Original Research Article

Enhancement of the Small-Signal Stability of Nigerian 330 kV Transmission Network using Static Synchronous Compensator

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ABSTRACT

Aims: To analyze the small-signal stability of the Nigerian 330 kV transmission system and the performance of Static Synchronous Compensator (STATCOM) controller in enhancing the system's stability upon incorporation

Methodology: Newton-Raphson method of solution was adopted for the power flow analysis and Eigenvalues method was employed for small-signal stability analysis. Simulation was used for the analysis and was carried out on Power System Analysis Toolbox (PSAT) software version 2.1.11 in MATLAB environment.

Results: The voltage magnitudes from power flow results of Nigerian transmission network for five critical buses, buses Damatguru, Gombe, Jalingo, Maiduguri and Yola gave 0.8529, 0.8529 0.8299, 0.8249 and 0.83433 p.u respectively. While the corresponding magnitudes after incorporating STATCOM controller were 1.02, 0.9768, 0.9568, 1.05, 0.9607 p.u. Furthermore, the eigenvalues result for small-signal stability contains seven positive eigenvalues. After incorporating STATCOM controller, all positive eigenvalues changed to negative.

Conclusion: The Nigerian transmission network is weak with voltage limits violation but the incorporation of STATCOM was able to bring the voltage magnitudes of all buses within limits. Also, the network is small-signal unstable, however, STATCOM controller was able to enhance the stability when incorporated.

Keywords: Small-Signal Stability, STATCOM, Eigenvalues, PSAT.

1. INTRODUCTION

The growing population has resulted into drastic increase in demand for electricity. In order to meet up with the demand of electricity, transmission network is being overloaded and push closer to their stability limit (Okolo *et al.,* 2020).The Nigerian transmission network controlled by Transmission Company of Nigeria (TCN), is faced with many challenges affecting its stability and reliability.

In Nigeria, the transmission network is essential in transmitting electrical energy from power generation stations to distribution networks and electrical power users. The Nigerian transmission network, operated by Transmission Company of Nigerian (TCN), is often strained beyond its design capacity, leading to potential overloading and instability problem. Nigerian power grid is affected by a lot of problem which include, old, insufficient power grid equipment, insufficient generation and poor loadability. The 54-bus, 330 kV is comprises of

18 generators and 67 transmission lines. (Anyanor *et al.,* 2020). The gross installed generation capacity is about 13,300 MW, however, only 5900 MW net capacity has been available. The actual daily generation rarely reaches 4000 MW which is due to several outages, which maybe maintenance-based or forced outages. Also the power supply deficit necessitates load shedding which involves rationing of available power dispatch to meet only a portion of the total load demand (Adetokun and Muriithi, 2021).

Many system separations and blackouts has occurred in the history of power system industry as a result of oscillations generated from small disturbances (Hamarash, 2012).

Small-signal stability is the ability of power system to maintain synchronism under small disturbances such as small load variations and generations (Mondal *et al*., 2020). It is associated with small disturbances generated from continuous switching on and off of small loads (Gibbard *et al*., 2015). These small disturbances generate oscillations in power systems which, if not dampened out, can grow large, and result to instability and even blackout.

Several methods and approaches have been used by researchers in the analysis of small-signal stability of power systems such as, model-based analysis, measurement-based, and Eigenvalue analysis (Lin, 2015).

Eigenvalue analysis, adopted for this study, is used to determine the stability of power systems. Eigenvalues come in complex form. The system is stable if only negative real parts exists in the eigenvalues, and unstable if positive real parts exist.

To dampen out the oscillations generated as a result of small disturbances, controllers such as PSS, AVR and FACTS controllers are already in use.

The first proposed method for introducing damping torque is the conventional power system stabilizer and the second method is Heffron-Philip’s power system stabilizer (Doradla *et al.,* 2011).

Karthikeyan and Dhal (2015) worked on the enhancement of small-signal stability of IEEE-9 bus system via optimal placement of STATCOM controller. Eigenvalue method of analyzing small-signal stability was adopted.

