International Multilingual Journal of Science and Technology (IMJST)
ISSN: 2528-9810
Vol. 8 Issue 9, September - 2023

Optimum Location of Shunt FACTS Devices for Enhancement of Power System Loadability using Continuation Power Flow

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***Abstract*—Due to the growth of electricity demands and transactions in power markets, existing power networks need to be enhanced in order to increase their loadability. Stressed electric network, either due to increased loading because of system expansion, or due to extreme contingencies, often result in voltage limit violations and overload of lines leading to extreme degradation in the power system's network. This paper presents the study of the application of two shunt FACTS controllers; Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC) for transmission system loadability enhancement. Voltage magnitude profile without and with FACTS controllers was obtained in the Nigerian 330 kV, 48-bus power system network using power system analysis toolbox (PSAT), a commercially available software in MATLAB environment. Optimum location of the FACTS devices was achieved through the computation of the voltage stability factors (VSF) for all the buses after continuation power flow (CPF) was carried out. Simulation results obtained without and with the FACTS controllers revealed that the maximum loading point which is the critical loading point where voltage collapse is experienced, and the system loses voltage stability increases from 3.186 without FACTS devices to 3.233 and 3.796 with STATCOM and SVC respectively. This shows that loadability of the system is enhanced through increasing the voltage stability limits thereby preventing voltage collapse.**

Keywords—Optimum location; FACTS; Loadability; Continuation power flow; STATCOM; SVC.

I. INTRODUCTION

The implementation of hybrid energy system that integrate renewable and non-renewable sources within the primary grid, necessitates the deployment of intelligent power electronic devices to optimize the monitoring, protection and optimal power flow within the electrical transmission and distribution network. Also, due to limited resources and environmental restrictions coupled with the ever-increasing population which has made the demand of electrical power to exceed supply, a larger part of the world population is kept in blackout as a result of the fact that most transmission lines are been overloaded, leading to energy utilization peak. This has been a major cause of grid failure that often results to severe damage to the power system components. Efficient means to mitigate these occurrences are therefore very pertinent. Flexible alternating current transmission system (FACTS) devices gives a promising solution to these requirements due to their immense capacity to control voltage levels and reactive power flow in real time. The advent in technology has resulted to increasing energy need, however, the means to enhance system stability in the present and future power system is paramount.

