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Research Article

Enhancing the Efficiency of Nigeria's Electric Power Transmission System with Static Synchronous Compensator

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Abstract

This paper addresses the enhancement of the voltage profile in Nigeria's 330kV transmission power network using a Static Synchronous Compensator (STATCOM). The increasing power demand has led modern power systems to operate under highly stressed conditions, making it challenging to meet reactive power requirements, especially during planned or sudden voltage changes. Maintaining bus voltage within acceptable limits has thus become a significant challenge. This study introduces the Static Synchronous Series Compensator into the Nigeria National Grid (NNG) to improve electric power transmission. The 330kV, 58-bus NNG was modeled using PSAT and implemented in MATLAB/Simulink to compensate for the identified voltage violations. Transmission network data obtained from the Transmission Company of Nigeria (TCN) in Osogbo was used to model the test network. Simulation results reveal that STATCOM significantly improved the voltage stability of the violated buses in the Nigerian network, providing a 100% improvement in voltage stability compared to a network without any compensatory device.

Keywords	*Voltage Stability; Nigeria's Electricity Power Transmission; STATCOM; Transmission Company of Nigeria; Voltage Profile; MATLAB/SIMULINK; Nigeria National Grid*
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Introduction

Due to the rising demand for electricity, modern power system networks are now operating under highly stressed conditions. This has made it difficult to meet reactive power requirements, especially during planned or sudden voltage changes, and maintaining bus voltage within acceptable limits has become a major challenge. Despite using conventional methods such as excitation control and voltage regulators at generating stations, tap-changing transformers at the ends of transmission lines, shunt reactors during low loads, shunt capacitors during high loads, series capacitors in long transmission lines, and tap-changing transformers in industries and substations for reactive power compensation, voltage fluctuations at power stations persist. This paper introduces the Static Synchronous Compensator (STATCOM) into the Nigerian grid network to enhance electric power transmission.

The Nigerian power industry, once considered one of the greatest engineering achievements of the 20th century, is now facing significant stress and vulnerability. Dilapidated transmission lines and distribution networks has caused high energy losses in our national grid (Ikechukwu, 2021).With rapidly increasing electricity demand, the power system facilities are being pushed to their capacity limits. It is estimated that by 2020, the generating units need to triple to meet the growing demand, requiring about 10,000 MW of new generating capacity. Projections indicate that Nigeria's electricity demand could grow by 1.8% annually by 2020, necessitating over 40,000 MW of new generating capacity. This would involve approximately 10 new generating stations plus associated transmission and distribution facilities, requiring an investment of over $20 billion (Ogbuefi, 2015).

Technically, the limitation on power transfer capacity on a transmission line can always be addressed by adding new transmission capacity. In some cases, hybrid configurations can potentially deliver improved performance and better economic values for a given electrification situation (Okedu et al.,2015). However, economic, political, and environmental considerations make building new transmission facilities less desirable. Therefore, employing power electronic devices on the existing 330kV Nigerian power system is essential for efficient power delivery. Several methods can improve transmission line performance, including installing new transmission lines, reconductoring, replacing transmission line/terminal equipment, upgrading voltage, converting from single to double circuits, phase shifting, and reactive power compensation (Oleka et al., 2016).

Installing transmission lines is often the first option considered when a transmission line is limited in power transmission capacity. This can alleviate overloading by providing additional paths for power flow, increasing the transmission system's reliability. However, it must overcome economic, political, and environmental hurdles. Flexible Alternating Current Transmission System (FACTS) devices are a range of high voltage, large power electronic converters that enhance AC system controllability, stability, and power transfer capability (Sharma and Jagtap, 2016). FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of line trips. They also offer benefits such as increased energy sales, reduced wheeling charges, and delayed investment in high voltage transmission lines or new power generation facilities (Kumar and Dubey, 2015). It is widely analysed that instability in our transmission line is as result of the per unit volts not falling within 0.95 through 1.05 volts (Bakare et al.,2021). While many argued that, in hydro turbines, instability could result due to low speed or rotation of hydro turbines(Ngang,2020).This is usually overcome by increase in water volume at upper side of the dam.

Maintaining steady system parameters like bus voltage, reactive power, and active power under normal and abnormal conditions is a major challenge in power systems. Regaining synchronism after a major fault is critical, as faults can lead to loss of synchronism. Faults occur due to insulation breakdown, lightning, power cables blowing together, animals or plants contacting wires, salt spray, pollution on insulators, system overloading, long transmission lines with uncontrolled buses, shortage of local reactive power, intrinsic factors, harsh weather, and small generation reserve margins. These disturbances have led to the introduction of FACTS devices such as Static Var Compensators (SVC), Static Synchronous Series Compensator (SSSC), STATCOM, Unified Power Controller (UPFC), and Interline Power Flow Controller (IPFC) (Karthik and Arul, 2013; Makkar and Dewan, 2015). In stable power systems, synchronous machines will either return to their original state or reach a new state without loss of synchronism when disturbed, unless there is a net change in power (Satheesh and Manigandan, 2015). Recall that from the point of classical approach, power system instability can be seen as loss of synchronizing power coefficient or synchronism (Aneke,2021). FACTS devices help transmit power through chosen routes, mitigating losses and preventing system tripping or outages. STATCOM, UPFC, and SSSC are versatile FACTS controllers. Conventional approaches require precise mathematical models of the controlled systems, but in large, complex, and geographically widespread power systems like Nigeria's, parameter uncertainty and unexpected events make global control challenging.

