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Voltage Profile Improvement of the Nigerian 330-kV Transmission Network using STATCOM

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Abstract—*This paper aims to investigate the effect of STATCOM on the Nigerian 330kV transmission network. The Newton-Raphson iteration algorithm was used to solve the non-linear problem, which was modelled using MATLAB Software. The result shows that some of the buses fell outside the statutory limit of 0.95pu $\leq V \leq$ 1.05pu, which includes: 16 (Kano, 0.8721pu), 17 (Kaduna, 0.9046pu), 18 (Jos, 0.8731pu), 19 (Gombe, 0.8735pu), 20 (Yola, 0.8580) and 21 (Katampe, 0.9167pu). On incorporating STATCOM on these weak buses. The voltage magnitude was improved as follows: 16 (Kano, 1.0000pu), 17 (Kaduna, 0.9678), 18 (Jos, 1.0000pu), 19 (Gombe, 1.0188pu), 20 (Yola, 1.0106pu) and 21 (Katampe, 1.0000pu). The improvement of the bus voltage profiles, ranging from 7% at Kaduna (bus 17) to 17.8% at Yola (bus 20), with the proposed STATCOM enables the voltage profiles to fall within the acceptable statutory limits. The result of this simulation shows the effectiveness of the STATCOM in improving the bus voltages of the Nigerian 330kV transmission grid.*

Keywords: Newton-Raphson algorithm, Nigerian 330-kV network, Power flow, STATCOM, Transmission network, Voltage magnitude.

1. Introduction

Power system network in many third world countries including Nigeria suffered voltage instability, voltage insecurity, appreciable real power losses and insufficient reactive power compensation (Bharat and Umesh, 2016). Anumaka (2012) and Makoju (2002) reported that both the distribution and transmission system in Nigeria account for about 40% of the total system losses with transmission lines losses alone incurring an estimated value of 9.2% (PHCN National Control Centre Oshogbo, 2004; PHCN National Control Centre Oshogbo, 2005). The need to address these problems is a unique area of interest to the power system researchers (Luis, 2015). Transmission system serves as intermediary between the generation stations and distribution systems, its roles in transporting electricity cannot be

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over-emphasised. However, its integrity in doing this assigned task is being enormously affected by steady-state and dynamic limitations. Consequently, transmission line power transfer capability and system stability are brought under great threat (Obulesu et *al.*, 2011). Imbalance of reactive power on network system exists when fault occurred, lines are heavily loaded or voltage fluctuation exists within the system (Kamarposhti and Lesani, 2011).

Effective and efficient distribution of reactive power plays a leading role in mitigating losses on transmission lines as well as in enhancement of system voltage profile (Musa and Mustapha, 2015). Modern approach to supply of reactive power boiled down to the use of power electronic devices; which are the foundational building block pivoting the advent of Flexible Alternating Current Transmission System (FACTS) (Okundamiya, 2016). FACTS devices are endowed with fast speed response in controlling electrical signal, space reduction and over time, found to be highly reliable in increasing the transmission line efficiency (Musa and Mustapha, 2015). They are generally categorised into four major classes, which are series compensators, shunt compensators, series–shunt compensators and series-series compensators (Eseosa and Odiase, 2012). A member of shunt-connected FACTS device found versatile in raising defective voltage buses coupled with adequate means of supplying reactive power compensation is Static Synchronous Compensators (STATCOM). This inherent ability of STATCOM is largely due to its attractive steady state performance and operating characteristics (Amarnath and Manohar, 2012; Nwohu, 2011).

The STATCOM, as a voltage source converter, is connected in shunt with the transmission line via a shunt transformer (Canizares, 2000). Its uses gate turn off thyristors and DC capacitor to produce a three-phase synchronous voltage at fundamental frequency (Claudio *et al.*, 1997). As a reactive power source and a voltage controller, it regulates the voltage at midpoint of transmission line by absorbing/generating the reactive power at the point of common coupling (Maturu and Shenov, 2010). Principally, if the output voltage of the STATCOM is higher than the AC system voltage at the point of connection, then it produces reactive current. Conversely, it absorbs reactive power when the voltage amplitude of the STATCOM is lower (Aggarwal *et al.*, 2010). The identified benefits of STATCOM so far include oscillation damping in power system, transient stability margin enhancement, steady-state power transfer capability improvement, and ability to diminish temporary over-voltage as well as enhanced voltages control and regulation among others ((Aggarwal *et al.*, 2010; Adebisi *et al.*, 2015).