II. REVIEW OF RELATED LITERATURE

The authors in [1] applied optimization technique, namely, NSGA-II, to find out the optimal number of multi-devices of Thyristor controlled series compensator (TCSC) and Static VAR compensator (SVC) in order to improve the system loadability and to ensure the steady state security of the network. They performed a contingency analysis procedure based on severity index (SIL) on the IEEE 30-bus test system to identify and classify the most severe line contingencies and also determined the optimal placement and parameter setting of FACTS devices in power system by using the above optimization approach to alleviate the line overloads. The results showed that the stress on the power system, FACTS installation cost and total real power losses were drastically reduced. Also, the benefits of utilizing FACTS devices to improve operation of electrical power system, comparison of different types of FACTS controllers, semiconductor technology development and application of FACTS to power system was discussed in [2]. Optimization of the system's capacity to handle various loads efficiently was a paramount study in [3].In this study, the authors used Gbest gravitational search algorithm (GGSA) to optimally locate SVC and TCSC to improve the performance of the power system network through the maximization of the system's loadability. These devices were used in controlling major power system parameters such as voltage, phase angle and impedance which affected AC power supply. The paper also proposed the sizing of the multi-type FACTS devices on a tested algorithm of IEEE 30 bus system which significantly improved the system loadability and a corresponding reduction in transmission line losses. In [4] and [5], the authors employed SVC and STATCOM optimally placed in the Nigerian 48-bus power system network using voltage stability sensitivity factor. The comparative analysis of the system which was modeled using PSAT in MATLAB environment without and with FACTS devices under a contingency of fault application at bus 33 (Geregu), with the FACTS installed at bus 21 (Jos), showed a significant improvement on overall performance of the transmission network which included improvement in the damping of power system oscillation as well as the voltage profile for power system dynamic stability. The results were validated with the eigenvalue method of stability analysis which showed the superiority of SVC over STATCOM. In [6],the authors used the rectangular coordinates for complex voltage method to develop a linear programming frame work to verify if an operating point is on the loadability boundary, compute the margin of an operating point to the loadability boundary, and calculate the loadability point in any direction. The proposed method gave a more accurate result and ease of analysis since it does not require solving of non-linear optimization problems or calculating eigenvalues of the power flow Jacobian. The method met the IEEE standard test cases unlike the current state of the-arts methods. Easy fault identification at point of occurrence in the existing power transmission network is still a major challenge that limits the power quality. Power stability monitoring system can be improved by optimal location of FACTS devices using artificial neural network (ANN) called the optimal power flow artificial neural network (OPFANN). This device identifies the weakest line with the most probability of voltage collapse and provides a straight forward method and faster scheme for voltage stability in accordance with efficient monitoring of the transmission lines through the introduction of unified power flow controllers (UPFC) to enhance the voltage stability and system loadability[7]. The incorporation of FACTS devices has significantly improved the system stability, necessitating effective study of its various types and their effects on power system performance. FACTS devices such as the SVC and controlled series Compensator (CSC) were optimally located in power system network using the maximum power transfer capability of the transmission lines and buses to improve power quality[8]. Several disturbances which occur in the power systems network result to instability and reduction in power quality as observed in the studies carried out in [9]. Here, the authors deployed a novel method based on Artificial Algae Algorithm to determine the optimal location of UPFC under N-1 contingency criterion. Simulation of IEEE 14 and 30 bus systems showed that adoption of the AAA novel technique enhanced the location of UPFC with proper parameter settings which significantly improved the power quality, reliability, and stability of the power system. The studies in [10, 11, 12, 13] also showed that FACTS devices perform several functions when integrated with the main grid. The comparative analysis using the genetic algorithm (GA) and particle swarm optimization (PSO) applied to the IEEE 30-bus system when the system was loaded from base load to 200% of base load was used to determine the system performance. Results showed that the genetic algorithm approach gave a better solution. Stressed electric network, either due to increased loading because of system expansion, or due to extreme contingencies, often result in voltage limit violations and overload of lines leading to extreme degradation in the system's damping torque, hence, resulting to dynamic instability. The authors in [14] and [15] investigated the system responses during line outages for dynamic stability improvement by optimally locating Static synchronous series compensator (SSSC) and TCSC after continuation power flow for the simulation of the line outages which was achieved using breakers. Results show that the two FACTS controllers effectively improved the system stability by reducing the rotor angle and speed and by damping the post outage oscillations of the bus voltage and real power. The complexity of modern power system necessitated the adoption of advanced fault protection scheme to ensure stability of supply and optimal power flow. Novel evaluation of two area power system network to ascertain their performances when SVC, STATCOM, UPFC, and TCSC were employed was carried out in [16] and [17]. Simulation results showed that adoption of UPFC on transient stability improved the system behavior better than other FACTS devices. Increase in energy need necessitated the integration of more energy source mix majorly renewables such as wind and PV system. The means of protecting them became a major concern, hence, the study in [18] and [19] on the enhancement of voltage stability using distributed static synchronous compensator (DSTATCOM) on a wind turbine system using PSAT. The output from the wind generator when fed to STATCOM gave a smooth output and improve the power system stability. In multi-type FACTS controllers for power systems compensation, the authors in [20] investigated the effects of the installation of the combination of two kinds of FACTS controllers; SVC and TCSC compared with the installation of SVC or TCSC alone in the system. 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. Reactive power has large effects on power system supply, therefore, to increase the amount of active power flow requires that FACTS devices be introduced to control the state of voltage and power control in the transmission system. The authors in [21] employed the gravitational search algorithm (GSA) based optimization method to appropriately locate FACTS devices in the IEEE 30 and 57 test bus systems to meet up this demand. The studies in [22, 23, 24, 25] discussed the various analytical technique deployed by several authors to determine the location of FACTS and recommended the Meta-heuristic approach due to its high efficiency and accuracy in optimal location of FACTS devices within the transmission network. Likewise, the study in [26] which employed Genetic Algorithm technique to find the optimal location of SVC. By evaluating the voltage performance index on the IEEE 30 bus system, the authors discovered that the system enhanced the reduction in power losses on the transmission lines and voltage deviation.

This present study is significant as it will attempt to evaluate the performance of various shunt FACTS devices (SVC and STATCOM) in enhancing power system loadability using continuation power flow method.

III. LOADABILITY TECHNIQUE

A. *Continuation Power Flow (CPF) Method*

The Jacobian matrix of power flow equations becomes singular at the voltage stability limit. Continuation power flow overcomes this problem. Continuation power flow finds successive load flow solutions according to a load scenario. It consists of prediction and correction steps. From a known base solution, a tangent predictor is used so as to estimate next solution for a specified pattern of load increase. The corrector step then determines the exact solution using Newton-Raphson technique employed by a conventional power flow. After that a new prediction is made for a specified increase in load based upon the new tangent vector. Then corrector step is applied. This process goes on until critical point is reached. The critical point is the point where the tangent vector is zero. The illustration of predictor-corrector scheme is depicted in Fig. 1[27].

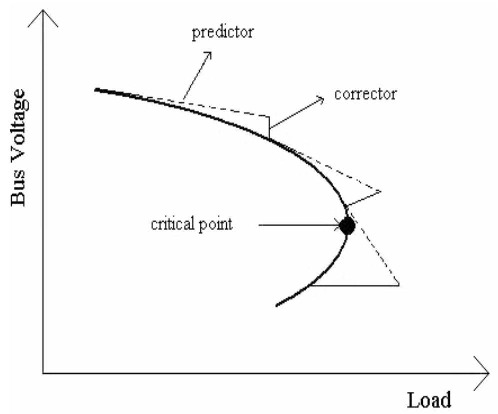

Fig. 1. Illustration of prediction-correction steps [27]

Injected powers can be written for the i^{th} bus of an n-bus system as follows in (1) to (3).

$$P_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos Q_{ik} + B_{ik}\sin Q_{ik}) \quad (1)$$
$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin Q_{ik} + B_{ik}\cos Q_{ik} \quad (2)$$
$$P_i = P_{Gi} - P_{Di}, Q_i = Q_{Gi} - Q_{Di} \quad (3)$$

where the subscripts G and D denote generation and load demand respectively on the related bus. In order to simulate a load change, a load parameter λ is inserted into demand powers P_{Di} and Q_{Di}.