Materials and Methods

For positive sequence power flow analysis, the STATCOM can be represented by a synchronous voltage source with maximum and minimum voltage magnitude limits (Acha et al., 2004). This voltage source represents the fundamental Fourier series component of the switched voltage waveform at the STATCOM's AC converter terminal. The bus where the STATCOM is connected is treated as a PV bus, which may change to a PQ bus if limits are violated. In such cases, the generated or absorbed reactive power would reach its maximum limit. The STATCOM equivalent circuit, as shown in Figure 3.1, is used to develop the mathematical model of the controller for incorporation into power flow algorithms (Adepoju and Komolafe, 2011).

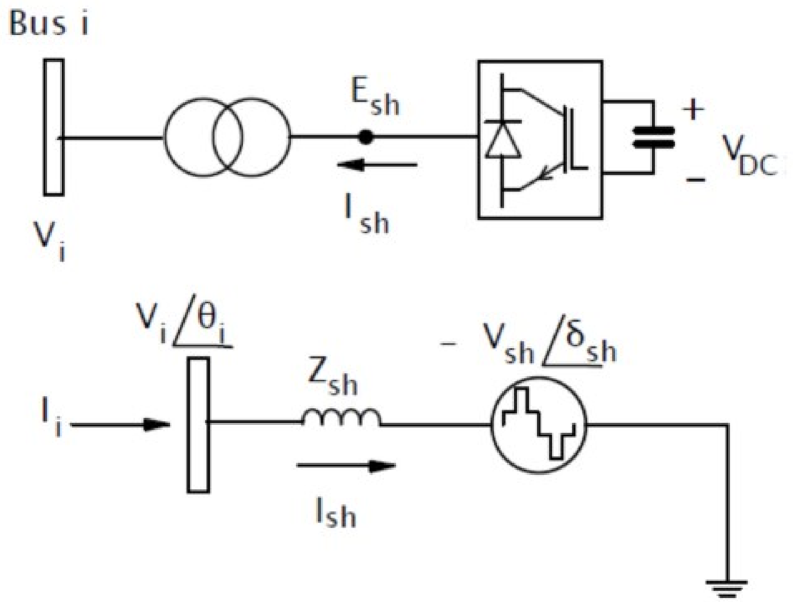


Fig.1: Thevenin’s equivalent circuit diagram of STATCOM: (a) STATCOM schematic diagram; (b) STATCOM equivalent circuit

Recall that the power flow equations for the STATCOM are given From the works of (Aborisade et al ,2014) with voltage representation.

$$V_{sh} = v_{sh}\angle\delta_{sh}\text{ , also } V_i = v_i\angle\theta_i, \tag{1}$$

$$E_{sh} = V_{sh}(\cos\delta_{sh} + j\sin\delta_{sh}) \tag{2}$$

From the STATCOM equivalent circuit of figure 1;

$$S_{sh} = V_{sh}I_{sh}^{*} = V_{sh}\,Y_{sh}^{*}(V_{sh}^{*} - V_i^{*}) \tag{3}$$

After performing some complex operations, the following active and reactive power equations are obtained for the converter and bus i, respectively:

$$P_{sh} = V_{sh}^2 G_{sh} + V_{sh}V_i[G_{sh}\cos(\delta_{sh} - \theta_i) + B_{sh}\sin(\delta_{sh} - \theta_i)] \tag{4}$$

$$Q_{sh} = V_{sh}^2 B_{sh} + V_{sh}V_i[G_{sh}\sin(\delta_{sh} - \theta_i) - B_{sh}\cos(\delta_{sh} - \theta_i)] \tag{5}$$

$$P_i = V_i^2 G_{sh} + V_iV_{sh}[G_{sh}\cos(\theta_i - \delta_{sh}) + B_{sh}\sin(\theta_i - \delta_{sh})] \tag{6}$$

$$Q_i = V_i^2 B_{sh} + V_iV_{sh}[G_{sh}\sin(\theta_i - \delta_{sh}) - B_{sh}\cos(\theta_i - \delta_{sh})] \tag{7}$$

Using these power equations, the linearized STATCOM model is as given in equation (8), where the voltage magnitude V_{sh} and phase angle $\delta_{\ h}$ are taken to be the state variables (Acha et al, 2000)

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \\ \Delta P_{sh} \\ \Delta Q_{sh} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_i}{\partial\theta_i} & \frac{\partial P_i}{\partial V_i}V_i & \frac{\partial P_i}{\partial\delta_{sh}} & \frac{\partial P_i}{\partial V_{sh}}V_{sh} \\ \frac{\partial Q_i}{\partial\theta_i} & \frac{\partial Q_i}{\partial V_i}V_i & \frac{\partial Q_i}{\partial\delta_{sh}} & \frac{\partial Q_i}{\partial V_{sh}}V_{sh} \\ \frac{\partial P_{sh}}{\partial\theta_i} & \frac{\partial P_{sh}}{\partial V_i}V_i & \frac{\partial P_{sh}}{\partial\delta_{sh}} & \frac{\partial P_{sh}}{\partial V_{sh}}V_{sh} \\ \frac{\partial Q_{sh}}{\partial\theta_i} & \frac{\partial Q_{sh}}{\partial V_i}V_i & \frac{\partial Q_{sh}}{\partial\delta_{sh}} & \frac{\partial Q_{sh}}{\partial V_{sh}}V_{sh} \end{bmatrix} \begin{bmatrix} \Delta\theta_i \\ \frac{\Delta V_i}{V_i} \\ \Delta\delta_{sh} \\ \frac{\Delta V_{sh}}{V_{sh}} \end{bmatrix} \tag{8}$$

