750 p.u. and 0.42352 p.u. respectively.

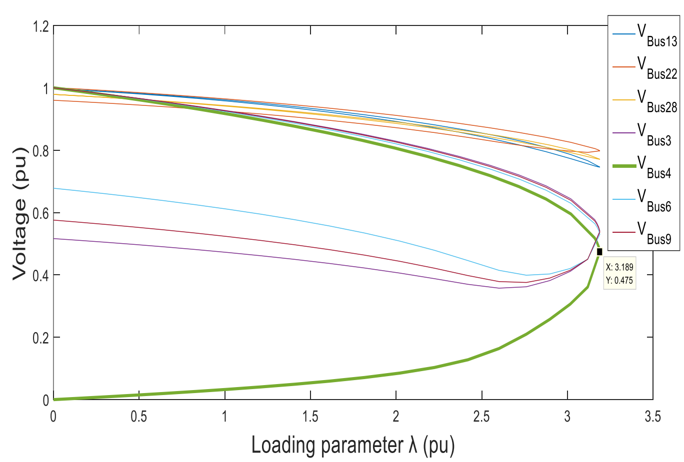

Figure 4: Voltage P-V nose curves for seven low voltage buses.

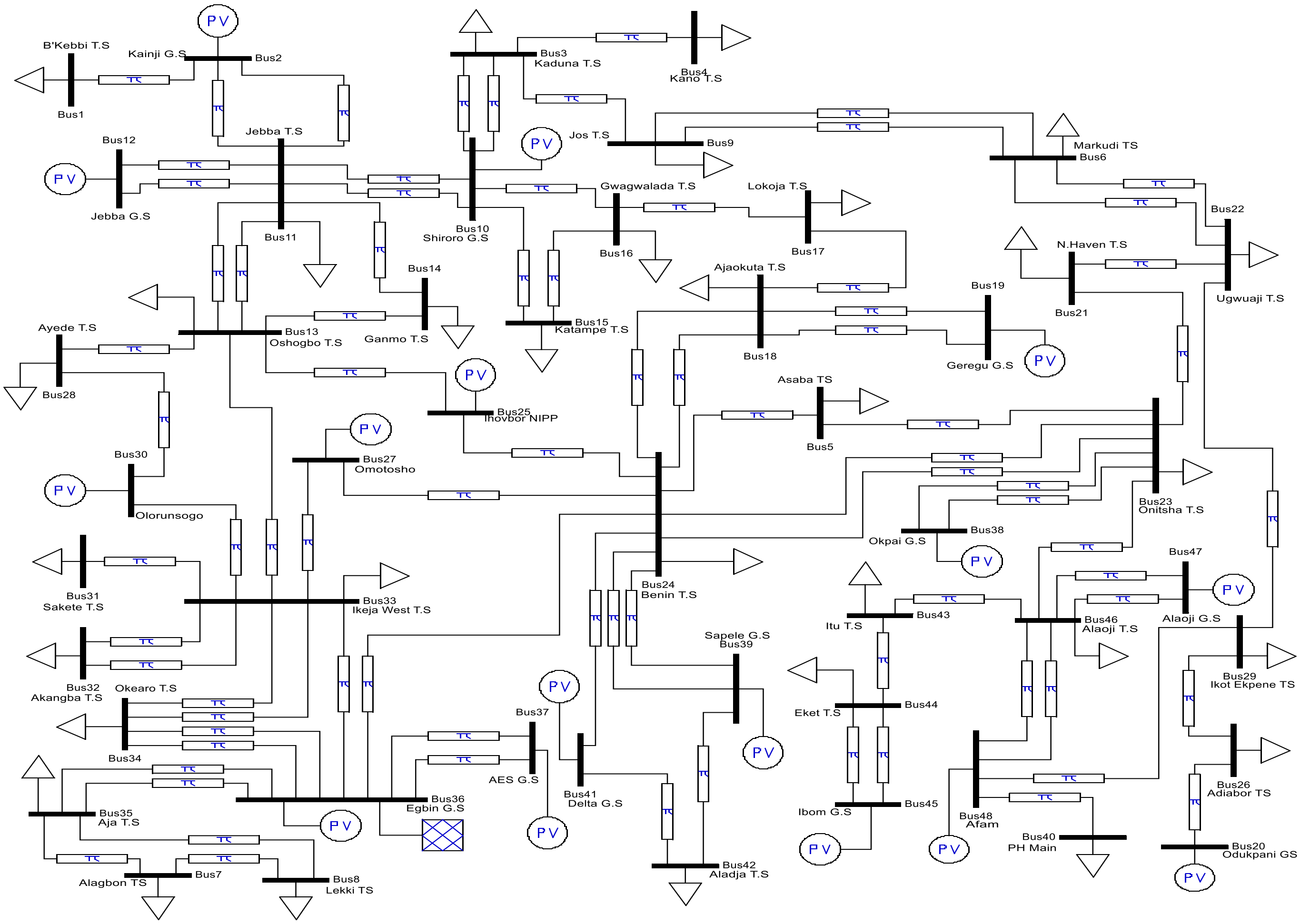

Figure 3: Nigerian 48-bus system.

IV. SIMULATION RESULTS AND DISCUSSION

The results of the power flow summarized in Table 4 and the voltage magnitude profile graphically represented in Figure 5 show that for the unfortified case system, simulation results show that the total real power generation in p.u. stood at 57.94345 while the reactive power was 43.25271 p.u. The