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Enhancement of voltage stability in an interconnected network using unified power flow controller

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ABSTRACT

In this paper, the optimal placement of Unified Power Flow Controllers (UPFC) in a large-scale transmission network in order to improve the loadability margin was considered. In other to achieve this aim, the Line Stability Factor (LQP) as a technique for the optimal location of UPFC in the IEEE 14-bus network and 56-bus Nigerian national grid was adopted. The power injection model for the UPFC was employed to secure improvements in the loading margin of the IEEE 14-bus network and 56-bus Nigerian national grid system. Continuation power flow was used to assess the effect of UPFC on the loadability margin. Steady-state simulations using Power System Analysis Toolbox (PSAT) on MATLAB was applied to determine the effectiveness of placing UPFC between bus 13 and bus 14 in the IEEE 14-bus network and between bus 44 (Ikot-Ekpene) and bus 56 (Odukpani) in the 56-bus Nigerian national grid system. The results showed that the loadability margin increased by 8.52 % after UPFC was optimally placed in the IEEE 14-bus network and increased by 195.5 % after UPFC was optimally placed in the 56-bus Nigerian national grid system. Thus, these enhance the voltage stability of both network and utilizing the network efficiently.

1. Introduction

The economic development and growth of any nation requires electrical energy. The electric power sector in Nigeria, which consists of three sub sector such as the generation, transmission and distribution is currently characterized by frequent power shortages and poor quality of power supply [1]. Nigeria as a developing nation with an increasing population of over one hundred and seventy million [2] has rising energy demand but still, the supply of electricity is relatively stagnant, the expansion of generation facilities and transmission lines has been severely limited due to insufficient resources and environmental factors. This gives a cause for concern as it adds to the constant power failure in Nigeria, since a lot of demands have been placed on the transmission network by the constant addition of load due to the increase in the number of consumers. The unreliable supply of electric power in Nigeria has been the main source of complaint by electricity consumers. This has led to a huge capital investment by large consumers in alternative power standby sources and also financial losses to the power industry for energy not supplied [3].

The aforementioned problems therefore call for a widespread evaluation to assess the current performance of Nigerian power system, and to look into the efficiency of new

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devices for system reliability and stability enhancements [4]. In a long-term, such setbacks have been resolved by the building of new transmission lines and power plants, a solution that takes a long time to construct, expensive to implement and also brings about resistance from pressure groups. It is necessary for an alternative solution to such operational drawbacks to depend on the improvement of existing transmission lines by the incorporation of the state-of-the-art power electronics equipment to the lines. This new technological device is called FACTS – an acronym for Flexible Alternating Current transmission system.

FACTS is well-known to give higher controllability and better utilization of the existing power system capabilities using high speed and reliable power electronic devices. FACTS is a new device originating from recent innovative technology in power electronics that promises to improve the flexibility and security of existing power transmission systems while retaining the operating margins, which is necessary for power system stability [3]. This brings about, more power reaching the consumers with a little effect on the ecosystem and at a lower investment cost when compared to the alternatives of building new transmission lines and generation stations [5]. The effect of FACTS devices is attained via series compensation, switched or controlled shunt compensation or phase shift control. The FACTS device works electrically as fast current, voltage or impedance controllers. The power electronic allows very short reaction time down to far below one second [6]. However, FACTS devices when used do not stop the occurrence of faults in the power system, rather they have the ability to stabilize the remaining and healthy part of the system while the faulty part is being disconnected [4].

Voltage collapses are highly dangerous anytime they occur. It does not occur frequently in developed countries despite their large and complex networks but it occurs more frequently on the power networks of most developing countries including Nigeria. The Nigerian interconnected power system delivery of electrical energy to various consumers has been very unsatisfactory. These operational problems amongst others have motivated this research work to offer alternative solutions to eliminate these problems on the Nigerian inter-connected power system, thereby enhancing voltage stability and improving the reliability of the network.

2. Review of Related Literature

Efficiency enhancement of Nigeria 330 kV network using FACTS devices was looked into in [7]. The study discovered that with the proper placement of FACTS devices, using genetic algorithm, losses were reduced compared to when the network had no such device. Moreover, fundamental transmission line parameters such as voltage magnitude, line impedance, phase angles were regulated to function within the maximum tolerable power carrying capacity of the lines. However, the literature used the old Nigerian Network for its analysis.

In [5], voltage stability trends as well as the continuation power flow technique utilized in the analysis of voltage stability in power systems were presented. The technique was applied to a 14-bus sample test system. Voltage magnitude and bus voltage versus load parameter curves were obtained for several scenarios by using PSAT Software. The effect of compensation was examined by adding shunt capacitors in different per unit values to the bus defined in sample system. It was observed that adding shunt capacitor to a bus enhances the voltage stability of the whole bus in the sample system. However, no optimization was carried out for the placement of shunt capacitor.