Development of Simulation Model and Simulation of 58 Bus Nigeria 330kV Transmission Network with STATCOM Device

The power flow model for STATCOM was derived and formulated in equation 8. Using this equation, the 58-bus 330 kV transmission network of Nigeria was modeled in PSAT 2.1.8 and simulated in the Matlab 2015b environment. Figure 2 presents the developed PSAT model. The Newton-Raphson method was used for the power flow solution of the Nigeria 330kV network. Egbin substation was designated as the slack bus. Voltage violations were identified from the load flow analysis results based on the permissive voltage bus limit criteria of 0.95 to 1.05 pu or 5% of the rated bus voltage. The optimal placement of the STATCOM device was determined by considering the positions of the violated buses. STATCOM, being a shunt device, was inserted at these violated buses. The best placement was identified based on the degree of performance enhancement achieved.

Simulation of Nigeria 330kV Transmission Line

All simulations were conducted in the MATLAB 2015b environment using the specially designed power system analysis tool PSAT 2.1.8. This tool allows for the simulation of power flow in the system and provides various results such as bus voltage and phase angle, line flows, and line losses. Simulations were performed both with and without the STATCOM device connected to the 330kV network.

Ananti & Nwosu (2020)

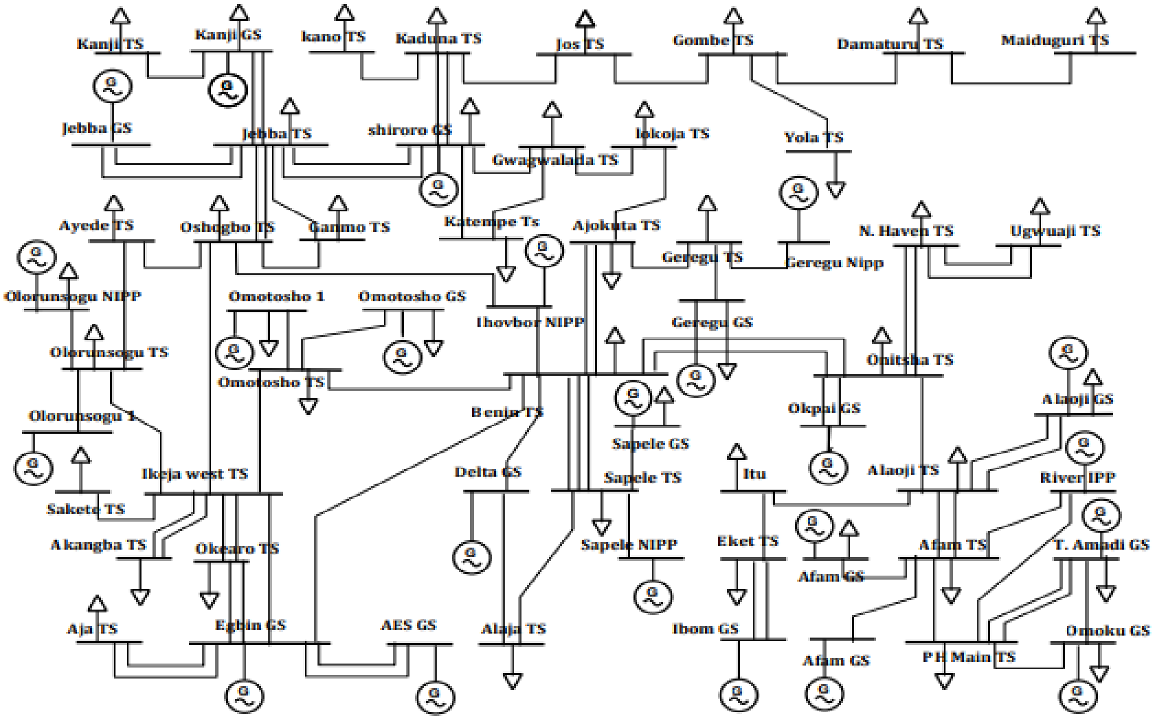


Figure 1: 58 Buses Nigeria 330 kV Transmission Line(Dikki,2014),

Simulating the system with STACOM

STATCOM device was inserted at bus 7 and simulations were performed at different conditions of compensations shown below:

