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Importance of Synchronous Compensator for Suitable Solution of Mitigating Power Qualityproblem on Electrical Power System

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ABSTRACT
Transmission system is the bulk movement of electrical energy between generating stations and distribution centers catering for industrial, commercial and domestic consumers of electricity. Increased usage of non-linear loads has led to Power Quality (PQ) problems such as voltage sag which have undesirable impacts on the operation of the network among others. This study provides suitable mitigating techniques for PQ problem on electrical power system by appropriate placement of Static Synchronous Compensator (STATCOM) in the power system using analytical method. The performance of the STATCOM was tested and implemented on the IEEE 14 bus and Nigerian 330 kV grid system, respectively. The sag voltage and sag duration at contingency was determined for both systems. The simulation results indicated that application of STATCOM controller in the power system improved the voltage magnitude during contingency andthe voltage sag was minimized and regulated effectively. This study has established that, implementation of STATCOM controller on electric power system provided an extremely viable approach in averting against voltage sag in power transmission system without violation of the bus voltage profile thereby improving the overall efficiency of the power system.

Keywords: *Non-linear Load, Power Quality, STATCOM, Voltage Sag, Sag Duration.*

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I. INTRODUCTION

Nowadays,consumption of electricity has been increasing rapidly butdue to inadequate resources, transmission system expansion has been severely limited. This contributes to the electricity supply failure since greater demands have been placed on the transmission system by the continuous addition of load [1]. The high demand of electricity has made the power management to modify the patterns of load demands for consumer of a power utility and thus, give rise to the issues of Power Quality (PQ) problem [2-4].

The concept of PQ deal with the capability of the electricity grid in provides customers with ideal, reliable and non-tolerant electricity. A PQ issue isextremely serious problems in electrical power system due to its impact on electricity suppliers [5]. Most of the PQ problems occurred in a power system were as results of faults, dynamic operations, or nonlinear loads [6, 7-8]. However, one of the major PQ issue is power system stability, which is the capability of power system to maintain an operating equilibrium point during disturbance [9].

The stability of a power system can be broadly divided into voltage and rotor angle stability. The voltage stability includes transients, voltage drop, voltage imbalance, short duration of variations and long duration variations. While the rotor angle stability includes waveform distortion (dc offset, harmonics, inter harmonics, notching and noise) and power frequency variations [10]. The former is the stability of the system under conditions of relatively slow change in load while the latter refers to the maximum power transfer possible through a point without losing stability [2, 11].

However, the main difference between them is that voltage stability depends on the balance of reactive power demand and generation in the system where as the rotor angle stability mainly depends on the balance between real power generation and demand [3, 12-14].

Thus, in order to mitigate all these PQ problems in electrical power system, Flexible Alternating Current Transmission Systems (FACTS) devicessuch as such as Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM) and synchronous condensers have been widely recognized as powerful tools in providing a veritable way to reduce the excess voltage or current to avoid damage to the power system [2. 13, 15, 16-18].

II. RELATED WORKS

The STATCOM according to More *et al.,* (2014).Nwohu *et al.,*(2017), Obi, (2013) and Okelola, (2018) is important members of shunt-connected FACTS devices shown in Figure 1, is a solid-state voltage source inverter coupled with a transformer and tied directly to the connected points; consequently behaving as either inductive or a capacitive reactance at those connected points. Hence, it is more often used to enhance the PQ performance of power system [17-20].The advantage of STATCOM over SVC and Synchronous condensers is that its compensating current is independent of network voltage level of the transmission at the point of connection. Thus, adequate compensation of transmission networks with STATCOM solve PQ problems [19, 21-22].

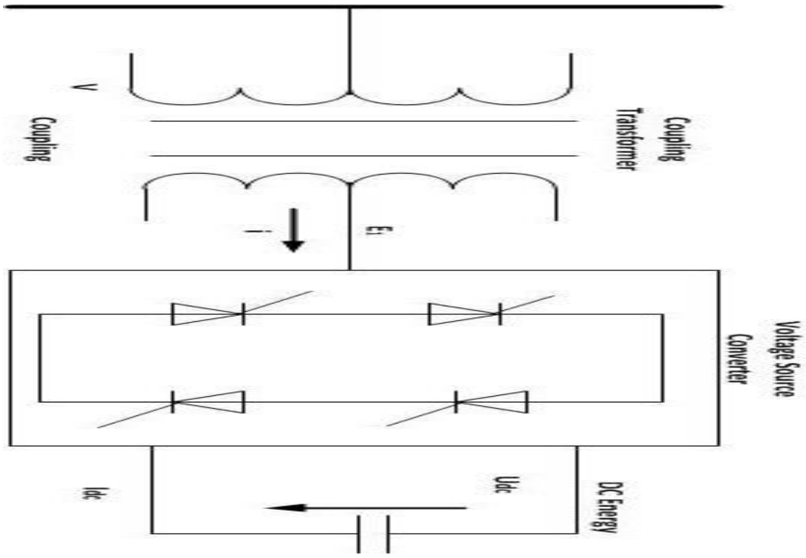


Figure 1: Static Synchronous Compensator

A. Case study

In this research paper, IEEE 14- bus test system and Nigerian 28-bus transmission systems were used to implement the effectiveness of STATCOM controller for mitigation of PQ.

i. IEEE 14-bus test system

The IEEE 14-bus test system is a standard test system. The test system had five (5) generator buses (PV), 9 load buses (PQ), 20 interconnected lines or branches and three transformers with off-nominal tap ratio in lines 6-4, 7-9, 7-8 as shown in Figure 2[23-25].