total real power load of the system was 57.35 p.u., and the reactive power of the load was 39.52 p.u. It was also found out that the total real power losses in p.u. was 0.59345 while the reactive power losses was 3.73251 p.u. SVC, which is a shunt-connected device of fixed capacitance in parallel with a thyristor controlled reactor helps to maintain acceptable voltage profile by supplying reactive power in the capacitive mode.

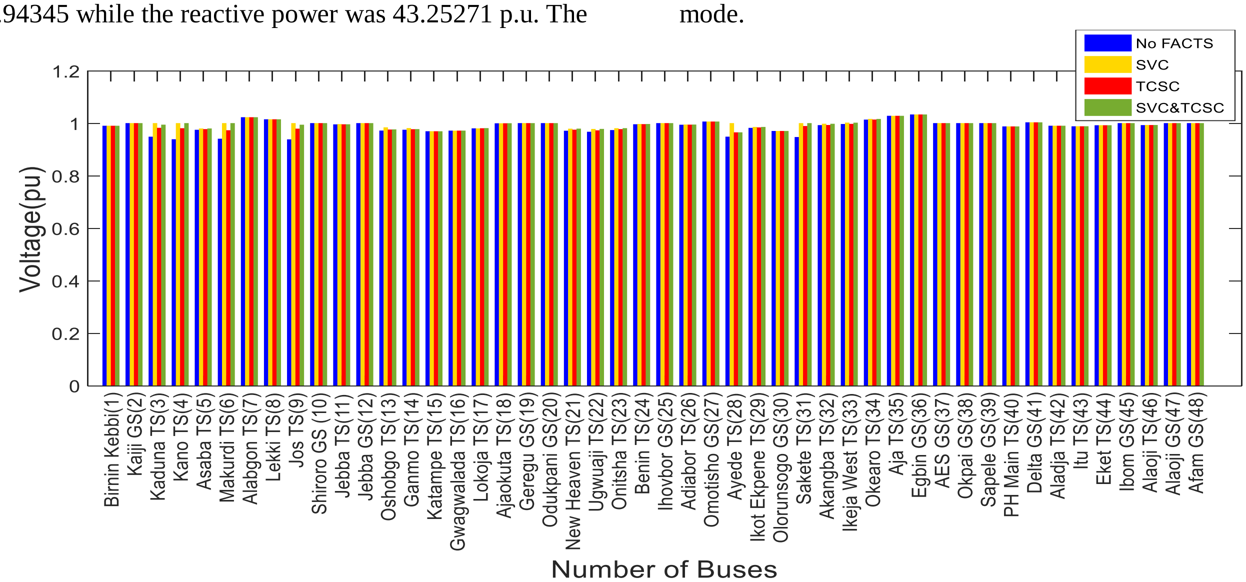

Figure 5: Voltage profile without FACTS, with SVC, TCSC and combined SVC&TCSC.