In [8], a comparison of the enhancement of voltage stability and loss reduction capabilities of static synchronous compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) FACTS controllers in a 28-bus Nigerian network was considered. Power flow analysis was carried out using MATLAB and the buses with the low voltages identified. Both STATCOM and SSSC FACTS controller's devices gave satisfactory result, raising the magnitude of the voltage at the buses where devices were applied and at the other load buses sufficiently maintaining the voltage at 1.0 p.u., thereby reinforcing the grid. However, no optimization was carried out for the placement of FACTS devices. Also, the old Nigerian network was used for the analysis.

Static var compensator was utilized in [9], voltage stability improvement of a power system. The paper described the basic structure of thyristor-controlled reactor fixed capacitor source voltage control (SVC) and simulations were done in Simulink/MATLAB environment. The result showed that SVC could be utilized to enhance the voltage stability of power systems. However, no optimization was carried out for the placement of SVC device and the old Nigerian network was used for the analysis.

Power flow control in the Nigeria 330 kV integrated power network using unified power flow controller (UPFC) was investigated in [10]. It was found that when the UPFC was connected to the weak buses, there was improvement in their voltage profile; all within the allowable tolerable voltage limit of 0.95 – 1.05 p.u. However, no optimization was carried out for the placement of UPFC device.

The enhancement of voltage profile for the Nigeria north east 330 kV power network using STATCOM was discussed in [11]. STATCOM was optimally placed in the network by utilizing ant colony technique. The research work successfully applied the basic structure of STATCOM operating under different voltage control. Simulations carried out established that the STATCOM is capable of providing a swift voltage support to avoid the possibility of voltage sagging or system collapse of the Nigerian 330 kV network especially during fault conditions. Nevertheless, the study used only the Nigerian North East network for its analysis.

The efficiency of the optimal placement of UPFC for improving the security of power systems under steady state contingencies was examined in [12]. Differential Evolution (DE) was effectively utilized to produce optimal location of UPFC device on the IEEE 14-bus test system. Installing UPFC at optimal location considerably increased the bus voltage profile. To further justify the global acceptability of the proposed approach, it should be implemented on a higher network. In [13], the use of genetic algorithm was employed to find the location of Thyristor Controlled Series Compensator (TCSC) on the Nigerian 330 kV grid network at the appropriate line where its effectiveness is prominently observed on the network. The results indicated that the transmission power loss reduced from 2.1 % (when TCSC was not installed) to 1.5 %. Also, the voltage stability improved when the TCSC was installed. Again, as with previous studies, the study used the old Nigerian network for its analysis.

Optimal location and sizing of reactive power source for voltage improvement using power flow program implemented in MATLAB environment was presented in [14]. The Nigerian 330 kV, 24-bus grid system was utilized as a case study. Newton-Raphson algorithm was utilized to carry out the power flow analysis with and without shunt compensation. Buses with voltage magnitude less than 0.95 p.u., were identified and a calculated amount of reactive power was injected to raise the voltage within acceptable limit of 0.95 – 1.05 p.u. However, the optimal placement of the shunt capacitor was done using power flow analysis and the old Nigerian network was also considered for its analysis.

In the study in [15], it is discussed that the existing Nigerian power grid is being under-utilized because of the radial nature of the network as well as lack of voltage control devices. Hence, there is need for investment into expanding and reinforcement of the power grid. It was advised that the grid should be reinforced with voltage control devices mainly in the form of FACTS devices placed at strategic points on the grid to control voltage sags as well as to enhance the power handling capacity of the grid thereby increasing utilization of the grid [15].

A review of the application of FACTS devices on Nigerian 330 kV Transmission system was carried out in [16]. The assessment showed that the incorporation of FACTS devices in the Nigerian grid system will greatly enhance the voltage profile of the transmission system. However, the study showed that little work has been done on the incorporation of FACTS devices on the Nigerian transmission system with the literature available. Also, the optimal placement of these FACTS devices was not discussed. An attempt to identify causes of system collapse on an island mode in the Nigeria grid was carried out in [17] and contingencies analysis in [18]. Low voltage profile was experienced at Benin bus [17] upon simulation of faults in steady and dynamic states while capacitors were placed in the network in [18] for systems efficiency.

From the literature reviewed, it can be observed that a lot of attention has been given to the application of FACTS device on transmission networks. However, some of the literature did not optimally place this FACTS device on the network while other used the old Nigerian network for the analysis. This gap in the literature has motivated the current research with a view to enhancing voltage stability on the latest Nigerian interconnected network.

3. Methodology

Fig. 1 shows the power flow between two nodes in a typical power system network, where P and Q are the active and reactive power, respectively.