Application of STATCOM to enhance Nigerian longitudinal transmission system has been attempted by several researchers (Eseosa and Odiase, 2012; Ambafi *et al.*, 2013; Aborisade *et al.*, 2014; Adebisi *et al.*, 2015) using different bus systems. Eseosa and Odiase (2012), Aborisade *et al.* (2014) and Adebisi *et al.* (2015) used the Nigerian 28-bus system while Ambafi *et al.* (2013) used the Nigerian North-East 330kV as test case system. This paper employed the Nigerian 330kV, 32-bus system as test case system to validate the proposed efficiency of the STATCOM in combating real power losses and enhancement of system voltage profile.

2. Methods

2.1 Description of the Test Case System

The Nigerian 330kV, 32-bus grid system spans through 5,523.8km and consists of eleven generating stations, twenty-one loads buses, twenty-seven transmission lines and seven transformers. It is a mix of hydro-thermal power stations with total generating installed capacity of 7461MW (Nwohu and Sadiq, 2013), The single one-line diagram of the Nigerian 330kV, 32 bus system is shown Figure 1.

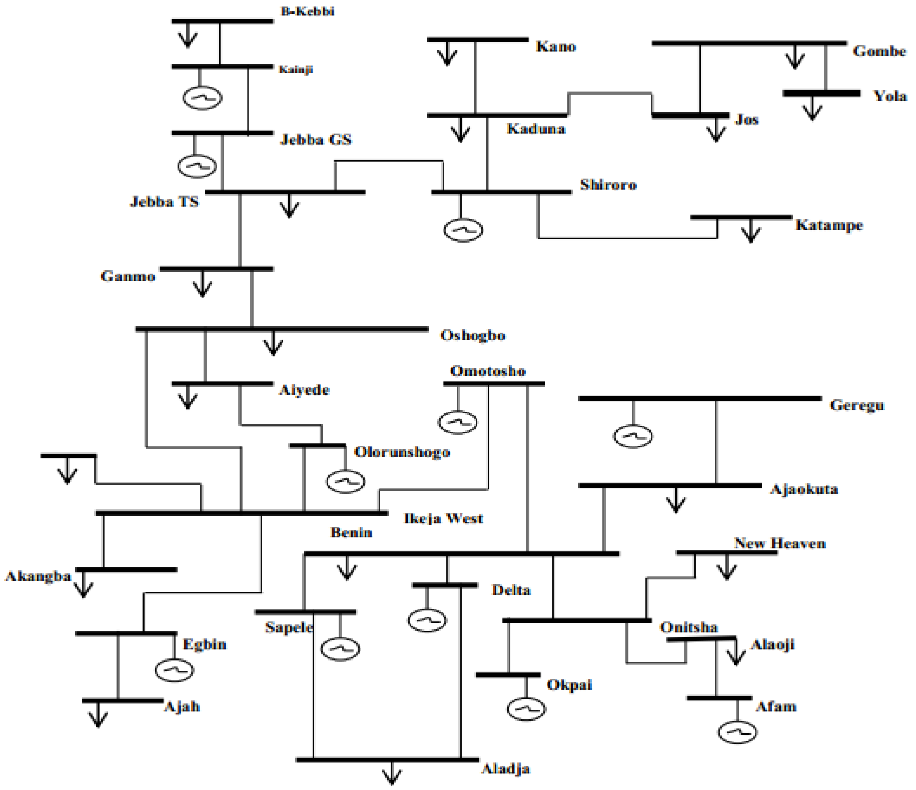

Figure 1: One-line diagram of the Nigerian 330-kV, 32-bus transmission network.