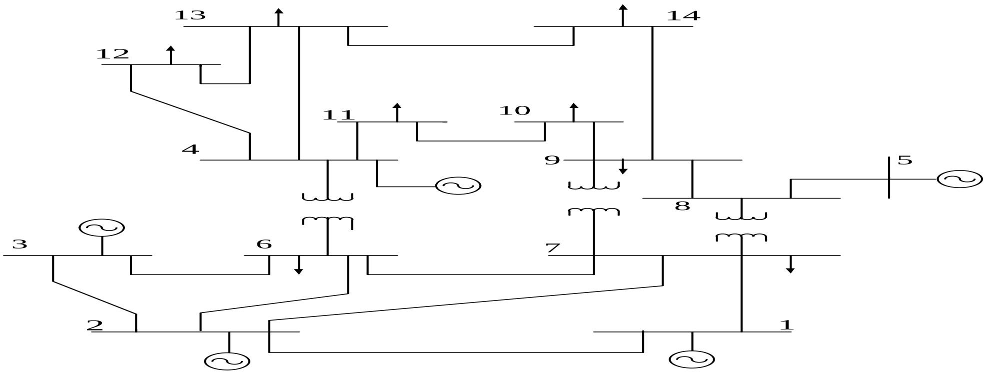


Figure 2: IEEE 14-Bus Test System

ii. Nigerian28-bus, 330 kV transmission system

Figure 3 shows the single-line diagram of the Nigerian 28-bus transmission system. The network has 60 transmission line circuits, 8 effective generation stations, 20 load stations and 52 transmission lines. The entire grid system is sectioned into North, South-East and the South-West geographical zones [17, 26-28].

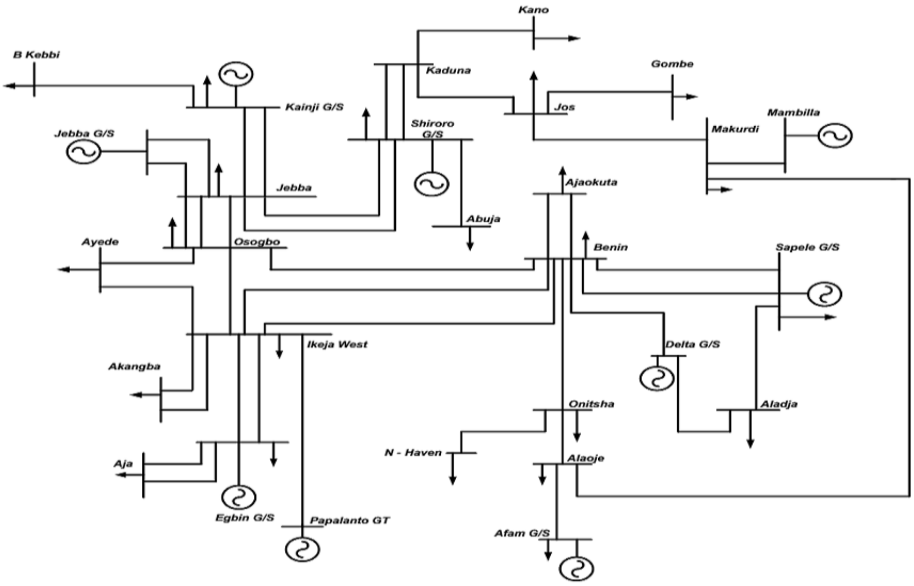


Figure 3: Nigerian 330 kV, 28 –Bus Transmission System

III. METHODOLOGY

Electric utilities are to supply reliable electricity to their customers. However, customerneeds are changing with the addition of sensitive power-electronic based end-use equipmentwhich results in Power Quality (PQ) problems such as voltagefluctuations, voltage sags, voltage swells, switching transients, impulses, flickers andharmonics among others. These PQ disturbances result intoequipment malfunction, computer data loss and memory malfunction of the sensitiveequipment. Thus, thereis the need for aproper analytical approach to study and minimize these PQ disturbances in powersystem. Therefore, suitable placement of STATCOM in power system solves PQ problems.

. Therefore, the objective function is the system load peak voltage which is formulated as in equation (1):

$$OF = \min \left(\frac{(1 - V_i)}{I_{STC}} P_{Load} + V_{Sag} \right) \qquad (1)$$

Subjected to the following constraints:

$$50 \le Q_{Gi} \le 125\% \quad (2)$$

$$0 \le Q_{STC} \le 100 MVAR \quad (3)$$

$$0.95 \le V_{Gi} \le 1.05 pu \quad (4)$$

$$0.5 \le V_{sag} \le 0.9 pu \quad (5)$$

$$0.5 \le D_{Sag} \le 1 \min \quad (6)$$

where; V_i is the peak source voltage, I_{STC} is the STATCOM controller current, V_{Sag} is the voltage sag, D_{Sag} is the voltage sag duration, Q_{Gi} is the reactive power generation, V_{Gi} is the voltage magnitudes, θ_{ij} is the angle between buses i and j, δ_i and δ_j are the voltage angle, N is the number of buses, Ng is the number of generators, N_B is the number of load buses, Q_{STC} is the STATCOM reactive power.

A. STATCOM with Newton-Raphsonload flow

Load flow of power system was performed for transient stability of the transmission system using Newton-Raphson (NR) to obtain system conditions prior to the contingencies. Then, contingency was introduced by varying the reactive power for load buses by 75 % from the base case one at a time to check the stability of the system..

In order to mitigate the PQ problem associated with voltage sags in the load buses at contingency, NR model with inclusion of Power Injection Model (PIM) of STATCOM controller was formulated. The STATCOM controller was used as compensator device to inject reactive power at defective buses where voltage magnitude falls outside the acceptable voltage range of ±5 %in the NR contingencies results.