Table 4: Voltage profile (p.u.) and power details without and with FACTS devices.

Bus No	Bus Name	No FACTS	With SVC	With TCSC	With SVC & TCSC
1	Birnin Kebbi	0.98989	0.98989	0.98989	0.98989
2	Kainji GS	1.0	1.0	1.0	1.0
3	**Kaduna**	**0.94822**	**1.0**	**0.98206**	**0.99405**
4	**Kano**	**0.93852**	**1.0**	**0.98046**	**1.0**
5	Asaba	0.97450	0.97951	0.97708	0.97962
6	**Makurdi**	**0.94047**	**1.0**	**0.97278**	**1.0**
7	Alagbon	1.02247	1.0225	1.02247	1.0225
8	Lekki	1.01456	1.0146	1.01456	1.0146
9	**Jos**	**0.93810**	**1.0**	**0.97884**	**0.99387**
10	Shiroro GS	1.0	1.0	1.0	1.0
11	Jebba	0.99522	0.9961	0.99550	0.99553
12	Jebba GS	1.0	1.0	1.0	1.0
13	Oshogbo	0.97160	0.98383	0.97547	0.97603
14	Ganmo	0.97467	0.98107	0.97676	0.97712
15	Katamkpe	0.969	0.96901	0.96898	0.96893
16	Gwagwalada	0.97132	0.97131	0.97136	0.97142
17	Lokoja	0.98	0.97986	0.98038	0.98096
18	Ajaokuta	0.99934	0.99934	0.99935	0.99961
19	Geregu GS	1.0	1.0	1.0	1.0
20	Odukpani GS	1.0	1.0	1.0	1.0
21	New heaven	0.97093	0.97872	0.97496	0.97893
22	Ugwuaji	0.96702	0.97763	0.97248	0.97787
23	Onitsha	0.97343	0.98059	0.97709	0.9807
24	Benin	0.99563	0.99658	0.99612	0.99662
25	Ihovbor	1.0	1.0	1.0	1.0
26	Adiabor	0.99378	0.9945	0.99415	0.99452
27	Omotosho GS	1.006	1.006	1.006	1.006
28	**Ayede**	**0.94829**	**1.0**	**0.96482**	**0.96489**
29	Ikotekpene	0.98185	0.98533	0.98364	0.9854
30	Olorunsogo GS	0.97	0.97	0.97	0.97
31	**Sakete**	**0.94689**	**1.0**	**0.98883**	**1.0**
32	Akangba	0.99231	0.99762	0.9928	0.99741
33	Ikeja West	0.99657	1.0019	0.99705	1.0016
34	Okearo	1.01333	1.016	1.01358	1.0159
35	Aja	1.02783	1.0278	1.02783	1.0278
36	Egbin GS	1.033	1.033	1.033	1.033
37	AES GS	1.0	1.0	1.0	1.0
38	Okpai GS	1.0	1.0	1.0	1.0
39	Sapele GS	1.0	1.0	1.0	1.0
40	PH Main	0.98741	0.98741	0.98741	0.98741
41	Delta GS	1.003	1.003	1.003	1.003
42	Aladja	0.99	0.99	0.99	0.99
43	Itu	0.98783	0.98808	0.98796	0.98808
44	Eket	0.99188	0.99196	0.99192	0.99196
45	Ibom GS	1.0	1.0	1.0	1.0
46	Alaoji	0.99243	0.99284	0.99264	0.99285
47	Alaoji GS	1.0	1.0	1.0	1.0
48	Afam GS	1.0	1.0	1.0	1.0
Generated real power		57.94345	57.88503	57.83732	57.83996
Generated reactive power		43.25271	42.88223	42.76825	42.71227
Real power load		57.35	57.35	57.35	57.35
Reactive power load		39.52	39.52	39.52	39.52
Real power losses		0.59345	0.53503	0.48732	0.48996
Reactive power losses		3.73271	3.36223	3.24825	3.19227
% Decrease of active power losses			9.844	17.884	17.439
% Decrease of reactive power losses			9.925	12.979	14.478
Total % decrease of active and reactive power losses			19.769	30.863	31.917