2.2 *Mathematical Modelling of the Test Case System*

The Newton-Raphson iterative algorithm was used to model the test case system as this algorithm is an efficient iterative tool found to be superior to other load flow techniques due to its excellent quadratic convergence with little iteration among others. With this technique, a set of non-linear simultaneous equations are approximated to a set of linear simultaneous equations by means of Taylor’s series expansion with the terms limited to the first approximation (Obanisola *et al.*, 2017). For a typical two bus power system represented by bus i and bus k; current I_i injected into bus i is given as follows:

$$I_i = V_i \sum_{j=1}^{n} y_{ij} V_j, \tag{1}$$

where y is line admittance and V is bus voltage

In polar form (1) can be expressed as:

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_i| \angle\theta_{ij} + \delta_j. \tag{2}$$

Y is bus admittance and θ is bus phase angle. The complex power at bus i is written as follows:

$$P_i - jQ_i = V_i^* I_i = |V_i| \angle - \delta_i \sum_{j=1}^{n} |Y_{ij}||V_i| \angle\theta_{ij} + \delta_j, \tag{3}$$

where P is real power and Q is reactive power

The real and imaginary parts of (3) can be expressed as (4) and (5) respectively.

$$P_i = \sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{4}$$

$$Q_i = -\sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{5}$$

In compact matrix form, applying Taylor's series to expand (4) and (5), the initial estimate gives (6).

$$\left(\begin{array}{c} \Delta P_2^{(r)} \\ \vdots \\ \Delta P_n^{(r)} \\ \hline \Delta Q_2^{(r)} \\ \vdots \\ \Delta Q_n^{(r)} \end{array}\right) = \left(\begin{array}{ccc|ccc} \frac{\partial P_2^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(r)}}{\partial \delta_n} & \frac{\partial P_2^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(r)}}{\partial |V_n|} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial P_n^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(r)}}{\partial \delta_n} & \frac{\partial P_n^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(r)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(r)}}{\partial \delta_n} & \frac{\partial Q_2^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(r)}}{\partial |V_n|} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial Q_n^{(r)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(r)}}{\partial \delta_n} & \frac{\partial Q_n^{(r)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(r)}}{\partial |V_n|} \end{array}\right) \left(\begin{array}{c} \Delta \delta_2^{(r)} \\ \vdots \\ \Delta \delta_n^{(r)} \\ \hline \Delta |V_2^{(r)}| \\ \vdots \\ \Delta |V_n^{(r)}| \end{array}\right) \tag{6}$$

The diagonal and off diagonal elements of the Jacobian matrix (6) is given in (Obanisola *et al.*, 2017), the power mismatches are as expressed by (7) and (8) while the updated voltage magnitudes and angles are given by (9) and (10).

$$\Delta P_i^{(k)} = P_{i,spec} - P_{i,cal} \tag{7}$$

$$\Delta Q_i^{(k)} = Q_{i,spec} - Q_{i,cal} \tag{8}$$

$$\left|V_i^{(K+1)}\right| = \left|V_i^{(k)}\right| + \Delta \left|V_i^{(k)}\right| \tag{9}$$

$$\delta_i^{(k+i)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \tag{10}$$

Where δ is voltage phase angle.

2.3 Mathematical Modelling of the STATCOM Power Flow

Generally, the bus at which the STATCOM is connected is represented as a PV (generator) bus and in the event of limits being violated it changes to a PQ (load) bus (Gholami *et al.*, 2010). The mathematical modelling of STATCOM incorporated into load flow algorithms is obtained using its equivalent circuit as shown in Figure 2.