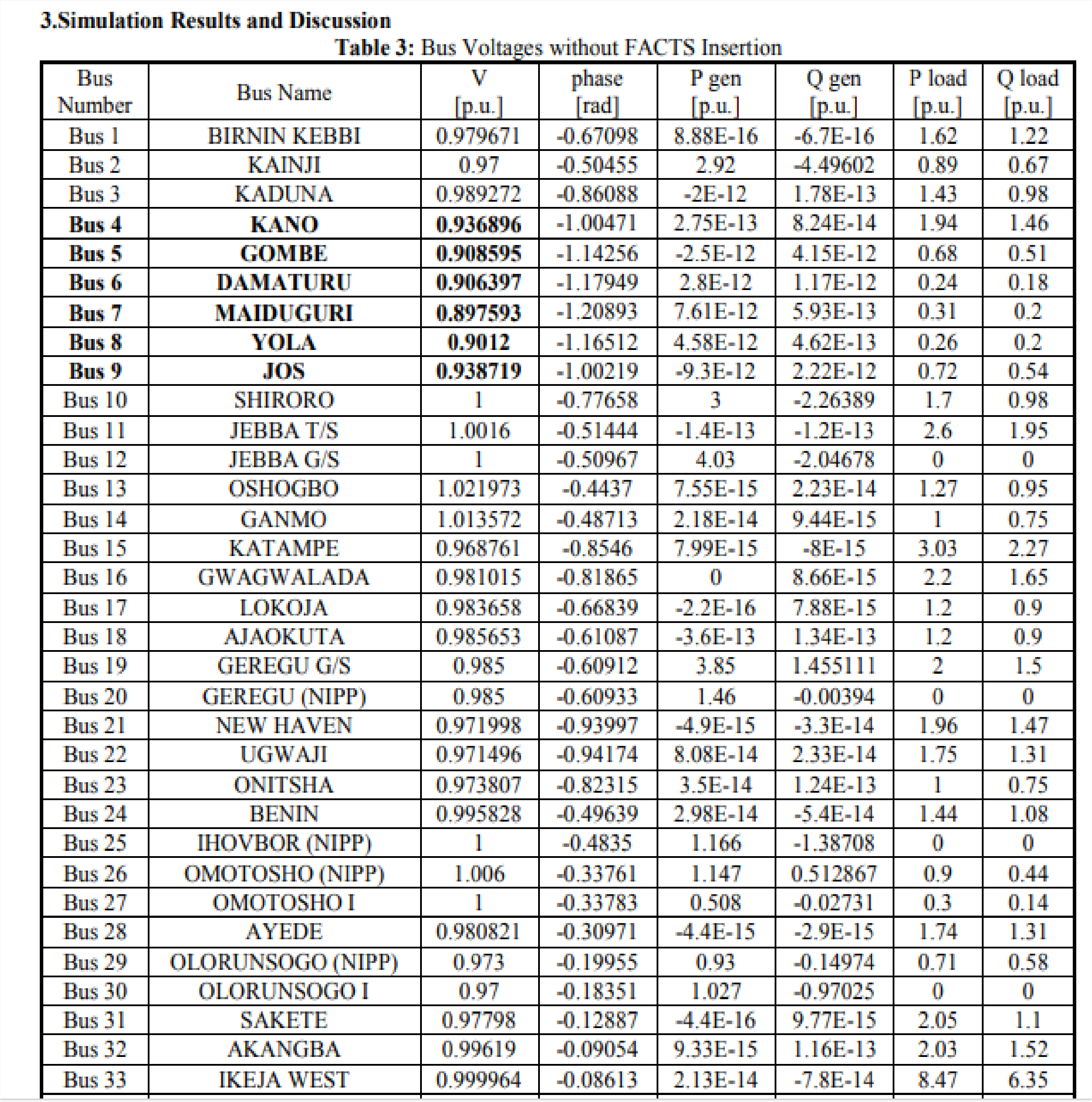
(i) The first conditions: power = 100MW and shunt current I_q = 0.7 pu
(ii) The second conditions: power = 100MW and shunt current I_q = 0.76 pu

Table 1: Statistics of the Network

	NETWORK STATISTICS	
Network condition	STACOM	No FACT
Buses	58	58
Lines	87	87
Generators	23	23
Loads	46	46

Table 2: Statistics of the Solution

	Solution Statistics	
Power Flow Solution Type	Newton-Raphson	
Simulation condition	STACOM	No FACT
Number of Iterations	5	5
Maximum P mismatch (P.U.)	41.22503	9.28E-12
Maximum Q mismatch (p.u)	10.03604	0.197854
Rated power (MVA)	100	100