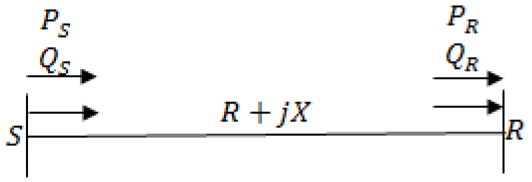

Fig. 1 Power flow from node S to node R [13].

The IEEE 14-bus test system comprises 5 generator buses (PV), 9 load buses (PQ) and 20 interconnected lines. The bus data and line data are used for the power flow analysis. Consequently, the Nigerian 56-bus test system consists of 15 generator buses (PV), 36 load buses (PQ) and 53 interconnected lines. In this paper, the 56-bus Nigerian network grid has been used to test the effectiveness in using UPFC for voltage stability enhancement. The Line Stability Factor (LQP) is derived in [19] as follows:

$$\text{LQP} = 4\left(\frac{X}{V_S^2}\right)\left(Q_R + \frac{XP_S^2}{V_S^2}\right). \qquad (1)$$

Equation (1) was calculated for all the lines in the system and the line with the highest stability factor value closest to 1.0 indicate the closeness to voltage collapse. The simplified Jacobian matrix equation is presented in equation (2) in accordance with [20] used to solve for the load flow of the lines.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & T \\ L & M \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}. \qquad (2)$$

Given that: ΔP and ΔQ are mismatch vectors; H, T, M and L are elements of the nodal admittance matrix (Y_{bus}); while $\Delta\delta$ and $\Delta|V|$ are elements of the nodal impedance matrix (V_{bus}).

The derived injected power model can be incorporated into a general Newton Raphson power flow algorithm by modifying the related elements in the normal Jacobian matrix as shown in equation (3) and the corresponding power mismatch equations as well.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & T \\ L & M \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta/v/ \end{bmatrix}. \qquad (3)$$

The corresponding power mismatches at buses i and j are modified as follows:

$$\Delta P_i = P_{iGen} - P_{iLoad} - (P_{iCalc} + P_{iUPFC}); \qquad (4)$$

$$\Delta P_j = P_{jGen} - P_{jLoad} - \left(P_{jCalc} + P_{jUPFC}\right); \qquad (5)$$

$$\Delta Q_i = Q_{iGen} - Q_{iLoad} - (Q_{iCalc} + Q_{iUPFC}); \qquad (6)$$

$$\Delta Q_j = Q_{jGen} - Q_{jLoad} - \left(Q_{jCalc} + Q_{jUPFC}\right); \qquad (7)$$

where, P_i, Q_i and P_j, Q_j are the base case real and reactive load power of the load and generator, calculated and UPFC placement at buses i and j respectively.

Fig. 2 is a flow chart showing the power flow process when incorporated with UPFC while Fig. 3 presents the approach taken to reach the LQP. The optimal location for the placement of UPFC device in networks was achieved using line stability factor method. The algorithm was implemented on MATLAB R2016a. The IEEE 14-bus network was investigated for optimal placement of UPFC by the use of line stability factor method. With respect to the IEEE 14-bus system, simulations were carried out in 1.777 seconds that identified 4 most susceptible lines, which qualifies for UPFC installations. The identifications of these lines were based on the closeness of their LQP value to 1. The value closest to 1 indicates the closeness to voltage collapse.

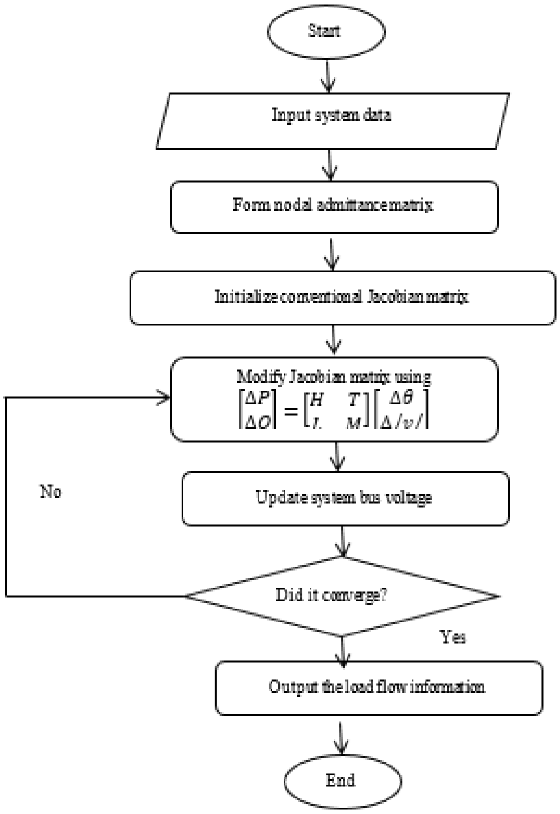

Fig. 2 Flow chart of power flow incorporated with UPFC.