$$P_{Di} = P_{Dio} + \lambda(P_{\Delta base}) \quad (4)$$
$$Q_{Di} = Q_{Dio} + \lambda(Q_{\Delta base}) \quad (5)$$

P_{Dio} and Q_{Dio} are original load demands on i^{th} bus whereas $P_{\Delta base}$ and $Q_{\Delta base}$ are given quantities of powers chosen to scale λ appropriately. After substituting new demand powers in (4) and (5) to (3), new set of equations can be represented as:

$$F(\theta, V, \lambda) = 0 \quad (6)$$

IV. TEST SYSTEM

A. *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 were achieved using PSAT software in MATLAB as shown in Fig. 2. The bus data and transmission line input data of the Nigerian power system network were picked from [28].

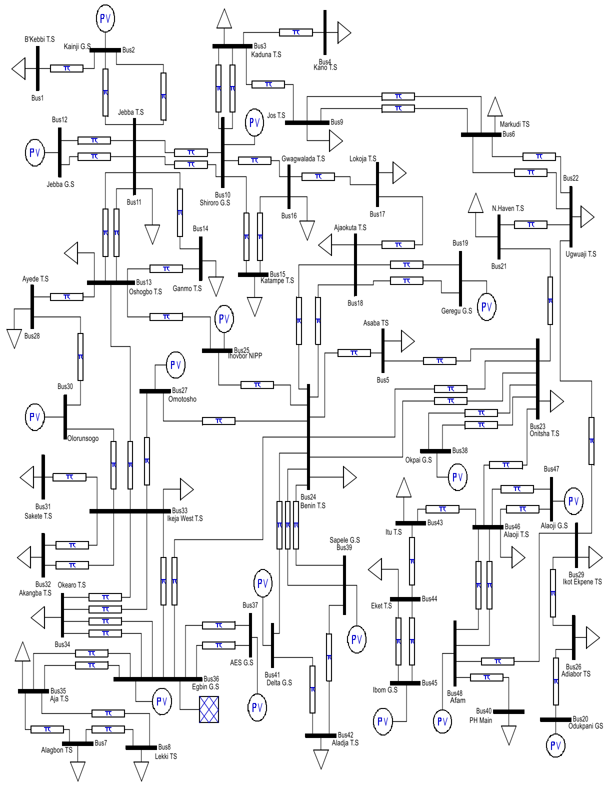

Fig. 2. Nigerian 48-bus system

B. Modelling of FACTS Devices

1) SVC

Fig. 3 demonstrates the SVC regulator model used in this study taking into consideration the firing angle α, assuming a balanced basic frequency operation.

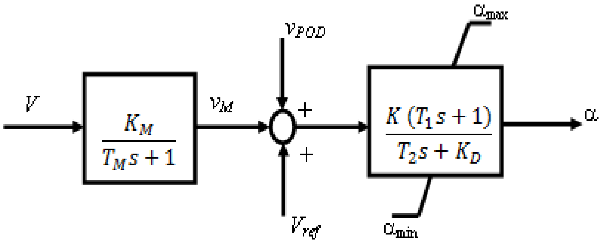

Fig. 3. SVC Regulator [29]

The algebraic and differential equations (7)-(9), according to [29] are as follows:

$$\dot{V}M = (K_m V - vm)/T_m \quad (7)$$

$$\dot{\alpha} = (-K_{D\alpha} + K\frac{T_1}{T_2 T_m}(vm - K_m V) + K(V_{ref} + vPOD - vm))/T_2 \quad (8)$$

$$Q = \frac{2\alpha - \sin 2\alpha - \pi(2 - \frac{X_C}{X_L})}{\pi X_L} V^2 = b_{SVC}(\alpha) V^2 \quad (9)$$

where:

$\dot{V}$ is the measure voltage rating, K_m is the measured gain, V is the voltage rating, *vm* 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.

2) STATCOM

The implemented STATCOM model shown in Fig. 4 is a current injection model who's current is always kept in quadrature in relation to the bus voltage so that only the reactive power is exchanged between the ac system and the STATCOM. From the dynamic model, it can be seen that STATCOM assumes a time constant regulator like SVC. The differential equation and the reactive power injected of the STATCOM mode are given respectively by:

$$i_{SH} = (K_r(V_{ref} + v_{POD} - V) - i_{SH})/T_r \quad (10)$$

$$Q = i_{SH} V \quad (11)$$

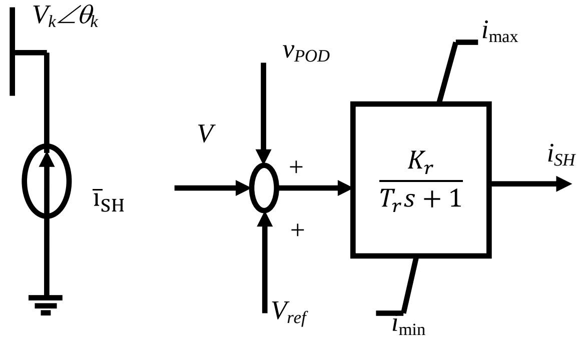

Fig. 4. STATCOM circuit and control block diagram [29]