3.Simulation Results and Discussion

Table 3: Bus Voltages without FACTS Insertion

Bus Number	Bus Name	V [p.u.]	phase [rad]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus 1	BIRNIN KEBBI	0.979671	-0.67098	8.88E-16	-6.7E-16	1.62	1.22
Bus 2	KAINJI	0.97	-0.50455	2.92	-4.49602	0.89	0.67
Bus 3	KADUNA	0.989272	-0.86088	-2E-12	1.78E-13	1.43	0.98
Bus 4	**KANO**	**0.936896**	-1.00471	2.75E-13	8.24E-14	1.94	1.46
Bus 5	**GOMBE**	**0.908595**	-1.14256	-2.5E-12	4.15E-12	0.68	0.51
Bus 6	**DAMATURU**	**0.906397**	-1.17949	2.8E-12	1.17E-12	0.24	0.18
Bus 7	**MAIDUGURI**	**0.897593**	-1.20893	7.61E-12	5.93E-13	0.31	0.2
Bus 8	**YOLA**	**0.9012**	-1.16512	4.58E-12	4.62E-13	0.26	0.2
Bus 9	**JOS**	**0.938719**	-1.00219	-9.3E-12	2.22E-12	0.72	0.54
Bus 10	SHIRORO	1	-0.77658	3	-2.26389	1.7	0.98
Bus 11	JEBBA T/S	1.0016	-0.51444	-1.4E-13	-1.2E-13	2.6	1.95
Bus 12	JEBBA G/S	1	-0.50967	4.03	-2.04678	0	0
Bus 13	OSHOGBO	1.021973	-0.4437	7.55E-15	2.23E-14	1.27	0.95
Bus 14	GANMO	1.013572	-0.48713	2.18E-14	9.44E-15	1	0.75
Bus 15	KATAMPE	0.968761	-0.8546	7.99E-15	-8E-15	3.03	2.27
Bus 16	GWAGWALADA	0.981015	-0.81865	0	8.66E-15	2.2	1.65
Bus 17	LOKOJA	0.983658	-0.66839	-2.2E-16	7.88E-15	1.2	0.9
Bus 18	AJAOKUTA	0.985653	-0.61087	-3.6E-13	1.34E-13	1.2	0.9
Bus 19	GEREGU G/S	0.985	-0.60912	3.85	1.455111	2	1.5
Bus 20	GEREGU (NIPP)	0.985	-0.60933	1.46	-0.00394	0	0
Bus 21	NEW HAVEN	0.971998	-0.93997	-4.9E-15	-3.3E-14	1.96	1.47
Bus 22	UGWAJI	0.971496	-0.94174	8.08E-14	2.33E-14	1.75	1.31
Bus 23	ONITSHA	0.973807	-0.82315	3.5E-14	1.24E-13	1	0.75
Bus 24	BENIN	0.995828	-0.49639	2.98E-14	-5.4E-14	1.44	1.08
Bus 25	IHOVBOR (NIPP)	1	-0.4835	1.166	-1.38708	0	0
Bus 26	OMOTOSHO (NIPP)	1.006	-0.33761	1.147	0.512867	0.9	0.44
Bus 27	OMOTOSHO I	1	-0.33783	0.508	-0.02731	0.3	0.14
Bus 28	AYEDE	0.980821	-0.30971	-4.4E-15	-2.9E-15	1.74	1.31
Bus 29	OLORUNSOGO (NIPP)	0.973	-0.19955	0.93	-0.14974	0.71	0.58
Bus 30	OLORUNSOGO I	0.97	-0.18351	1.027	-0.97025	0	0
Bus 31	SAKETE	0.97798	-0.12887	-4.4E-16	9.77E-15	2.05	1.1
Bus 32	AKANGBA	0.99619	-0.09054	9.33E-15	1.16E-13	2.03	1.52
Bus 33	IKEJA WEST	0.999964	-0.08613	2.13E-14	-7.8E-14	8.47	6.35

Bus 34	OKEARO	1.01469	-0.04388	-6.7E-15	3.72E-14	1.2	0.9
Bus 35	AJA	1.031295	-0.00213	-7.1E-15	-5E-14	1.15	0.86
Bus 36	EGBIN	1.033	0	41.23471	10.03976	0	0
Bus 37	AES	1	0.076642	2.452	-3.49485	0	0
Bus 38	OKPAI	1	-0.78611	4.66	1.692064	0	0
Bus 39	SAPELE G/S	0.985	-0.48992	0.67	-0.95668	0.4	0.18
Bus 40	SAPELE (NIPP)	1	-0.48001	1.111	-0.18175	0	0
Bus 41	DELTA	1.003	-0.4791	3.41	0.905989	0	0
Bus 42	ALADJA	0.992198	-0.49737	7.99E-15	-1E-14	2.1	1.58
Bus 43	ITU	0.97848	-1.53205	3.55E-15	-8.1E-15	1.99	0.91
Bus 44	EKET	0.988548	-1.56369	-1.1E-14	-9.8E-15	2	1.47
Bus 45	IBOM	1	-1.56214	0.305	1.496835	0	0
Bus 46	ALAOJI T/S	0.981995	-1.48959	1.33E-15	6.13E-14	2.4	1
Bus 47	ALAOJI G/S	1	-1.49044	2.5	9.415142	2.27	1.7
Bus 48	AFAM VI	1	-1.51254	6.46	8.916558	5.34	4.01
Bus 49	AFAM IV-V	0.956	-1.51175	0.54	-4.4108	0	0
Bus 50	PH MAIN	0.998574	-1.53855	-8.9E-14	5.84E-14	2.8	1.4
Bus 51	RIVERS (IPP)	1	-1.53337	0.8	1.498423	0	0

Bus Number	Bus Name	V [p.u.]	phase [rad]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus 52	TRANS AMADI	1	-1.53852	1	1.70441	0.8	0.24
Bus 53	OMOKU	1	-1.53867	0.448	0.208557	0.5	0.1
Bus 54	GEREGU T/S	0.984922	-0.6101	8.33E-13	1.02E-13	2	1.5
Bus 55	OMOTOSHO T/S	0.992783	-0.34213	-1.8E-15	2.61E-14	0.8	0.5
Bus 56	OLORUNSOGO T/S	0.980349	-0.2047	-8.9E-15	-2.7E-14	0.71	0.58
Bus 57	SAPELE T/S	0.996462	-0.4953	-5.9E-14	-2.7E-14	1	0.77
Bus 58	AFAM T/S	0.976824	-1.51604	-6.2E-15	1.47E-13	7.2	4.12