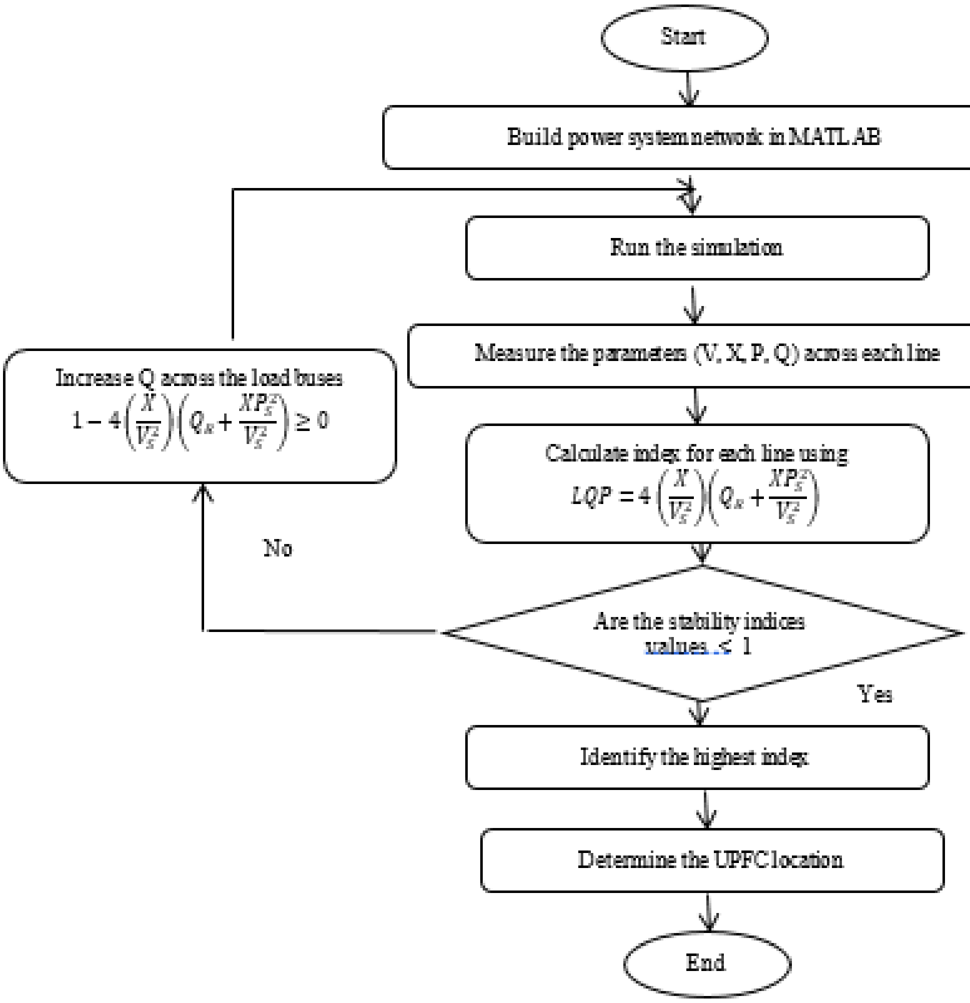

Fig. 3 Flow chart of LQP approach

4. Results and Discussion

The simulation results of line stability factor selected above for optimal placements of UPFC device with respect to networks of IEEE 14-bus and 56-bus Nigerian grid test systems are presented in Figs. 4 and 5. Figs. 6 and 7 show the bar chart of the LQP for the IEEE 14 bus and the Nigerian 56 bus network. The results obtained from the simulation and optimal placement of the UPFC device has been obtained and interpreted graphically on the MATLAB R2016a environment.

Fig. 6 depicts the bar chart of the LQP results of the IEEE 14-bus network. In this result, line 9 between bus 13 – bus 14 was identified as the weakest line, due to the fact that it's LQP value is closest to one. Hence, line 9 between bus 13 – bus 14 was considered as the optimal location for the placement of UPFC device. UPFC device was placed in line 9 between bus 13 – bus 14 and simulation was done in 1.777 seconds.

Fig. 7 depicts the bar chart of the LQP result. In this result, line 49 between bus 44 (Ikot-Ekpene) – bus 56 (Odukpani) was seen as the weakest line, due to the fact that it's LQP value is closest to 1. Line 49 between bus 44 (Ikot-Ekpene) – bus 56 (Odukpani) was considered as the optimal location for the placement of UPFC device. Simulation was done in 0.301 seconds; there was improvement in the bus voltage and in the loading margin at Odukpani bus. Also, improvements are observed in the bus voltage as well as in the loading margin at buses 13 and 14 as shown in Figs. 8 and 9.