The assumptions made in formulating the STATCOM PIM are:

i. The transmission system is assumed to be balanced 3-phase system;
ii. Harmonic generated by the STATCOM is neglected.
iii. The STATCOM was equivalently represented by positive sequence voltage source.
iv. The transmission line was model as π model representation
v. The load at receiving bus was modeled as a constant power sink, $S_r = P_r + Qj_r$

The mathematical model of the PIM STATCOM is given as follows:

The uncompensated transmission system contingency active and reactive powe are given in equations (7) and (8):

$$P_{Coni} = P_{Di} - \sum_{j=1}^{n} V_i V_{ij} Y_{ij} Cos\left(\theta_{ij} + \delta_j - \delta_i\right) \qquad (7)$$

$$Q_{Coni} = Q_{Di} - \sum_{j=1}^{n} V_i V_{ij} Y_{ij} Sin\left(\theta_{ij} + \delta_j - \delta_i\right) \qquad (8)$$

With injection of reactive power via STATCOM, the power flow equation for active power and reactive power injected by STATCOM for compensated transmission system is given in equations (9) and (10):

$$P_{ij} = V_{ij}^2 G_{STC} + V_{ij} V_{STC}\left[G_{STC} Cos\left(\theta_{ij} - \delta_{STC}\right) + B_{STC} Sin\left(\theta_{ij} - \delta_{STC}\right)\right] (9)$$

$$Q_{ij} = -V_{ij}^2 G_{STC} + V_{ij} V_{STC}\left[G_{STC} Sin\left(\theta_{ij} - \delta_{STC}\right) + B_{STC} Cos\left(\theta_{ij} - \delta_{STC}\right)\right] \qquad (10)$$

The Jacobian matrix equation gives the linearized load flow for STATCOM PIM is given as in equation (11):

$$\begin{bmatrix} \Delta P_{ij} \\ \Delta Q_{ij} \\ \Delta P_{STC} \\ \Delta Q_{STC} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \theta_{ij}} & \frac{\partial P_{ij}}{\partial V_{ij}} V_{ij} & \frac{\partial P_{ij}}{\partial \delta_{STC}} & \frac{\partial P_{ij}}{\partial V_{STC}} V_{STC} \\ \frac{\partial Q_{ij}}{\partial \theta_{ij}} & \frac{\partial Q_{ij}}{\partial V_{ij}} V_{ij} & \frac{\partial Q_{ij}}{\partial \delta_{STC}} & \frac{\partial Q_{ij}}{\partial V_{STC}} V_{STC} \\ \frac{\partial P_{STC}}{\partial \theta_{ij}} & \frac{\partial P_{STC}}{\partial V_{ij}} V_{ij} & \frac{\partial P_{STC}}{\partial \delta_{STC}} & \frac{\partial P_{STC}}{\partial V_{STC}} V_{STC} \\ \frac{\partial Q_{STC}}{\partial \theta_{ij}} & \frac{\partial Q_{STC}}{\partial V_{ij}} V_{ij} & \frac{\partial Q_{STC}}{\partial \delta_{STC}} & \frac{\partial Q_{STC}}{\partial V_{STC}} V_{STC} \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta_{ij} \\ \frac{\Delta V_{ij}}{V_{ij}} \\ \Delta \delta_{STC} \\ \frac{\Delta V_{STC}}{V_{STC}} \end{bmatrix} \qquad (11)$$

The value of STATCOM required for compensation was calculated as in equation (12):

$$STC_{Value} = \frac{Q_{STC}}{2\pi \cdot f \cdot V^2} \qquad (12)$$

The active and reactive power mismatches were calculated as in equations (13) and (14):

$$\Delta P_{ij}^{(k)} = P_{ij}^{sch} - P_{ij}^{k}$$

(13)

$$\Delta Q_{ij}^{(k)} = Q_{ij}^{sch} - Q_{ij}^{k} \qquad (14)$$

The new state variables of the STATCOM is given in equations (15) and (16):

$$\left|V_{STC}^{(i+1)}\right| = \left|V_{STC}^{(i)}\right| + \Delta\left|V_{STC}^{(i)}\right| \qquad (15)$$

$$\delta_{STC}^{(i)} = \delta_{STC}^{i} + \Delta\delta_{i}^{i} \ (16)$$

The power loss in the system was calculated using equations (22)

$$P_{loss} = \sum_{k=1}^{NL} G_k\left(V_{ij}^2 + V_{STC}^2 - 2V_{ij} V_{STC} Cos\delta_{ij}\right) \qquad (17)$$

where: V_{STC}STATCOM voltage magnitude, δ_{STC}STATCOM phase angle, I_{STC}^{*}STATCOM reference current, Y_{STC}^{*}STATCOM reference admittance, V_{STC}^{*}STATCOM reference voltage, V_{ij}^{*} is the reference bus voltage, G_{STC} is the STATCOM conductance, B_{STC} is the STATCOM susceptance, θ_{ij} is the firing angle between bus i and j, V_{ij} is the bus voltage between bus i and j, I_1 is the load current, P_{Coni} is the contingency real power for uncompensated system, $P_{D\,i}$ *and* Q_{Di} are active and reactive power consumed at bus i, P_{ij} *and* Q_{ij} are active and reactive power generated between bus i and j, $P_{ij}^{(k)}$and $Q_{ij}^{(k)}$ are calculated active and reactive power between bus i and j, P_{ij}^{sch} and Q_{ij}^{sch} are scheduled active and reactive power between bus i and j, Y_{ij} is the element of bus admittance matrix between buses i and j, $\delta_i^{(k)}$ is the calculated angle, k and (k+1) denote previous and next iteration respectively.