Bus Voltage

No FACTS Inserted

1.05

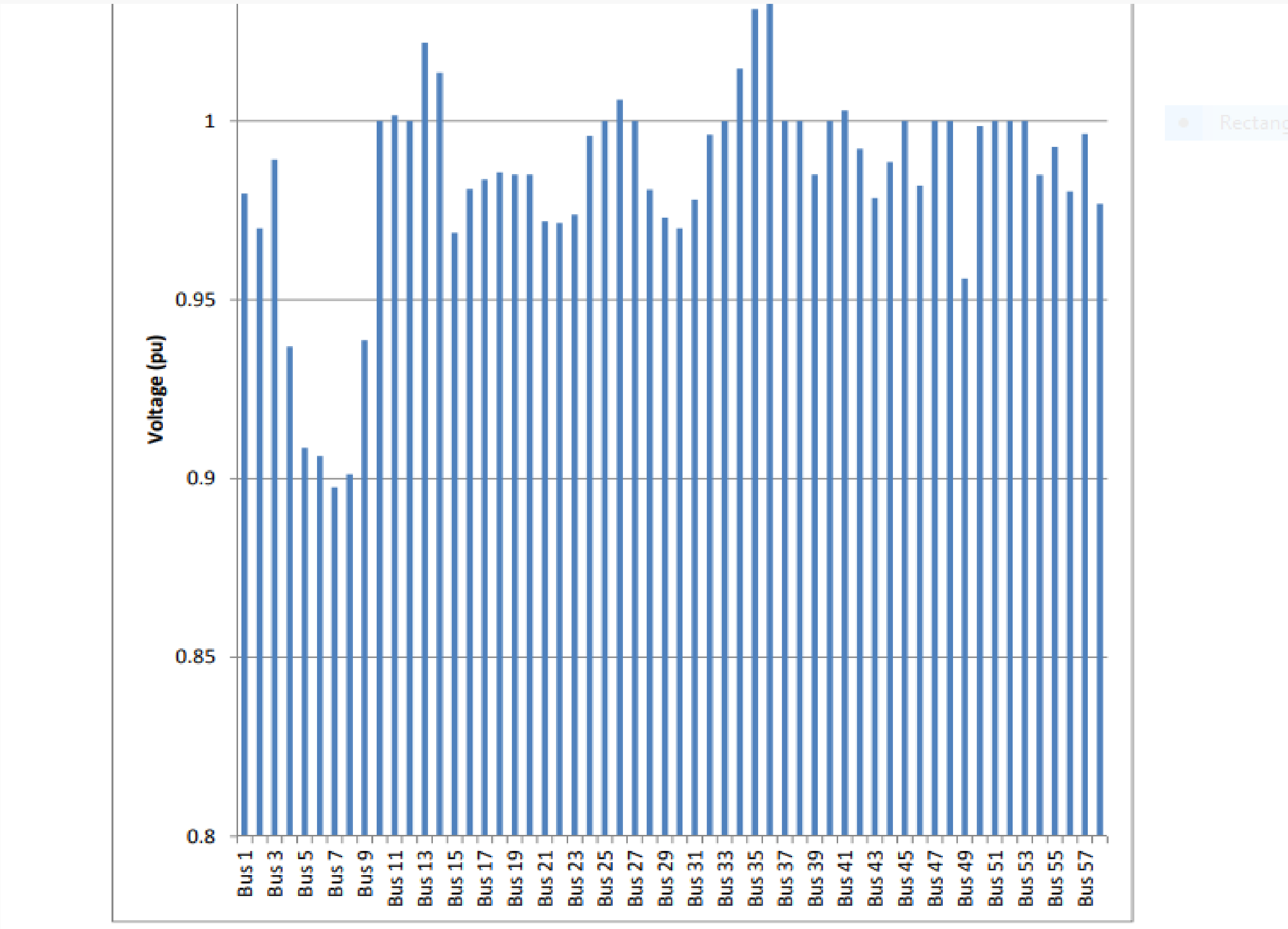
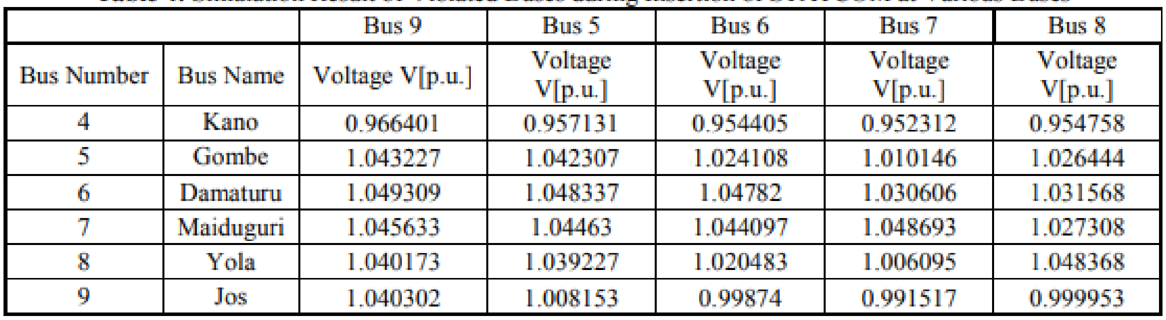