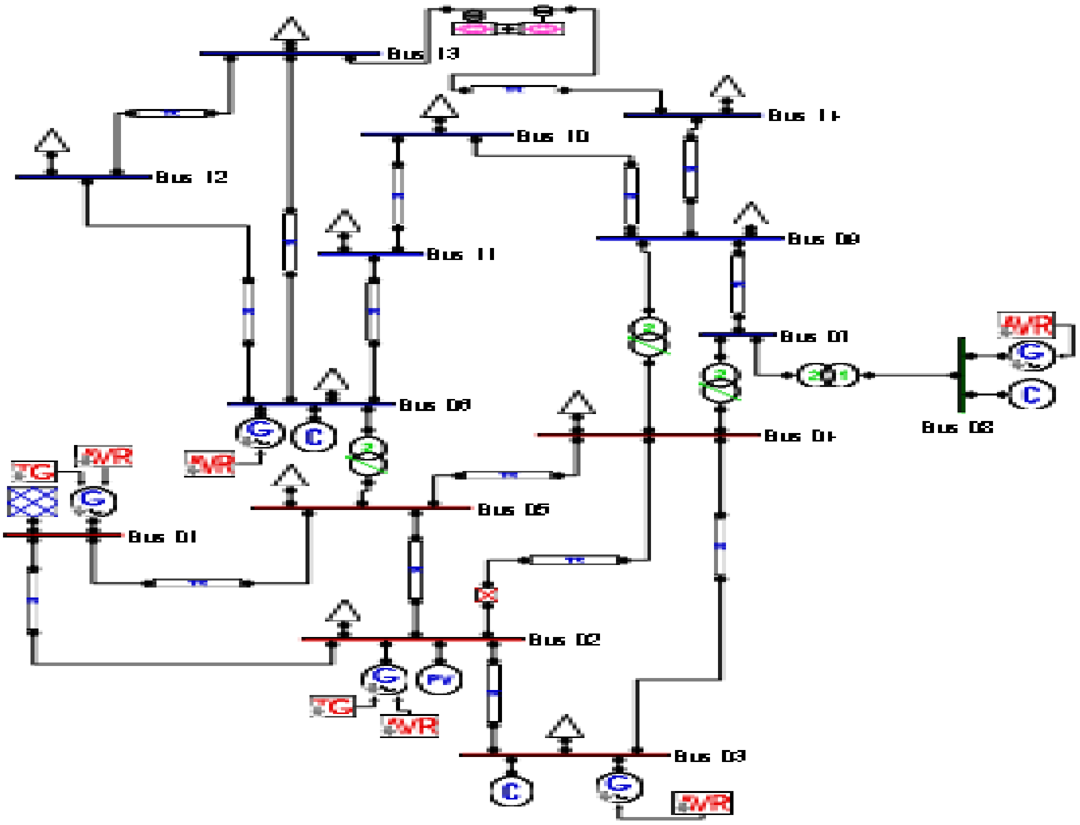

Fig. 4 PSAT model of IEEE 14-bus network with UPFC.