V. SIMULATION RESULTS AND DISCUSSION

A. Newton-Raphson Power Flow without FACTS Controllers

The result of the power flow solution of network of Fig. 2 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 [30], 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) – 0.9278, 4(Kano) – 0.91787, 6(Makurdi) – 0.92456, and 9(Jos) – 0.9268

TABLE I. POWER FLOW RESULTS OF NIGERIAN 48-BUS SYSTEM WITHOUT FACTS

BUS NO	BUS NAME	VOLTAGE (pu)	PHASE ANGLE (rad)	REAL POWER (pu)	REACTIVE POWER (pu)
1	Birnin Kebbi TS	0.98989	0.41634	-1.0	-0.62
2	Kainji GS	1.0	0.43002	4.92	0.5806
3	**Kaduna TS**	**0.9278**	**0.34185**	**-1.2**	**-0.9**
4	**Kano TS**	**0.91787**	**0.32833**	**-0.41**	**-0.26**

5	Asaba TS	0.97257	0.32524	0	0
6	**Makurdi TS**	**0.92456**	**0.33006**	**-1.0**	**-0.6**
7	Alagbon TS	1.0216	-0.0125	-0.7	-0.43
8	Lekki TS	1.0137	-0.01712	-1.1	-0.78
9	**Jos TS**	**0.9268**	**0.33748**	**0**	**0**
10	Shiroro GS	1.0	0.41182	5.0	3.4017
11	Jebba TS	0.99087	0.33227	-2.6	-1.95
12	Jebba GS	1.0	0.3403	4.03	3.5846
13	Oshogbo TS	0.95852	0.21855	-1.27	-0.95
14	Ganmo TS	0.96869	0.27874	0	0
15	Katampe TS	0.98286	0.4069	-3.03	-2.27
16	Gwagwalada TS	0.98664	0.40578	0	0
17	Lokoja TS	0.99214	0.40598	0	0
18	Ajaokuta TS	0.99907	0.42036	-1.2	-0.9
19	Geregu GS	1.0	0.423	5.31	1.2634
20	Odukpani GS	1.0	0.48089	2.6	0.48545
21	New heaven TS	0.96558	0.36393	-1.96	-1.47
22	Ugwuaji TS	0.96496	0.36748	0	0
23	Onitsha TS	0.96655	0.36357	-1.0	-0.75
24	Benin TS	0.98743	0.25552	-1.44	-1.08
25	Ihovbor GS	1.0	0.25875	1.166	2.064
26	Adiabor TS	0.9962	0.46841	0	0
27	Omotosho GS	0.9813	0.15898	0	0
28	Ayede TS	0.95176	0.10603	-1.9	-1.51
29	Ikot Ekpene TS	0.9832	0.42017	-1.65	-0.74
30	Olorunsogo GS	0.97	0.08252	1.96	0.56235
31	Sakete TS	0.99021	0.00762	0	0
32	Akangba TS	0.98156	-0.00129	-2.03	-1.52
33	Ikeja West TS	0.9902	0.00763	-8.47	-6.35
34	Okearo TS	1.0116	0.00373	0	0
35	Aja TS	1.027	-0.00667	0	0
36	Egbin GS	1.033	0	-2.9189	15.2575
37	AES GS	1.033	0	0	0
38	Okpai GS	1.0	0.44061	4.66	1.5688
39	Sapele GS	0.99248	0.26593	0	0
40	PH Main TS	0.98741	0.42834	-2.8	-1.4
41	Delta GS	1.003	0.28729	3.41	1.2631
42	Aladja TS	0.99941	0.28015	0	0
43	Itu TS	0.98328	0.40233	-1.99	-0.91
44	Eket TS	0.9855	0.38962	-2.0	-1.47
45	Ibom GS	1.0	0.3899	0.305	2.045
46	Alaoji TS	0.98973	0.42836	0	0
47	Alaoji GS	1.0	0.5341	2.5	0.08151
48	Afam GS	1.0	0.44678	7.0	3.3177

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 (λmax) yielding 3.186. It is observed that buses 3(Kaduna), 4(Kano), 6(Makurdi), and 9(Jos) are found to be very weak buses with voltages well below 0.500 p.u. Validating the above result, voltage stability sensitivity factor (VSSF) was computed for all the load buses as shown in 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. It is noticed that buses 4 (Kano), 3(Kaduna), 6(Makurdi) and 9(Jos) have high sensitivity factor of 0.58444, 0.49778, 0.49047 and 0.459 respectively when there is no compensation. They are therefore adjudged the weakest buses for the installation of the FACTS devices. Figs. 5 and 6 depicts the voltage profile of CPF of the system without and with FACTS devices.