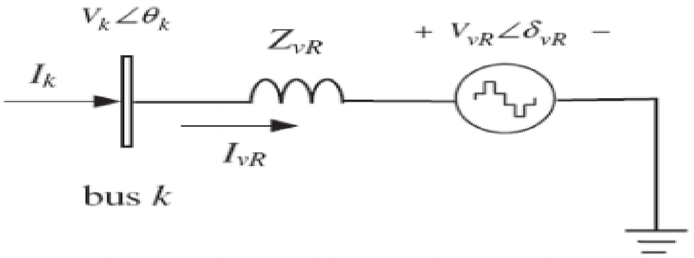

Figure 2: Equivalent Circuit for STATCOM (Gholami *et al.*, 2010)

The STATCOM power flow equations can be obtained as follows:

$$E_{VR=}V_{VR}(cos\delta_{VR} + jsin\delta_{VR}) \tag{11}$$

The complex power based on shunt connection as shown Figure 1 above is given as;

$$S_{VR} = V_{VR}Y_{VR}^{*}(V_{VR} - V_{K}^{*}) \tag{12}$$

The active power obtained for the converter and the bus k is given as;

$$P_{VR} = V_{VR}^{2}G_{VR} + V_{VR}V_{K}[G_{VR}cos(\delta_{VR} - \theta_{K}) + B_{VR}sin(\delta_{VR} - \theta_{K})] \tag{13}$$

$$P_{K} = V_{K}^{2}G_{VR} + V_{k}V_{VR}[G_{VR}\,cos(\theta_{K} - \delta_{VR}) + B_{VR}(\theta_{K} - \delta_{VR})] \tag{14}$$

The reactive power obtained for the converter and the bus k is given as;

$$Q_{VR} = -V_{VR}^{2}B_{VR} + V_{VR}V_{K}[G_{VR}sin(\delta_{VR} - \theta_{K}) + B_{VR}\,cos(\delta_{VR} - \theta_{K})] \tag{15}$$

$$Q_{K} = -V_{K}^{2}B_{VR} + V_{K}V_{VK}[G_{VR}sin(\theta_{K} - \delta_{VR}) - B_{VR}cos(\theta_{K} - \delta_{VR})] \tag{16}$$

The linearized model for STATCOM using these power flow equations (11) – (16) is as:

$$\begin{bmatrix} \Delta P_{K} \\ \Delta Q_{K} \\ \Delta P_{VR} \\ \Delta Q_{VR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{K}}{\partial \theta_{K}} & \frac{\partial P_{K}}{\partial V_{K}}V_{K} & \frac{\partial P_{K}}{\partial \delta_{VR}} & \frac{\partial P_{K}}{\partial V_{VR}}V_{VR} \\ \frac{\partial Q_{K}}{\partial V_{K}} & \frac{\partial Q_{K}}{\partial V_{K}}V_{K} & \frac{\partial Q_{K}}{\partial \delta_{VR}} & \frac{\partial Q_{K}}{\partial V_{VR}}V_{VR} \\ \frac{\partial P_{VR}}{\partial \theta_{K}} & \frac{\partial P_{VR}}{\partial V_{K}}V_{K} & \frac{\partial P_{VR}}{\partial \delta_{VR}} & \frac{\partial P_{VR}}{\partial V_{VR}}V_{VR} \\ \frac{\partial Q_{VR}}{\partial \theta_{K}} & \frac{\partial Q_{VR}}{\partial V_{K}}V_{K} & \frac{\partial Q_{VR}}{\partial \delta_{VR}} & \frac{\partial Q_{VR}}{\partial V_{VR}}V_{K} \end{bmatrix} \begin{bmatrix} \Delta\theta_{K} \\ \frac{\Delta V_{K}}{V_{K}} \\ \Delta\delta_{VR} \\ \frac{\Delta V_{VR}}{V_{VR}} \end{bmatrix} \tag{17}$$

The developed linearized model (17) was tested on the Nigerian 330kV, 32-bus grid system and the results are presented and discussed in the following section.

3. Results and Discussion

The results of the power flow simulation of the Nigerian 330kV, 32-bus network using Newton-Raphson algorithm are presented in Tables 1 and 2. Table 1 presents the bus no, bus name, bus voltage profile without STATCOM and bus voltage profile with STATCOM, while Table 2 shows the percentage voltage profile improvement. Figures 3 and 4 depict the bar chart and graphical illustration of the voltage profile with and without STATCOM respectively.