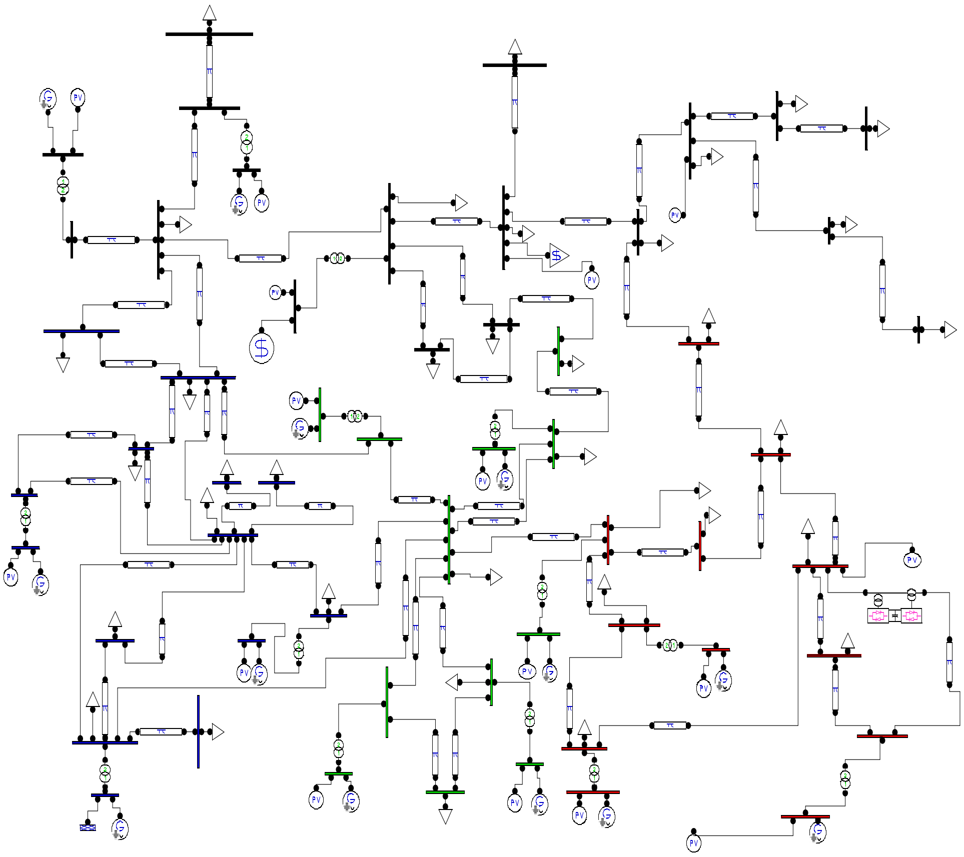

Fig. 5 PSAT model of 56-bus Nigerian national grid with UPFC.

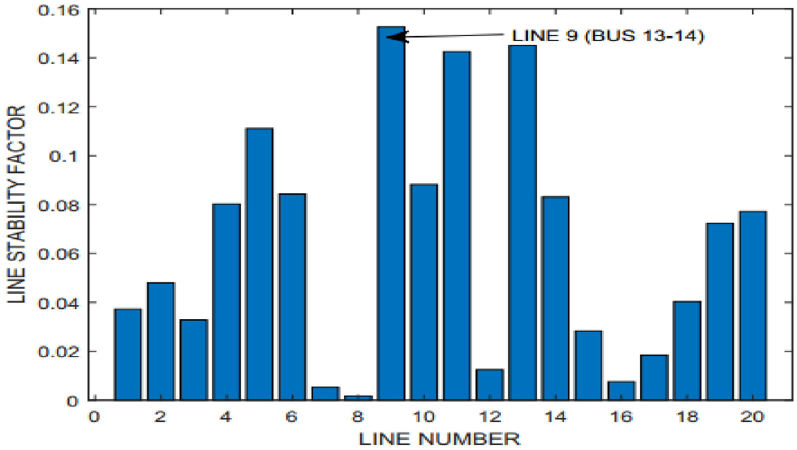

Fig. 6 The bar chart of LQP versus line number for IEEE 14-bus network.

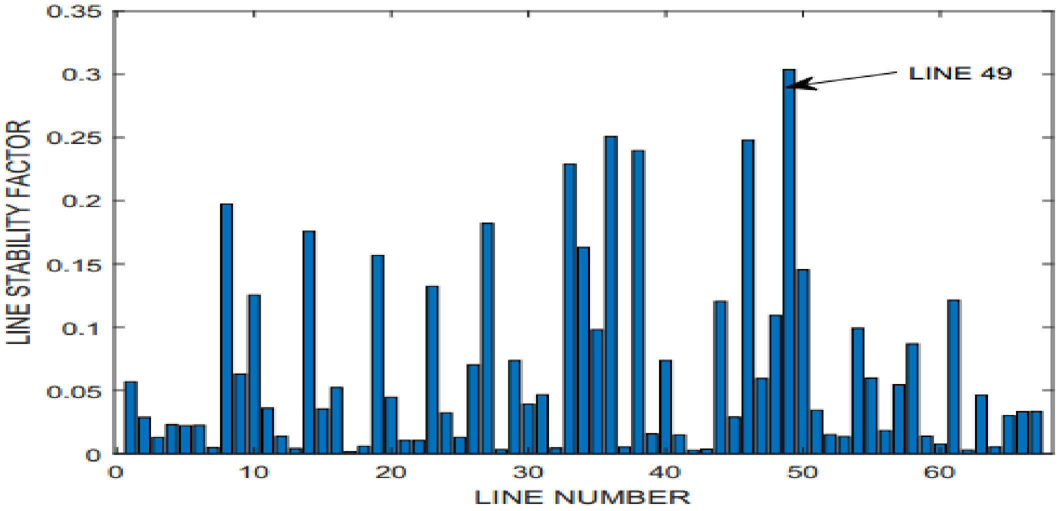

Fig. 7 The bar chart of LQP versus line number for 56-bus Nigerian grid.

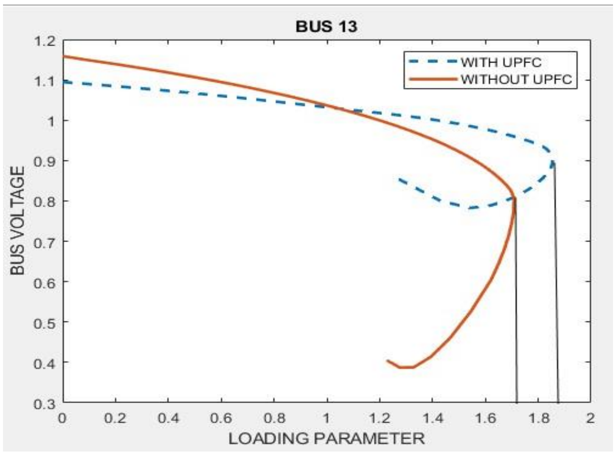

Fig. 8 Voltage profile for bus 13.