TABLE II. VOLTAGE PROFILE OF CONTINUATION POWER FLOW

BUS NO	BUS NAME	NO FACTS	WITH STATCOM	WITH SVC
1	Birnin Kebbi TS	0.9676	0.96957	0.97933
2	Kainji GS	1.0	1.0	1.0
3	**Kaduna TS**	**0.43002**	**0.47004**	**0.72238**
4	**Kano TS**	**0.33343**	**0.3837**	**0.66803**
5	Asaba TS	0.82752	0.84929	0.86349
6	**Makurdi TS**	**0.43409**	**0.46077**	**0.61912**
7	Alagbon TS	0.99598	0.99884	0.99926
8	Lekki TS	0.97027	0.97665	0.99538
9	**Jos TS**	**0.4318**	**0.46693**	**0.68484**
10	Shiroro GS	1.0	1.0	1.0
11	Jebba TS	0.95498	0.95576	0.97212
12	Jebba GS	1.0	1.0	1.0
13	Oshogbo TS	0.77706	0.77885	0.81703
14	Ganmo TS	0.837	0.8448	0.88878
15	Katampe TS	0.94446	0.94864	0.96148
16	Gwagwalada TS	0.95699	0.95889	0.98494
17	Lokoja TS	0.97699	0.98134	0.98812
18	Ajaokuta TS	0.99595	0.99608	0.99665
19	Geregu GS	1.0	1.0	1.0
20	Odukpani GS	1.0	1.0	1.0
21	New heaven TS	0.80222	0.81442	0.85459
22	Ugwuaji TS	0.79462	0.80809	0.83622
23	Onitsha TS	0.80738	0.81945	0.84884
24	Benin TS	0.90115	0.91883	0.93631
25	Ihovbor GS	1.0	1.0	1.0
26	Adiabor TS	0.97768	0.97943	0.98963
27	Omotosho GS	0.82387	0.83175	0.83727
28	Ayede TS	0.79416	0.80799	0.80999
29	Ikot Ekpene TS	0.90701	0.90962	0.87651
30	Olorunsogo GS	0.97	0.97	0.97
31	Sakete TS	0.88654	0.89008	0.89821
32	Akangba TS	0.85571	0.86726	0.86826
33	Ikeja West TS	0.88654	0.88988	0.89982
34	Okearo TS	0.95977	0.95985	0.96154
35	Aja TS	1.0132	1.012	1.0079
36	Egbin GS	1.033	1.033	1.033
37	AES GS	1.033	1.033	1.033
38	Okpai GS	1.0	1.0	1.0
39	Sapele GS	0.93351	0.94184	0.94214
40	PH Main TS	0.95901	0.96664	0.97824
41	Delta GS	1.003	1.003	1.003
42	Aladja TS	0.97915	0.98853	0.98892
43	Itu TS	0.93213	0.94767	0.95868
44	Eket TS	0.94608	0.94769	0.94901
45	Ibom GS	1.0	1.0	1.0
46	Alaoji TS	0.94967	0.95629	0.95815
47	Alaoji GS	1.0	1.0	1.0
48	Afam GS	1.0	1.0	1.0

TABLE III. VOLTAGE STABILITY FACTOR WITHOUT AND WITH FACTS DEVICES

BUS NO	BUS NAME	NO FACTS	WITH STATCOM	WITH SVC
1	Birnin Kebbi TS	0.02229	0.02032	0.01056
2	Kainji GS	0.0	0.0	0.0
3	**Kaduna TS**	**0.49778**	**0.45776**	**0.20542**
4	**Kano TS**	**0.58444**	**0.53417**	**0.24984**
5	Asaba TS	0.14505	0.12328	0.10908
6	**Makurdi TS**	**0.49047**	**0.46378**	**0.30544**
7	Alagbon TS	0.02562	0.02276	0.02234
8	Lekki TS	0.04343	0.03705	0.01832
9	**Jos TS**	**0.459**	**0.45987**	**0.24196**
10	Shiroro GS	0.0	0.0	0.0
11	Jebba TS	0.03589	0.03511	0.01875
12	Jebba GS	0.0	0.0	0.0
13	Oshogbo TS	0.18146	0.17967	0.14199
14	Ganmo TS	0.13169	0.12389	0.07991
15	Katampe TS	0.0384	0.03422	0.02138
16	Gwagwalada TS	0.02965	0.02775	0.0017
17	Lokoja TS	0.01515	0.0108	0.00402
18	Ajaokuta TS	0.00312	0.00299	0.00242
19	Geregu GS	0.0	0.0	0.0
20	Odukpani GS	0.0	0.0	0.0
21	New heaven TS	0.16336	0.15116	0.11099
22	Ugwuaji TS	0.17034	0.15687	0.12874
23	Onitsha TS	0.15917	0.1471	0.11771
24	Benin TS	0.08628	0.0686	0.05112
25	Ihovbor GS	0.0	0.0	0.0
26	Adiabor TS	0.01852	0.01677	0.00657
27	Omotosho GS	0.15743	0.14955	0.14403
28	Ayede TS	0.1576	0.14377	0.14177
29	Ikot Ekpene TS	0.07619	0.07358	0.10669
30	Olorunsogo GS	0.0	0.0	0.0
31	Sakete TS	0.10367	0.10013	0.092
32	Akangba TS	0.12585	0.1143	0.1133
33	Ikeja West TS	0.10366	0.10032	0.09038
34	Okearo TS	0.05183	0.05175	0.05006
35	Aja TS	0.0138	0.015	0.0191
36	Egbin GS	0.0	0.0	0.0
37	AES GS	0.0	0.0	0.0
38	Okpai GS	0.0	0.0	0.0
39	Sapele GS	0.05897	0.05064	0.05034
40	PH Main TS	0.0284	0.02077	0.00917
41	Delta GS	0.0	0.0	0.0
42	Aladja TS	0.02026	0.01088	0.01049
43	Itu TS	0.05115	0.03561	0.0246
44	Eket TS	0.03942	0.03781	0.03649
45	Ibom GS	0.0	0.0	0.0
46	Alaoji TS	0.04006	0.03344	0.03158
47	Alaoji GS	0.0	0.0	0.0
48	Afam GS	0.0	0.0	0.0