B. Simulation

The simulation for NRwithout and with STATCOM controller at contingency for mitigating the PQ problem was carried out in MATLAB (R2018b) based on the following steps:
Step 1: The system data such as the number and types of buses, transmission line data, load data and STATCOM control parameters for power flow calculation were input;
Step 2: The load flow of steady state were performed;
Step 3: The contingency load are generated
Step 4: The system voltage sag and duration were determined using equations (18) and (19)and the system admittance matrix was formed;

$$V_{Sag} = \frac{V_i + S_{Con}}{S_G + S_{Con}} \qquad (18)$$

$$D_{Sag} = \frac{Z_{Con}}{t_s} \times \frac{V_i}{1 - V_i} \qquad (19)$$

where; S_{Con} contingency apparent power, S_G generator apparent power, Z_{Con} impedance at contingency, t_s is the settling time constant.
Step 5: STATCOM impedance was added into the admittance matrix and the conventional Jacobian matrix were modified with reactive power injected by the STATCOM;
Step 6: The value of STATCOM required for compensation was calculated;
Step 7: The mismatched power flow equations with inclusion of STATCOM were modified and calculated;
Step 8: New state variables of the STATCOM and bus voltage at each iteration are updated;
Step 9: The convergence are checked if there is any voltage instability after Jacobian matrix is modified with STATCOM controller, If yes, Step 4 is repeated, else power equation were mismatched until convergence is achieved;
Step 10: The system required load voltage was calculated using equation (1) and power flow results were displayed.
Step 11: Stop the algorithm.
The flowchart of NR load flow withinclusion of STATCOM for mitigation of Power Quality (PQ) problem with contingency is shown in Figure 4.

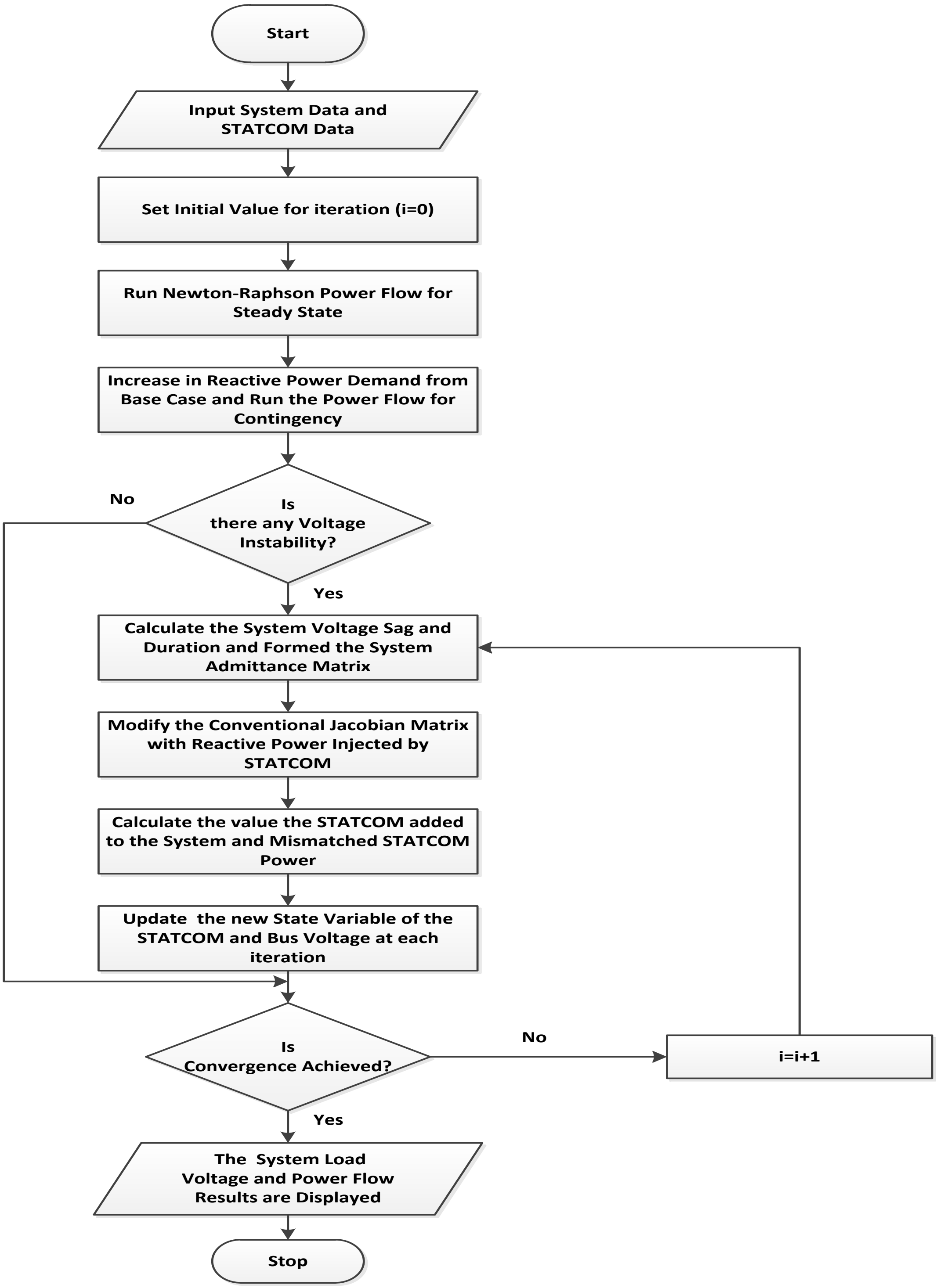


Figure 4: Flowchart of NRwith inclusion of PIM STATCOM

IV. RESULTS AND DISCUSSION

The simulation for NRwithout and with STATCOM for mitigatingPQ based on voltage sag at 75% load buses on IEEE 14-bus test system and Nigerian 28-bus system were analyzed and presented. Power flow analysis was performed with permissible working rangevalues of 0.95 to 1.05 p.u. and the stability level of the test system was evaluated. The simulation results were presented in Tables 2 to 3.

Table 1 showed the results of load flow of the IEEE 14-bussystem at steady state. From Table 1, buses whose voltage falls short of the ±5 % tolerance margin of the voltage criterion were buses 5 and 7 with voltage magnitude of 0.9490 and 0.9364 p.u.

Table 2 analyzed the results of load flow for contingency without and with STATCOM. Buses whose voltage falls short of the ±5 % tolerance margin of the voltage criterion without STATCOM were buses 4, 5, 7, 9, 10, 11 and 13 with voltage magnitude of 0.9060, 0.9190, 0.8562, 0.9347, 0.9425, 0.8625 and 0.9266 p.u.. The values of voltage magnitude at these buses with STATCOM were 0.9785, 0.9786, 1.0030, 1.0081, 0.9815, 0.9711 and 0.9918 p.u..