It is observed from Table 1 that the most susceptible lines (lines 9, 13, 11 and 5) radiated from bus 13 to bus 14, from bus 4 to bus 3, from bus 2 to bus 1 and from bus 11 to bus 6 respectively. Therefore, the suggestion for the optimal location for placement of the UPFC would be along line 9, i.e., bus 13 – 14.

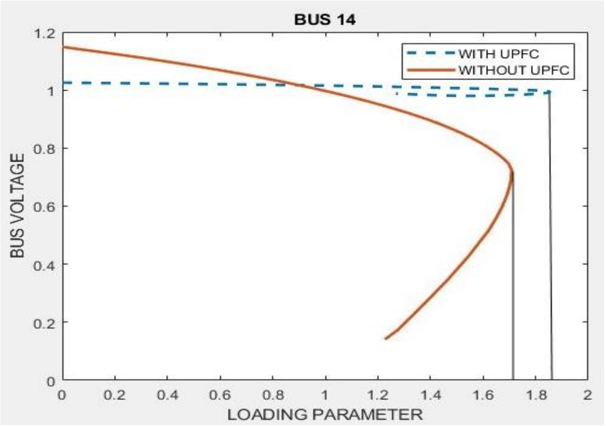

Fig. 9 Voltage profile for bus 14

The PSAT model of 56-bus Nigerian national grid with and without UPFC is shown in Figs. 10 and 11 respectively. The line stability factor calculated indicated line 49, between bus 44 (Ikot-Ekpene) - bus 56 (Odukpani) as the weakest line in the network due to the fact that it's LQP value is closest to 1. Hence, line

49 was chosen as the optimal location for the UPFC device. The loading profile for Odukpani bus (bus 56) with and without UPFC is presented in Fig. 10 and Table 2.

Table 1 LQP result for IEEE 14-bus network.

Line no.	From bus	To bus	Voltage stability index LQP
1	5	2	0.03723
2	12	6	0.04800
3	13	12	0.03288
4	13	6	0.08023
5	11	6	0.11108
6	10	11	0.08427
7	10	9	0.00533
8	14	9	0.00178
9	13	14	0.15266
10	9	7	0.08821
11	2	1	0.14252
12	2	3	0.01248
13	4	3	0.14499
14	5	1	0.08308
15	4	5	0.02829
16	4	2	0.00762
17	6	5	0.01843
18	9	4	0.04032
19	7	4	0.07230
20	7	8	0.07712

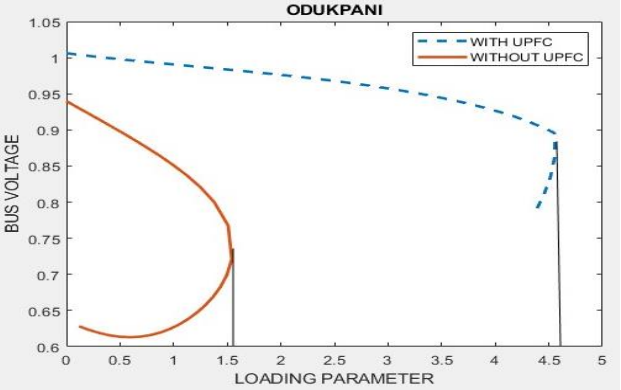

Fig. 10 Loading profile for bus 56 (Odukpani).

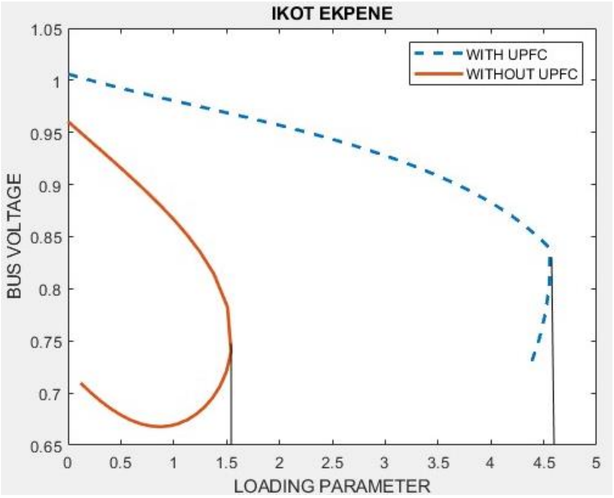

Fig. 11 Loading profile for bus 44 (Ikot Ekpene).