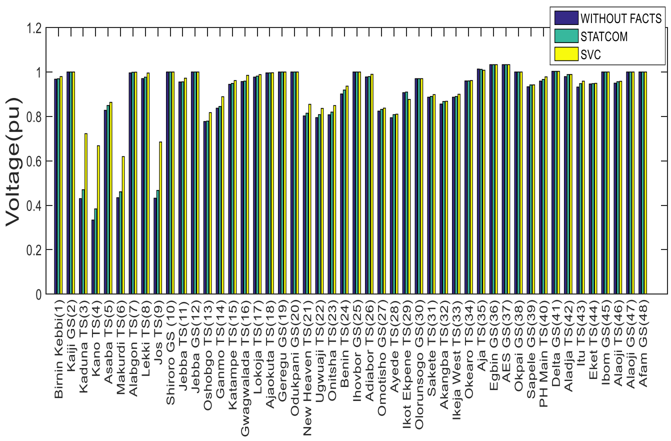

Fig. 5.Voltage profile of CPF without and with FACTS devices

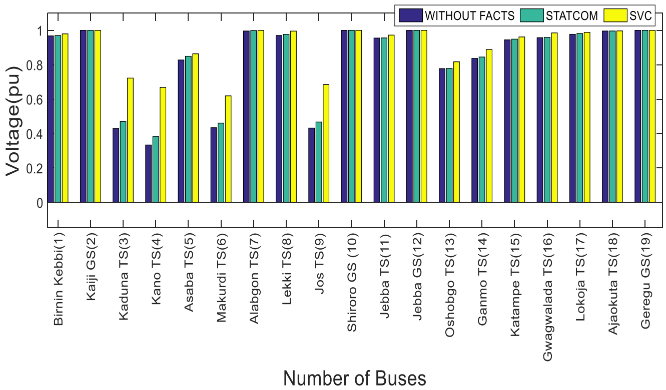

Fig. 6. A section of the voltage profile of CPF without and with FACTS devices

The P-V nose curves for the four weak buses illustrated in Fig. 7 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 3.186, causing an unstable power system and near-voltage collapse. The bus voltages are plotted with respect to the load parameter in Fig. 7. As the load parameter is increased, bus voltages of load buses decrease as it is expected. When Fig. 7 is examined in conjunction with Table 2, it can be seen that the most reduction in bus voltages occurs in Kano bus. It can be concluded from this result that Kano bus is the weakest bus in this sample system. The increase in loads with the insertion of load parameter causes generators to reach their generating capacities and forces to exceed limits. Since it is not possible to exceed these limits, sample system loses its voltage stability at the critical point where the load parameter value is 3.186 as seen in Fig. 7. The critical point can be taken as voltage collapse point. System becomes voltage unstable beyond this point and voltage decreases rapidly due to requirement of reactive power in the system.

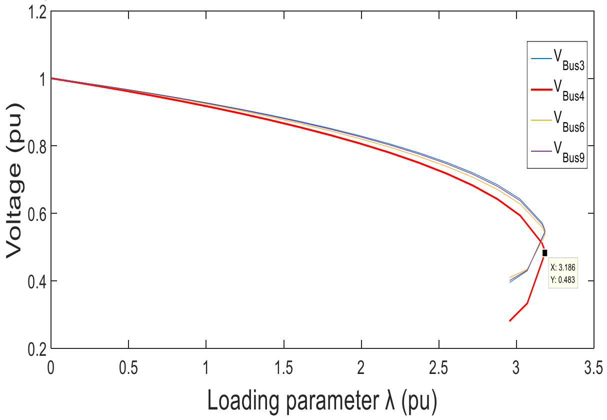

Fig. 7. PV curve for system without FACTS devices

C. *Power Flow with FACTS Controllers*

Two FACTS devices are placed at the weak buses one after the other in the Nigerian 48-bus system. For STATCOM, power flow simulation result of the system which lasted for 0.234s converges at 2.0188×10^{-10}p.u. after 5 iterations. With SVC also 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. Figs. 8 and 9 shows the P-V curves after the application of STATCOM and SVC to the test system respectively as obtained in continuation power flows. It is obviously seen that maximum loading point increases from 3.186 to 3.233 in the case of the application of STATCOM while in the case of optimally placing SVC in the system, the maximum loading point increases to 3.796. This shows that application of FACTS devices to the test system enhances the loadability of the power system by increasing the voltage stability limits and thereby preventing voltage collapse. Distinctively, it is also seen that of the two FACTS devices, SVC enhances power system loadability better than STATCOM as depicted in Fig. 10.

In addition, application of FACTS devices on the weak buses improves the voltage stability limit not only in the weak buses alone but also in other buses as depicted in Table 3 where it is evident in the reduction of the sensitivity factors.