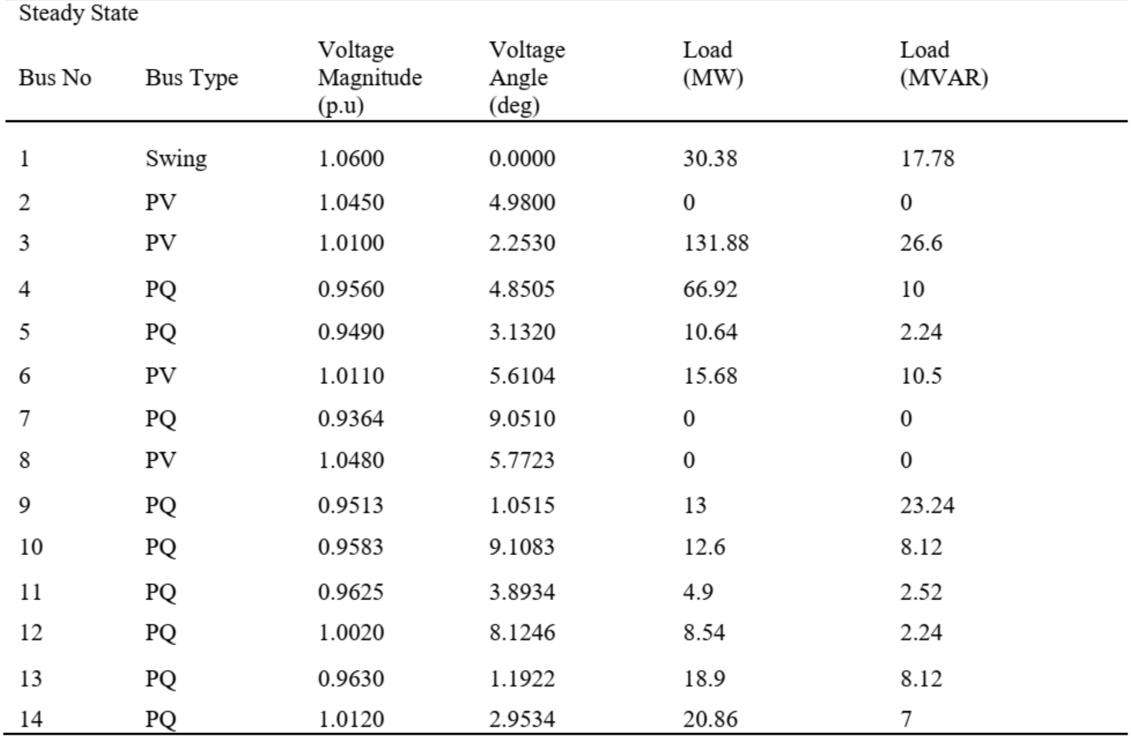
Figure 5 presented the relationship between sag voltage and sag duration for contingency. Seven (7) sag triggering points at duration of 0.5100, 0.5518, 0.9800, 0.9600, 0.6000, 0.5600 and 0.6000 sec, were detected at buses 4, 5, 7, 9, 10, 11 and 13, respectively, without STATCOM controller. While, the value of sag voltage with STATCOM at these buses were 0.0546, 0.0767, 0.0987, 0.0079, 0.0179, 0.0877 and 0.0861 p.u...

Table 3 showed the results of power flow of the Nigerian 28-bus system. From the Table, buses whose voltage falls short of the ±5 % tolerance margin of the voltage criterion were buses 6, 13, 16 and 17 with voltage magnitude of 1.0580, 0.9360, 0.9040 and 1.0510 p.u..

Table 4 revealed the Nigerian 28-bus system results of power flow for contingency without and with STATCOM. Buses whose voltage falls short of the ±5 % tolerance margin of the voltage criterion without STATCOM controller were buses 3, 4, 9, 13, 14, 16, 19, 22, 25 and 26 with voltage magnitudes0.8928. 0.9435, 0.9258, 0.8905, 0.9213, 0.9230, 0.9338, 0.9373, 0.9283 and 0.9363 p.u., respectively. The values of voltage magnitude at these buses with STATCOM controller were 1.0499, 1.0024, 0.9901, 0.9728, 0.9885, 0.9900, 0.9895, 0.9986, 0.9897 and 1.0098 p.u..

Figure 6 showed the relationship between Nigerian 28-bus system sag voltage and duration for contingency. Ten (10) sag triggering point at durations of 0.5317, 0.5417, 0.8060, 0.0187, 0.5231, 0.9218, 0.5371, 0.7331, 0.7569 and 0.7610 sec were detected at buses 3, 4, 9, 13, 14, 16, 19, 22, 25 and 26, respectively, without STATCOM. The values of sag voltage with STATCOM controller at these buses were 0.0475, 0.0356, 0.0568, 0.0493, 0.0610, 0.0325, 0.0678, 0.0520, 0.0489 and 0.0635 p.u..