In this process, the total transmission line reactance is reduced while the voltage across the impedance is increased, leading to the increase in the line currents and transmitted power. Therefore, it can be noticed from the simulation that the voltage magnitude profiles with the system fortified using SVC compared with the uncompensated network are improved. The real and reactive power generated by the system are 57.88503 p.u. and 42.88223 p.u. while the real and reactive power losses reduced from 0.59345 p.u. and 3.73271 p.u. to 0.53503 p.u. and 3.36223 p.u. giving 9.844% decrease and 9.925% decrease, all, respectively. The voltage profiles of the affected buses are duly compensated and raised up to ±5% of the acceptable value.

Functioning in its capacitive boost mode, simulation results show that TCSC, which consists of compensating capacitor, bypass inductor, and thyristors, operates by absorbing energy and reducing short circuit current through the inductor connected in series with the bidirectional thyristors. The capacitor discharge current pulse will circulate through the parallel inductive branch, releasing its reactance in series with the transmission lines which result in increase in loading capability of the transmission line. The total real and reactive power generation for the system with TCSC are 57.83732 p.u. and 42.76825 p.u. respectively, while the real and reactive power losses are reduced to 0.48732 p.u. and 3.24825 p.u. respectively giving 17.884% decrease and 12.979% decrease, all, respectively. For the combination of SVC and TCSC in the power system network, simulation results clearly show that the voltage magnitude profile of the weak buses is adequately improved through the shunt connected SVC device which function to increase the voltage across the impedance of the transmission line.

The TCSC on the other hand enhances the loadability of the line by releasing its reactance in series with the line through its discharged current pulse. The reduction in the real and reactive power losses from 0.59345 p.u. and 3.73271 p.u. respectively to 0.48996 p.u. and 3.19227 p.u. respectively, resulting to 17.439% decrease for real power losses and 14.478% decrease for reactive power losses, shows a tremendous improvement in power transfer capabilities of the combination of these FACTS devices.

Summary of the active and reactive power losses of all the four scenarios as tabulated in Table 4. The total percentage decrease in the active and reactive power losses are also illustrated in the table where the combination of SVC and TCSC is seen to have the highest total loss reduction of 31.917% closely followed by TCSC with 30.869% and SVC with 19.769%. This shows that the combination enhances power transfer capability and hence, systems stability.

V. CONCLUSION

Effects of multiple FACTS controllers in the Nigerian 48-bus system have been investigated with the optimal installation of SVC, TCSC and the combination of SVC and TCSC. Results of bus voltage magnitude profiles, transmission lines real and reactive power losses without and with FACTS devices have been compared in the event of small disturbances like voltage drops because of long transmission lines and variation in loads. The FACTS devices showed sterling power transfer capabilities through stability enhancement by restoring the voltage magnitude profiles at the buses which had experienced voltage dips back to the acceptable value of ±5% of 330 kV (0.95 p.u – 1.05 p.u of 1.0 p.u) and mitigating against both real and reactive power losses in the system. Of the three scenarios of the controllers' applications, the combination of SVC and TCSC FACTS devices gave a better compensation for effective steady state stability of the Nigerian 48-bus system compared to stand alone SVC or TCSC. This was seen in their ability to curb excessive power losses by reducing total real and reactive power losses by 31.917% compared to that of SVC which was 30.863% and that of TCSC which was 19.769%.

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