Table 1: Summary of bus voltage magnitude of the Nigerian 330kV, 32-bus network before and after compensation

Bus No.	**Bus Name**	**Voltage Profile Before Compensation**		**Voltage Profile After Compensation**	
		Voltage Magnitude (per unit)	**Voltage Angle (Degrees)**	**Voltage Magnitude (per unit)**	**Voltage Angle (Degrees)**
1	Egbin G.S	1.0400	0.0000	1.0400	0.0000
2	Benin	1.0063	6.9193	1.0065	6.5802
3	Ikeja West	0.9811	-4.7260	0.9774	-4.9637
4	Akangba	0.9735	-5.4148	0.9698	-5.6577
5	Sakete	0.9623	-7.1567	0.9586	-7.4129
6	Aiyede	0.9471	-13.6748	**1.0000**	-14.6084
7	Olorunshogo G.S	0.9800	-6.4793	0.9700	-6.9026
8	Omotosho G.S	1.0200	6.8160	1.0200	6.5014
9	Oshogbo	0.9578	-22.0787	0.9704	-22.4828
10	Ganmo	0.9603	-27.6345	1.0000	-28.2862
11	Shiroro G.S	0.9700	-55.7140	0.9700	-57.4350
12	Jebba T.S	1.0026	-29.5556	0.9675	-29.7960
13	Jebba G.S	1.0100	-29.2973	0.9700	-29.4770
14	Birnin Kebbi	1.0302	-29.1309	0.9776	-29.2592
15	Kainji G.S	1.0200	-26.1358	0.9700	-25.9609
16	Kano	0.8721	-76.2603	**1.0000**	-76.4648
17	Kaduna	0.9046	-67.3781	**0.9678**	-68.7576
18	Jos	0.8731	-78.0406	**1.0000**	-77.8566
19	Gombe	0.8735	-87.1135	**1.0188**	-84.7409
20	Yola	0.8580	-90.1711	**1.0106**	-86.9971
21	Katampe	0.9167	-61.3107	**1.0000**	-63.3031
22	Ajaokuta	1.0199	12.0747	1.0199	11.7358
23	Geregu G.S	1.0200	12.1056	1.0200	11.7667
24	Onitsha	1.0059	9.0862	1.0060	8.7474
25	Alaoji	1.0145	12.9354	1.0145	12.5966
26	New Haven	0.9673	5.2336	0.9673	4.8950
27	Sapele G.s	1.0200	9.0861	1.0200	8.7476
28	Delta G.S	1.0200	10.2525	1.0200	9.9138
29	Okpai G.S	1.0200	10.9691	1.0200	10.6304
30	Afam G.S	1.0200	13.7384	1.0200	13.3996
31	Aja	1.0376	-0.2139	1.0376	-0.2139
32	Aladja	1.0147	9.2895	1.0147	8.9510

Table 2: Percentage improvement of the voltage profile of the Nigerian 330kV, 32-bus network

Bus No.	**Voltage before Compensation**	**Voltage after Compensation**	**% Improvement**
6	0.9471	1.0000	5.6
16	0.8721	1.0000	14.7
17	0.9046	0.9678	7.0
18	0.8731	1.0000	14.5
19	0.8735	1.0188	16.6
20	0.8580	1.0106	17.8
21	0.9167	1.0000	9.1