Table 2 LQP result for 56-bus Nigerian grid.

Line no.	From bus	To bus	Voltage stability index LQP
1	12	1	0.05681
2	3	12	0.02865
3	15	23	0.01289
4	3	30	0.02307
5	10	4	0.02224
6	10	13	0.02249
7	14	13	0.00476
8	2	11	0.19739
9	6	17	0.06288
10	19	6	0.12533
11	24	2	0.03591
12	25	5	0.01360
13	24	5	0.00406
14	9	29	0.17578
15	33	14	0.03538
16	34	33	0.05227
17	30	32	0.00141
18	28	3	0.00582
19	36	37	0.15673
20	32	36	0.04459
21	29	41	0.01042
22	42	17	0.01044
23	43	13	0.13231
24	22	19	0.03231
25	2	48	0.01293
26	7	48	0.07025
27	50	2	0.18203
28	30	10	0.00321
29	2	25	0.07360
30	51	7	0.03922
31	51	3	0.04665
32	15	54	0.00437
33	2	15	0.22900
34	29	50	0.16311
35	30	36	0.09802
36	7	29	0.25073
37	29	8	0.00522
38	42	44	0.23956
39	43	42	0.01570
40	3	7	0.07358
41	45	44	0.01492
42	52	14	0.00276
43	52	53	0.00356
44	7	9	0.12041
45	9	55	0.02881
46	29	55	0.24796
47	56	45	0.05943
48	22	44	0.10939
49	44	56	0.30368
50	2	6	0.14534
51	37	11	0.03440
52	15	29	0.01511
53	29	54	0.01335
54	16	15	0.09910
55	39	19	0.05981
56	40	55	0.01816
57	46	56	0.05454
58	47	48	0.08676
59	49	50	0.01375
60	26	12	0.00754
61	27	28	0.12140
62	21	22	0.00292
63	31	30	0.04632
64	20	24	0.00527
65	18	25	0.03002
66	35	11	0.03323
67	38	6	0.03337

Table 3 Loadability margin for the IEEE 14-bus network.

Number of UPFC	Location	Base case loadability margin (λ_0) without UPFC	Maximum loadability margin (λ_{max}) with UPFC	Loadability margin improvement $(LMI) = \frac{(\lambda_{max} - \lambda_0)}{\lambda_0} \times 100\%$
1	Line 9	1.7086	1.8542	8.52%

Table 4 Loadability margin for the 56-bus Nigerian national grid.

Number of UPFC	Location	Base case loadability margin (λ_0) without UPFC	Maximum loadability margin (λ_{max}) with UPFC	Loadability margin improvement $(LMI) = \frac{(\lambda_{max} - \lambda_0)}{\lambda_0} \times 100\%$
1	Line 49	1.5424	4.5583	195.5%

The loading margin increased from 1.7086 to 1.8542 which returned an increase of 8.52 % for the system maximum voltage stability limit as presented in Table 3. Consequently, the 56-bus Nigerian national grid system has been studied. Other buses were also looked into and presented based on their geographical zones, there were also improvement in these buses with their loading margin increasing to 4.5583 from 1.5424, which returned an increase of 195.5 % as presented in Table 4 for the system maximum voltage stability limit. This means that when UPFC device is added to the system, the system can be loaded more before its critical point is reached.

5. Conclusion

Voltage instability of power system disturbances in Nigeria has led to this research work in order to meliorate the situation of the power system. A review of existing literature on FACTS devices and various ways of optimal location for the placement of this FACTS devices showed that the use of FACTS devices could bring stability to the Nigerian national grid if properly placed in the network. Also, the effect of UPFC when placed in the electric power networks was noticed in terms of shifting in the loading margin, which improved voltage stability in the power system.

This paper has presented the voltage stability enhancement in interconnected power systems using FACTS devices. A case study of 56-bus Nigerian national grid system was taken into consideration. The line stability factor was used to find the optimum position for the placement of UPFC. This method was also applied on IEEE 14-bus network (Standard bus system), line 9 between bus 13 and bus 14 was found to be the optimum location for the placement of UPFC device. The loadability margin improved by 8.52 % after UPFC device was optimally placed in the system. The line stability factor method was applied to the 56-bus Nigerian network grid system, line 49 between bus 44 (Ikot-Ekpene) and bus 56 (Odukpani) was found to be the optimum location for the placement of UPFC device. This was simulated on MATLAB environment using PSAT toolbox and the results obtained showed an improvement in the loadability margin by 195.5 % when UPFC was optimally placed in the system. In conclusion, with the results achieved in this study, if implemented, the following can be achieved, the:

(a) voltage profile will be significantly improved for qualitative power delivery;
(b) lines will be able to be loaded more before voltage collapse point is reached; and
(c) Nigerian network grid system will be better utilized.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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