Table 1: LoadFlow Result of IEEE 14-Bus Test System at Steady State



Steady State					
Bus No	Bus Type	Voltage Magnitude (p.u)	Voltage Angle (deg)	Load (MW)	Load (MVAR)
1	Swing	1.0600	0.0000	30.38	17.78
2	PV	1.0450	4.9800	0	0
3	PV	1.0100	2.2530	131.88	26.6
4	PQ	0.9560	4.8505	66.92	10
5	PQ	0.9490	3.1320	10.64	2.24
6	PV	1.0110	5.6104	15.68	10.5
7	PQ	0.9364	9.0510	0	0
8	PV	1.0480	5.7723	0	0
9	PQ	0.9513	1.0515	13	23.24
10	PQ	0.9583	9.1083	12.6	8.12
11	PQ	0.9625	3.8934	4.9	2.52
12	PQ	1.0020	8.1246	8.54	2.24
13	PQ	0.9630	1.1922	18.9	8.12
14	PQ	1.0120	2.9534	20.86	7

Table 2: Load Flow Result of IEEE 14-Bus Test System at 75 % Loading

	Without STATCOM		With STATCOM	
Bus No	Voltage Magnitude (p.u)	Voltage Angle (deg)	Voltage Magnitude (p.u)	Voltage Angle (deg)
1	1.0600	0.0000	1.0600	0.0000
2	1.0450	6.0600	1.0450	6.1740
3	1.0100	2.5700	1.0100	3.0650
4	0.9060	7.0300	0.9785	6.1390
5	0.9190	3.1320	0.9786	2.9340
6	1.0110	5.6104	1.0110	8.2144
7	0.8562	4.5720	1.0030	5.0510
8	1.0480	7.1257	1.0480	9.5621
9	0.9347	4. 1557	1.0081	2.6200
10	0.9425	7.3520	0.9815	3.1083
11	0.8625	6.8742	0.9711	1. 3442
12	0.9660	6.1786	1.0172	5. 4261
13	0.9266	3.6832	0.9918	1.6528
14	0.9920	5. 3643	1.0328	2.4354

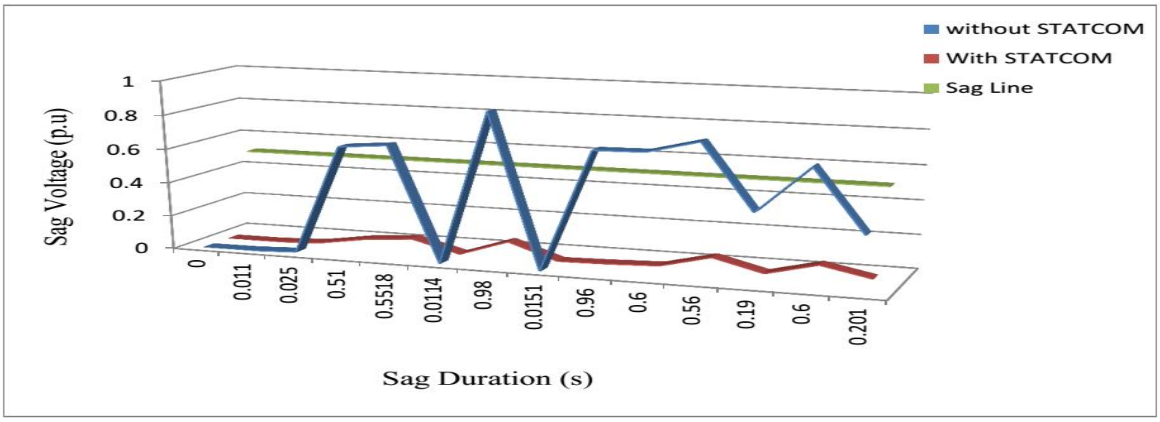
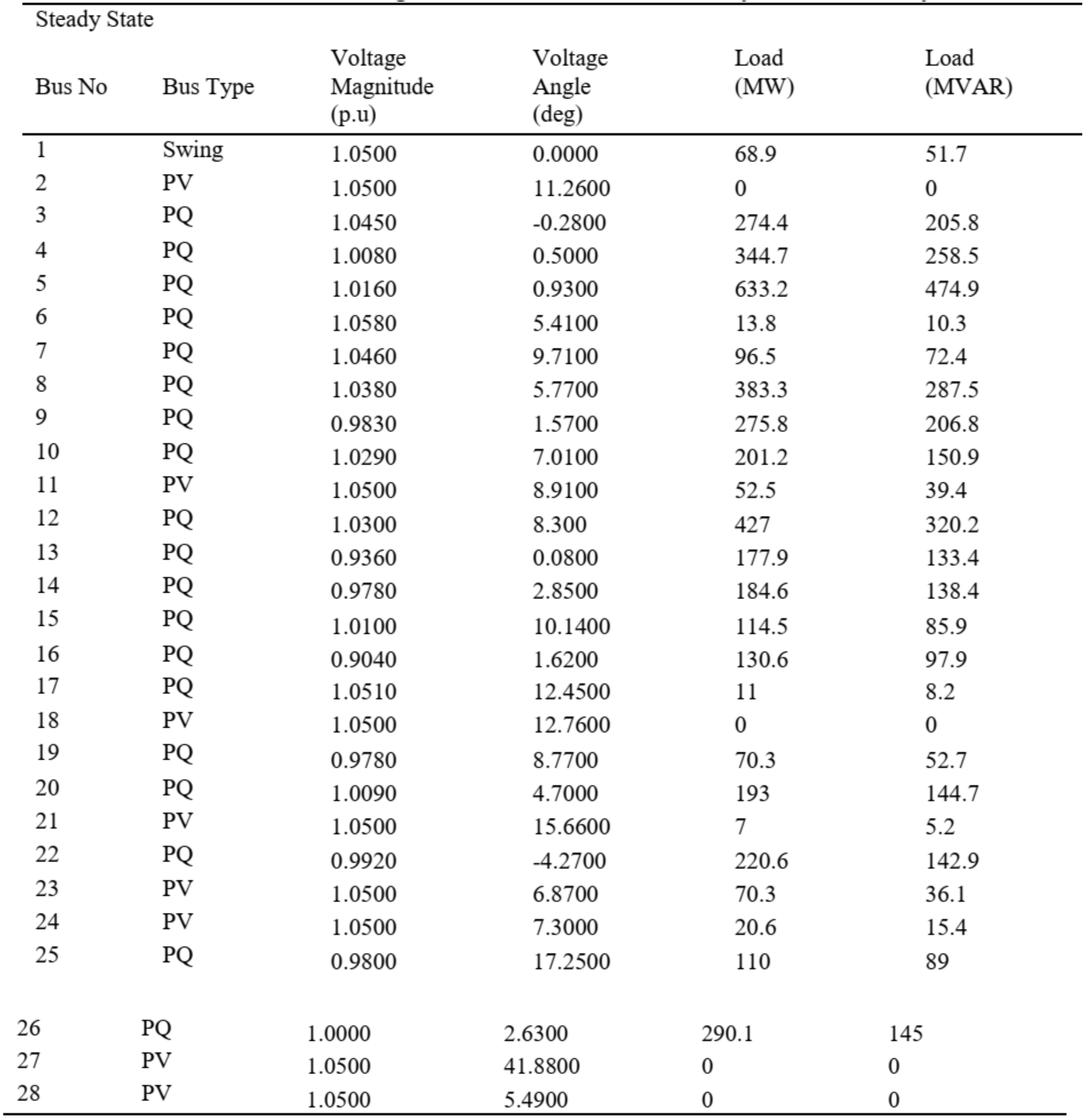