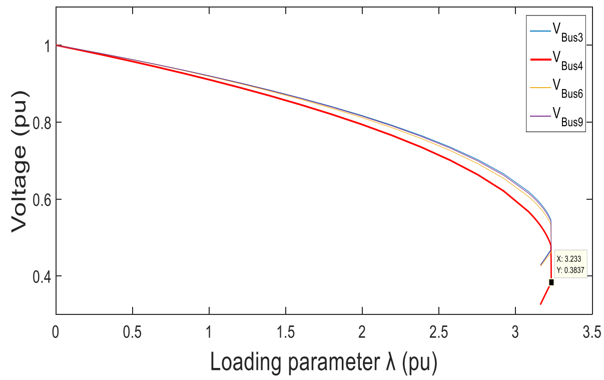

Fig. 8. PV curve for system with STATCOM

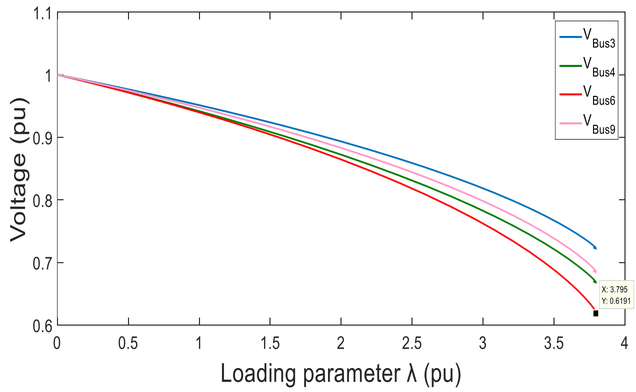

Fig. 9. PV curve for system with SVC

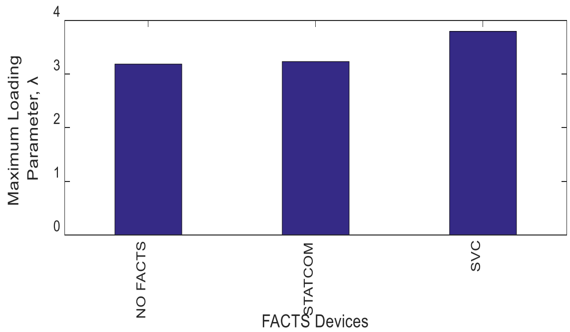

Fig. 10. Maximum loading parameters of system without and with FACTS devices

VI. CONCLUSION

Effects of shunt FACTS devices for the enhancement of power system loadability in the Nigerian 48- bus system has been investigated with the optimal installations of SVC and STATCOM devices in the test system. Simulation results showed that the FACTS devices exhibited sterling power systems loadability enhancement capabilities as is obviously seen that maximum loading point increases from 3.186 to 3.233 in the case of the application of

STATCOM, while in the case of optimally placing SVC in the system, the maximum loading point increases to 3.796. This shows that application of FACTS devices to the test system enhances the loadability of the power system by increasing the voltage stability limits and thereby preventing voltage collapse. The above results also identified SVC as the better device for the enhancement of power system loadability.

REFERENCES

[1] K. Tlijani, T. Guesmi, and H.H. Abdallah, "Optimal Allocation of Multi-Type FACTS Devices for Security and System Loadability Enhancement", International Review on Modelling and Simulation (IREMOS), vol. 6, pp. 1541-1549, 2013.

[2] A.K. Mohanty, and A.K. Barik, "Power System Stability Improvement Using FACTS Devices", International Journal of Modern Engineering Research (IJMER), vol. 1, pp. 666-672, 2019.

[3] P. Vanitha, and K. Niramathy, "Improvement of Transmission Line Loadability using Multi Type FACTS Devices", International Journal of Electrical and Power Engineering, vol. 13, pp. 56-60, 2019.

[4] I.E. Nkan, O.I. Okoro, P.I. Obi, C.C. Awah, and U.B. Akuru, "Application of FACTS Devices in a Multi-Machine Power System Network for Transient Stability Enhancement: A Case Study of the Nigerian 330 kV, 48-Bus System", IEEE Xplore, pp. 1-9, 2019.

[5] I.E. Nkan, O.I. Okoro, C.C. Awah, and U.B. Akuru, "Investigating the Steady-State Stability of the Nigerian 48-Bus Systems using FACTS Devices", Nigerian Journal of Technology (NIJOTECH), vol. 38, pp. 732-743, 2019.

[6] Y. Weng, R. Rajagopal, and B. Zhang, "A Geometric Analysis of Power System Loadability Regions", IEEE Transaction on Smart Grid, pp. 1949-3053, 2019.

[7] M.K. Saifullah, M.M. Kabir, and K.R. Islam, "Improvement of Voltage Stability and Loadability of Power System Employing the Placement of Unified Power Flow controller using Artificial Neural Network", International Journal of Electrical and Computer Engineering (IJECE), vol. 13, pp. 4868-4877, 2023.

[8] M. Moghavvemi, and M.O. Faruque, "Effects of FACTS Devices on Static Voltage Stability", IEEE Power and Energy Magazine, 2000.

[9] M. Zahid, J.L.Y. Chen, X. Duan, Q. Lei, W. Bo, G. Mohy-ud-din, and A. Waqar, "New Approach for Optimal Location and parameters Setting of UPFC for Enhancing Power Systems Stability under Contingency Analysis", Energies, pp. 17-38, 2017.