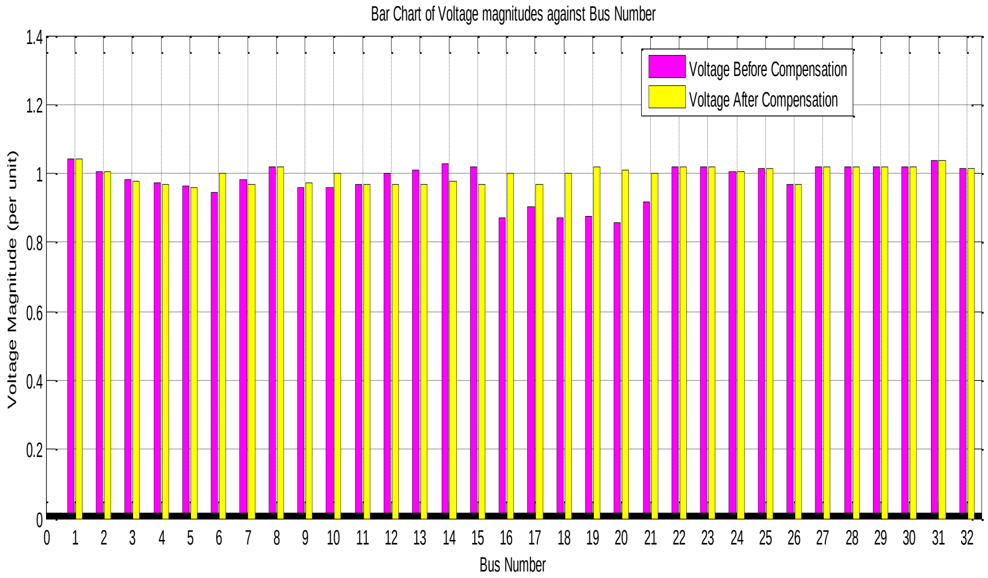

Figure 3: Voltage profile magnitude of the Nigerian 330kV, 32-bus network before and after compensation

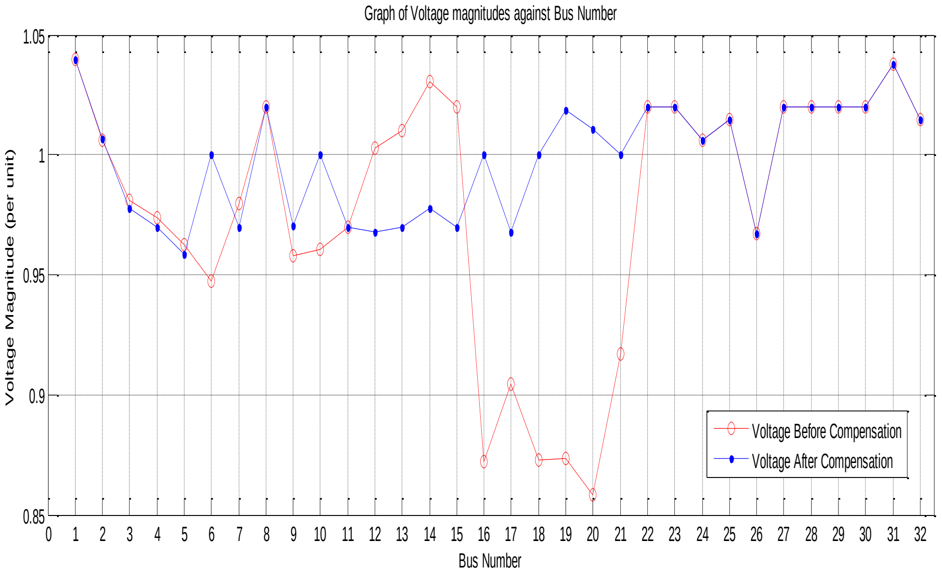

Figure 4: Graphical illustration of voltage profile magnitude of the Nigerian 330kV, 32-bus network before and after compensation

The results obtained from the simulation also identified buses whose voltages fell outside the statutory limit of 313.5kV (0.95pu) to 346.5kV (1.05pu), which includes: buses 16 (Kano, 0.8721pu), 17 (Kaduna, 0.9046pu), 18 (Jos, 0.8731pu), 19 (Gombe, 0.8735pu), 20 (Yola, 0.8580pu) and 21 (Katampe, 0.9167). On incorporating the network with STATCOM due to these buses that violate the voltage magnitude, their voltage magnitudes were now improved within the acceptable limit of 0.95pu ≤ V ≤ 1.05.

4. Conclusion

In this paper, a load flow analysis was carried out using Newton-Naphson iteration technique modelled using MATLAB Software. The test case was the Nigerian 330kV transmission network. The result obtained shows that some buses violate the required voltage magnitude of 0.95pu ≤ V ≤ 1.05pu. The effect of the application of STATCOM for enhancing these voltage magnitude was demonstrated satisfactorily by raising the voltage magnitude where they were applied; thereby, reinforcing the network. Conclusively, the result confirmed that STATCOM is an effective tool to improve the voltage stability of power system networks.

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