Figure 4: Bus voltages without FACTS insertion

Table 4: Simulation Result of Violated Buses during Insertion of STATCOM at Various Buses



		Bus 9	Bus 5	Bus 6	Bus 7	Bus 8
Bus Number	Bus Name	Voltage V[p.u.]	Voltage V[p.u.]	Voltage V[p.u.]	Voltage V[p.u.]	Voltage V[p.u.]
4	Kano	0.966401	0.957131	0.954405	0.952312	0.954758
5	Gombe	1.043227	1.042307	1.024108	1.010146	1.026444
6	Damaturu	1.049309	1.048337	1.04782	1.030606	1.031568
7	Maiduguri	1.045633	1.04463	1.044097	1.048693	1.027308
8	Yola	1.040173	1.039227	1.020483	1.006095	1.048368
9	Jos	1.040302	1.008153	0.99874	0.991517	0.999953

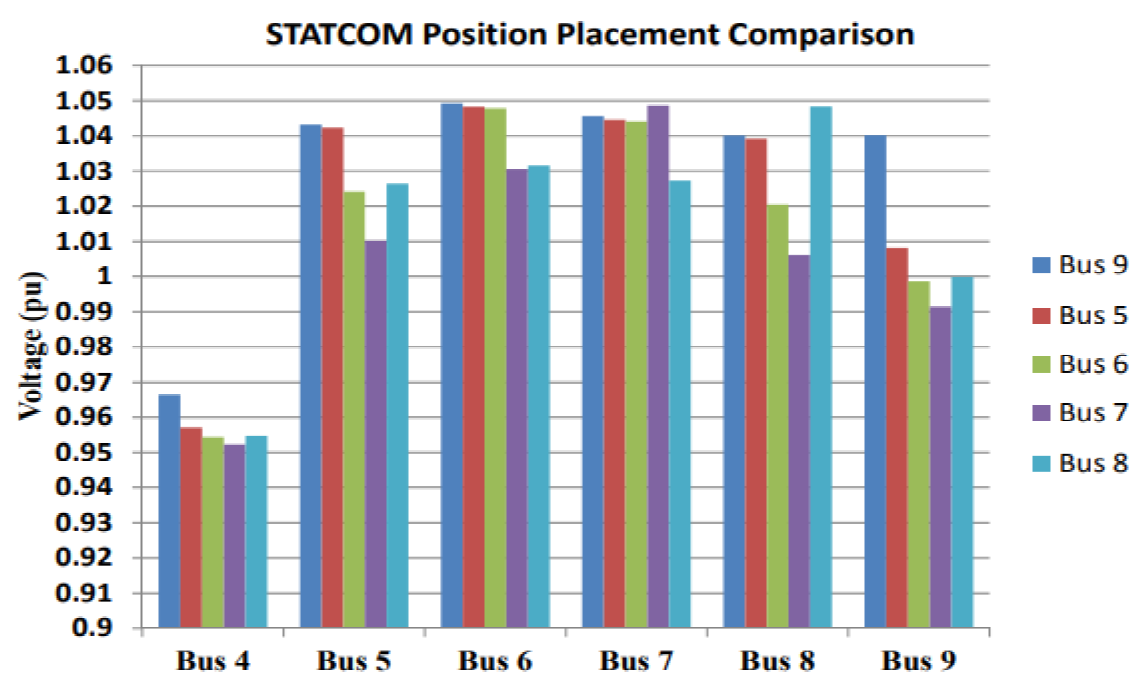
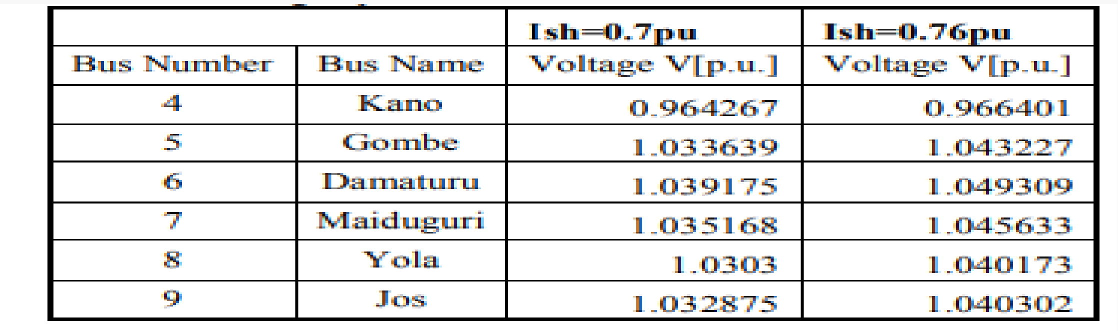


Figure 5: Comparing STATCOM Position Placement (Showing improvement in Voltage)

Table 5: Distorted Bus Voltage due to Shunt Current Variation of the connected STATCOM



		Ish=0.7pu	Ish=0.76pu
Bus Number	Bus Name	Voltage V[p.u.]	Voltage V[p.u.]
4	Kano	0.964267	0.966401
5	Gombe	1.033639	1.043227
6	Damaturu	1.039175	1.049309
7	Maiduguri	1.035168	1.045633
8	Yola	1.0303	1.040173
9	Jos	1.032875	1.040302