[10] P. Kotsampopoulos, P. Georgilakis, D.T. Lagos, V. Kleftakis, and N. Hatziargyriou, "FACTS Providing Grid Services: Application and Testing", Energies, vol. 12, pp. 2554, 2019.

[11] S. Sakthivel, D. Mary, R. Vetrivel, and S.V. Kannan, "Optimal Location of SVC for Voltage Stability Enhancement under Contingency Condition Through PSO Algorithm", International Journal of Computer Application, vol. 20, pp. 975-8887, 2011

[12] A.E. Amgad, H. Youssef, M.M. El-Metwally, and Z. Osman, "Maximum Loadability of Power Systems using Hybrid Particle Swarm Optimization", Electric Power Systems Research, vol. 76, pp. 485-492, 2006.

[13] R. Medeswaran, and N. Kamaraj, "Power System Loadability Improvement by Optimal Allocation of FACTS Devices using Real Coded Genetic Algoritm", Journal of Theoretical and Applied Information Technology, vol. 65, pp. 1817-3195, 2014.

[14] I.E. Nkan, E.E. Okpo, U.B. Akuru, and O.I. Okoro, "Contingency Analysis for Improved Power System Stability of the Nigerian 330 kV, 48-Bus System using Series FACTS Controllers", AIUE Congress 2020: International Conference on Use of Energy.

[15] I.E. Nkan, O.I. Okoro, C.C. Awah, and U.B. Akuru, "Investigating the Dynamic Stability of the Nigerian 48-Bus Systems for Improved System Performance using FACTS", 27th Domestic Use of Energy Conference, pp. 34-42, 2019.

[16] K.G. Damor, D.M. Patel, V. Agrawal, and H.G. Patel, "Improving Power System Transient Stability by using FACTS Devices", International Journal of Engineering Research and Technology (IJERT), vol. 3, 2014.

[17] I. Shrivastava, and H.K. Lade, "Power System Transient Stability Transmission Line Improvement with STATCOM Positioning", International Journal of Innovative Research in Science, Engineering and Technology, vol. 6, 2017.

[18] K. Sreerenjini, C. Paulose, and S. Nizamoni, "Increasing the Loadability of Power System Network using DSTATCOM", International Journal of Engineering Research and Technology (IJERT), vol. 8, 2019.

[19] A.Y. Abdelaziz, and M.A. Attia, "TCSC and SVC Optimal Location to Improve the Performance of Power System with Wind Penetration", Energy Trend in Electrical Electronics and Instrumentation Engineering: An international Journal (EEIEJ), vol. 1, 2014.

[20] I.E. Nkan, E.E. Okpo, and O.I. Okoro, "Multi-Type FACTS Controllers for Power System Compensation: A Case Study of the Nigerian 48-Bus, 330 kV System", Nigerian journal of Technological Development, vol. 18, pp. 63-69, 2021.

[21] B. Bhattacharyya, and S. Kumar, "Loadability Enhancement with FACTS Devices using Gravitational Search Algorithm", Electrical Power and Energy System, vol. 78, pp. 470-479, 2016.

[22] S. Sreedharan, T. Joseph, S. Joseph, C.V. Chandran, J. Vishnu, and D.P. Vipin, "Power System

Loading Margin Enhancement by Optimal STATCOM Integration - A Case Study", ELSEVIER, vol. 81, 2019.

[23] A.A. Ahmad, and R. Sirjani, "Optimal Placement and Sizing of Multi-type FACTS Devices in Power Systems using Metaheuristic Optimization Technique: An Updated Review", Ain Shams Engineering Journal, pp. 2090-4479, 2019.

[24] R. Sirjani, M. Azah, and H. Shareef, "Optimal Placement and Sizing of Shunt FACTS Devices in Power Systems Using Heuristic Optimization Techniques: A Comprehensive Survey", ResearchGate, 2012.

[25] K.S.L. Lavanya, and S.P. Rani, "A review on Optimal Location and Parameter Settings of FACTS Devices in Power Systems Era: Models, Methods", International Journal for Modern Trends in Science and Technology, vol. 2, 2016.

[26] N.S. Chauhan, N.V. Srikanth, and V.B. Kumar, "Optimal Placement of SVC to Minimize Loss and Improve Voltage Profile under Power System Contingency using Genetic Algoritm", SARC-IRF International Conference, New Deihi, India, 2014.

[27] M.B. Keskin, "Continuation Power Flow and Voltage Stability in Power Systems", A Thesis Submitted to The Graduate School of Natural and Applied Science of Middle East Technical University, pp. 15-17, 2007.

[28] E.C. Umoh, "Top of the Hour Maximum Power Flow of the Grid 330 kV Daily Load Flow", National Control Centre, Oshogbo (Transmission Company of Nigeria), 2022.

[29] M. Federico, "Documentation for Power System Analysis Toolbox version 2.0.0. Castilla-La Mancha, Ciudad Real, Spain, 2008.

[30] T.R. Ayodele, A.S. Ogunjuyigbe, and O.O. Oladele, "Improving the Transient Stability of Nigerian 330 kV Transmission Network using Static Var Compensation part 1: The Base Study", 2016.