Figure 5: Sag Voltage with Duration for IEEE 14-Bus Power System at 75 % Loading

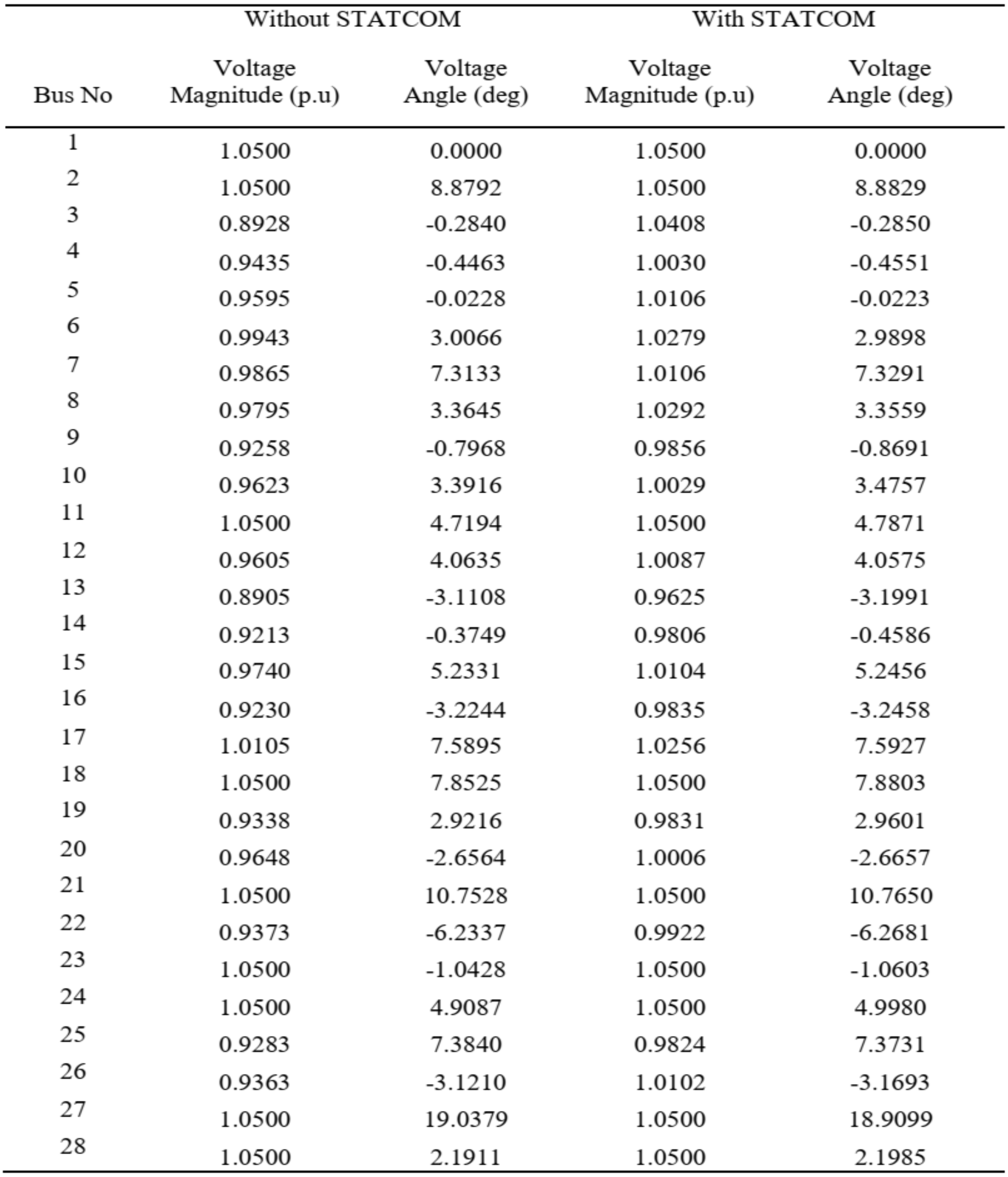
Table 3: Load Flow Result of Nigerian 28-Bus System at Steady Sate



Steady State

Bus No	Bus Type	Voltage Magnitude (p.u)	Voltage Angle (deg)	Load (MW)	Load (MVAR)
1	Swing	1.0500	0.0000	68.9	51.7
2	PV	1.0500	11.2600	0	0
3	PQ	1.0450	-0.2800	274.4	205.8
4	PQ	1.0080	0.5000	344.7	258.5
5	PQ	1.0160	0.9300	633.2	474.9
6	PQ	1.0580	5.4100	13.8	10.3
7	PQ	1.0460	9.7100	96.5	72.4
8	PQ	1.0380	5.7700	383.3	287.5
9	PQ	0.9830	1.5700	275.8	206.8
10	PQ	1.0290	7.0100	201.2	150.9
11	PV	1.0500	8.9100	52.5	39.4
12	PQ	1.0300	8.300	427	320.2
13	PQ	0.9360	0.0800	177.9	133.4
14	PQ	0.9780	2.8500	184.6	138.4
15	PQ	1.0100	10.1400	114.5	85.9
16	PQ	0.9040	1.6200	130.6	97.9
17	PQ	1.0510	12.4500	11	8.2
18	PV	1.0500	12.7600	0	0
19	PQ	0.9780	8.7700	70.3	52.7
20	PQ	1.0090	4.7000	193	144.7
21	PV	1.0500	15.6600	7	5.2
22	PQ	0.9920	-4.2700	220.6	142.9
23	PV	1.0500	6.8700	70.3	36.1
24	PV	1.0500	7.3000	20.6	15.4
25	PQ	0.9800	17.2500	110	89
26	PQ	1.0000	2.6300	290.1	145
27	PV	1.0500	41.8800	0	0
28	PV	1.0500	5.4900	0	0