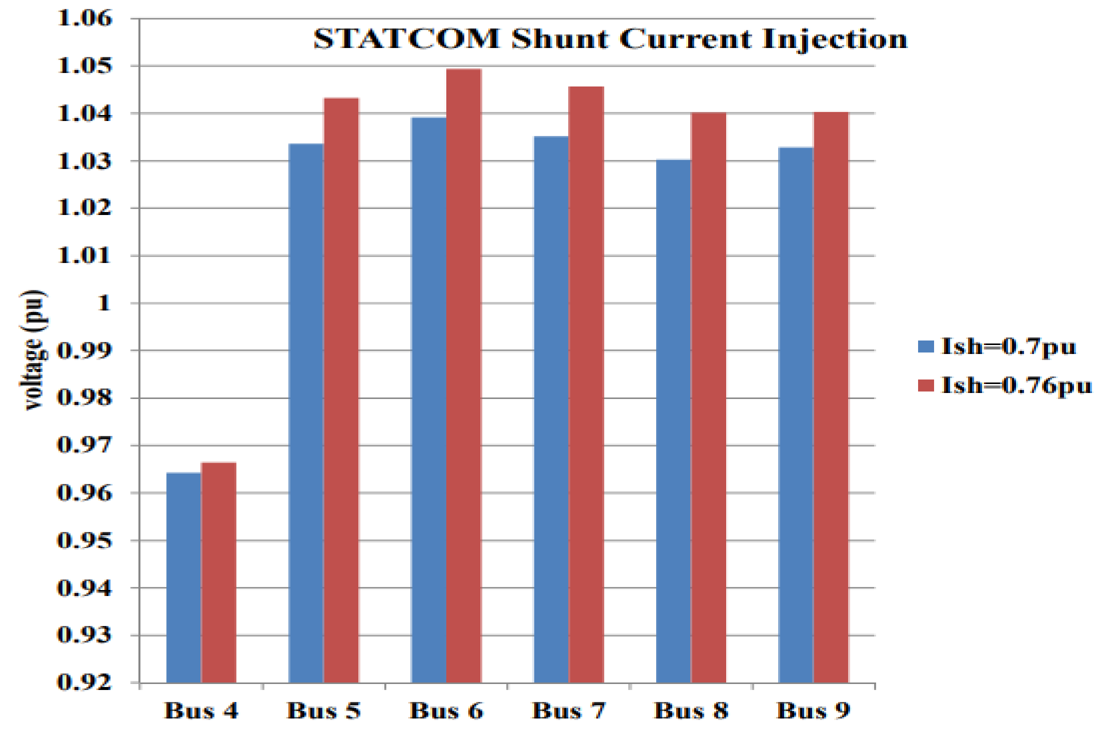


Figure 6: Distorted Bus Voltage response due to the Shunt Current Variation of the connected STATCOM

The simulation of the 58-bus, 330kV Nigerian transmission line network without compensation revealed voltage violations in six buses: bus 4 (Kano), bus 5 (Gombe), bus 6 (Damaturu), bus 7 (Maiduguri), bus 8 (Yola), and bus 9 (Jos), as detailed in Table 5 and Figure 4. These violations primarily occurred along the radial line from Kaduna to Maiduguri, with a single transmission line feeding the affected buses from the Kaduna substation. In Kano, the violations were due to high active and reactive power demands of 1.94 pu and 1.46 pu, respectively, primarily driven by reactive power demand. The violations along the Kaduna-Maiduguri line were largely caused by voltage drops over the long distance. The total power demand along this line, including the connection from Gombe to Yola, was 2.21 pu for active power and 1.63 pu for reactive power. Maiduguri experienced the highest voltage violation due to its distance from Kaduna (795 km) and a power demand of 1.95 + j1.43 pu, while Yola had the second-highest violation with a distance of 615 km from Kaduna and a power demand of 1.64 + j1.23 pu.

Discussion and Result Analysis of STATCOM Penetration

The simulation results are documented in Tables 4 and 5 and graphically in Figures 5 and 6, with simulation conditions outlined in Section 3.5. The optimal placement of STATCOM for performance enhancement was at bus 9 (Jos), as shown in Table 4 and Figure 5. The results indicated that STATCOM at bus 9 provided a better overall performance enhancement compared to other positions. At bus 7 (Maiduguri), STATCOM required the least shunt current to correct voltage violations, although with the least performance enhancement spread. The highest bus voltage improvement corresponded with the best performance spread, particularly at bus 9 (Jos), as compared to buses 5 (Gombe), 6 (Damaturu), 7 (Maiduguri), and 8 (Yola), as detailed in Table 4. Increasing the shunt current of STATCOM resulted in increased performance enhancement, as shown in Table 5 and Figure 6. Specifically, when STATCOM was placed at bus 9, the voltage at bus 7 (Maiduguri) improved from 0.897593 pu to 1.035168 pu and 1.045613 pu with shunt current variations of 0.7 pu and 0.76 pu, respectively.

Conclusion

The 58-bus, 330kV Nigerian transmission line network exhibited voltage violations at seven buses: Kano (0.9180 pu), Gombe (0.7890 pu), Damaturu (0.7634 pu), Maiduguri (0.7613 pu), Yola (0.7769 pu), and Jos (0.8756 pu). The introduction of STATCOM at the Jos substation bus significantly improved voltage levels, demonstrating a 100% enhancement over the uncompensated network.

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