Table 4: Load Flow Result of Nigerian 28-Bus System at 75 % Loading



	Without STATCOM		With STATCOM	
Bus No	Voltage Magnitude (p.u)	Voltage Angle (deg)	Voltage Magnitude (p.u)	Voltage Angle (deg)
1	1.0500	0.0000	1.0500	0.0000
2	1.0500	8.8792	1.0500	8.8829
3	0.8928	-0.2840	1.0408	-0.2850
4	0.9435	-0.4463	1.0030	-0.4551
5	0.9595	-0.0228	1.0106	-0.0223
6	0.9943	3.0066	1.0279	2.9898
7	0.9865	7.3133	1.0106	7.3291
8	0.9795	3.3645	1.0292	3.3559
9	0.9258	-0.7968	0.9856	-0.8691
10	0.9623	3.3916	1.0029	3.4757
11	1.0500	4.7194	1.0500	4.7871
12	0.9605	4.0635	1.0087	4.0575
13	0.8905	-3.1108	0.9625	-3.1991
14	0.9213	-0.3749	0.9806	-0.4586
15	0.9740	5.2331	1.0104	5.2456
16	0.9230	-3.2244	0.9835	-3.2458
17	1.0105	7.5895	1.0256	7.5927
18	1.0500	7.8525	1.0500	7.8803
19	0.9338	2.9216	0.9831	2.9601
20	0.9648	-2.6564	1.0006	-2.6657
21	1.0500	10.7528	1.0500	10.7650
22	0.9373	-6.2337	0.9922	-6.2681
23	1.0500	-1.0428	1.0500	-1.0603
24	1.0500	4.9087	1.0500	4.9980
25	0.9283	7.3840	0.9824	7.3731
26	0.9363	-3.1210	1.0102	-3.1693
27	1.0500	19.0379	1.0500	18.9099
28	1.0500	2.1911	1.0500	2.1985

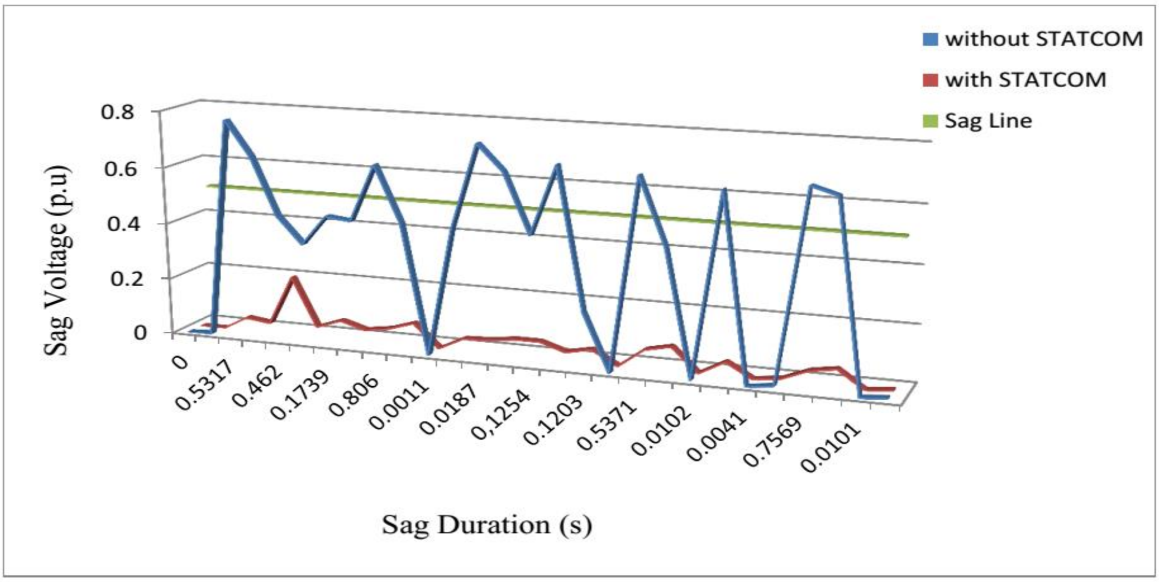


Figure 6: Sag Voltage - Duration for Nigerian 28-Bus System at 75 % Loading

V. CONCLUSION

Application and importance ofSTATCOM in mitigating the effect of voltage sag inelectrical power system has been successfully presented in this study.NR load flow was performed for both steady state and contingency at 75% loading and simulation was carried out in MATLAB R(2018b). The simulation revealed that, the IEEE 14-bus power system is more stable while Nigerian 28-bus system is not stable. Similarly, the voltage magnitude of the load buses for the two power system at 75% loading scenarios fell short of the ±5 % tolerance margin of the voltage criterion and voltage sag problem were detected with high sag duration. Therefore, it could be concluded that the two power system were not stable during contingency especially Nigerian power system. This verified the radial nature of the Nigeria power system. It was also revealed that,with the application of PIM STATCOM, the voltage sag in the two system was minimized and regulated effectively. The simulation results obtained verified the efficiency and importance of STATCOM for mitigation of PQ problem

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