Ogunjuyigbe and Gonoh (2022) examined the small-signal stability of 330 kV Nigerian network when subjected to small disturbances while adopting AVR for stability enhancement. Modal analysis method was employed to carry out the analysis.

FACTS controllers are technology which are capable of controlling one or more system parameters in order to improve controllability and power transfer capacity of the system (Mondal *et al.,* 2020).

STATCOM controller is a FACTS controller that has been widely used for enhancing voltage profiles of transmission systems, reducing active power losses in transmission lines and enhancing small-signal stability of power systems.

Adepoju *et al*. (2011) examined the power flow analysis of Nigerian transmission system with the incorporation of FACTS controllers. Three controllers were considered for the study; Static Synchronous Compensator (STATCOM), High Voltage Direct Current – Voltage Sourced Converter (HVDC-VSC) and Unified Power Flow Controller (UPFC), for voltage magnitude control, active and reactive power control.

Ambafi *et al*. (2012) investigated the performances of Power System Stabilizer (PSS) and Static Synchronous Compensator (STATCOM) controller in damping oscillations in power system when considered separately.

Aborisade *et al*. (2014) compared the voltage enhancement and loss reduction capabilities of STATCOM and SSSC controllers to address the problems of voltage instability, active and reactive power losses.

Jokojeje *et al*. (2015) investigated the effects of the application of STATCOM controller on the Nigerian transmission system performance using voltage magnitude and power profile as performance metrics.

Kumar and Kumar (2019) scrutinizes the effects of multiple combinations of Static Var Compensator (SVC) and STATCOM on load congestion mitigation of IEEE 14-bus system applying Weight Least Square (WLS) technique.

STATCOM capacity is determined by its voltage level and power rating. Thus, in installing a STATCOM controller, the power system's voltage level must match the voltage level of the installed controller.

Installing STATCOM requires a significant capital cost which includes, procurement cost, installation and commission cost and maintenance and operation cost. Although, initial cost of installing STATCOM is substantial, but its economic benefits supersede the cost of installation, as its deployment reduces financial losses arising from power losses and blackouts.

Incorporation of FACTS controllers into power system has shown enhancement in system stability. Many countries like China, Brazil, Canada, India and Saudi Arabia have installed FACTS controllers into their networks to support power transmission capabilities and grid stability Asad (2022).

2. MATERIAL AND METHODS

2.1 Small-Signal Stability of Power System Using Eigenvalue Analysis

PSAT uses a set of differential-algebraic equations (DAE) which is represented in the form:

$$\dot{x} = f(x, y) \tag{2.1}$$

$$0 = g(x, y) \tag{2.2}$$

Where x is the vector of the state variables, y the vector of algebraic variable, f vector of differential equations, and g is vector of algebraic equation (Milano, 2008). State matrix is computed by manipulating the Jacobian matrix and eigenvalues are calculated from the state matrix (Milano, 2008).

State matrix (A_s) are used to compute the eigenvalues. The state matrix is computed from the Jacobian Matrix of the linearized DAE.

Linearizing equations (2.1) and (2.2) gives

$$\begin{bmatrix} \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} F_x & F_y \\ G_x & G_y \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{2.3}$$

The State matrix (A_s) is then computed using

$$A_s = F_x - F_y G_x G_y^{-1} \tag{2.4}$$

2.2 Research System Materials

The small-signal stability of the Nigerian 54-bus 330 kV transmission network was conducted. Figure 1 shows the one-line diagram of the network. The simulation of the transmission network was carried out using PSAT 2.1.11 in MATLAB environment. The procedures below were followed and STATCOM controller was connected to the weakest bus with the lowest voltage profile. The simulation results were presented.

2.3 Approach for conducting small-signal stability

Modelling of the transmission network by careful selection of suitable and appropriate models of synchronous machine, Automatic Voltage Regulator (AVR), Turbine Governor (TG) and STATCOM controllers. Preparation of the selected models on PSAT. Newton-Raphson power flow methods was adopted for power flow solution. These procedures were followed to compute eigenvalues of the system and determine the system's stability.
The procedure for small-signal stability analysis is as follows:

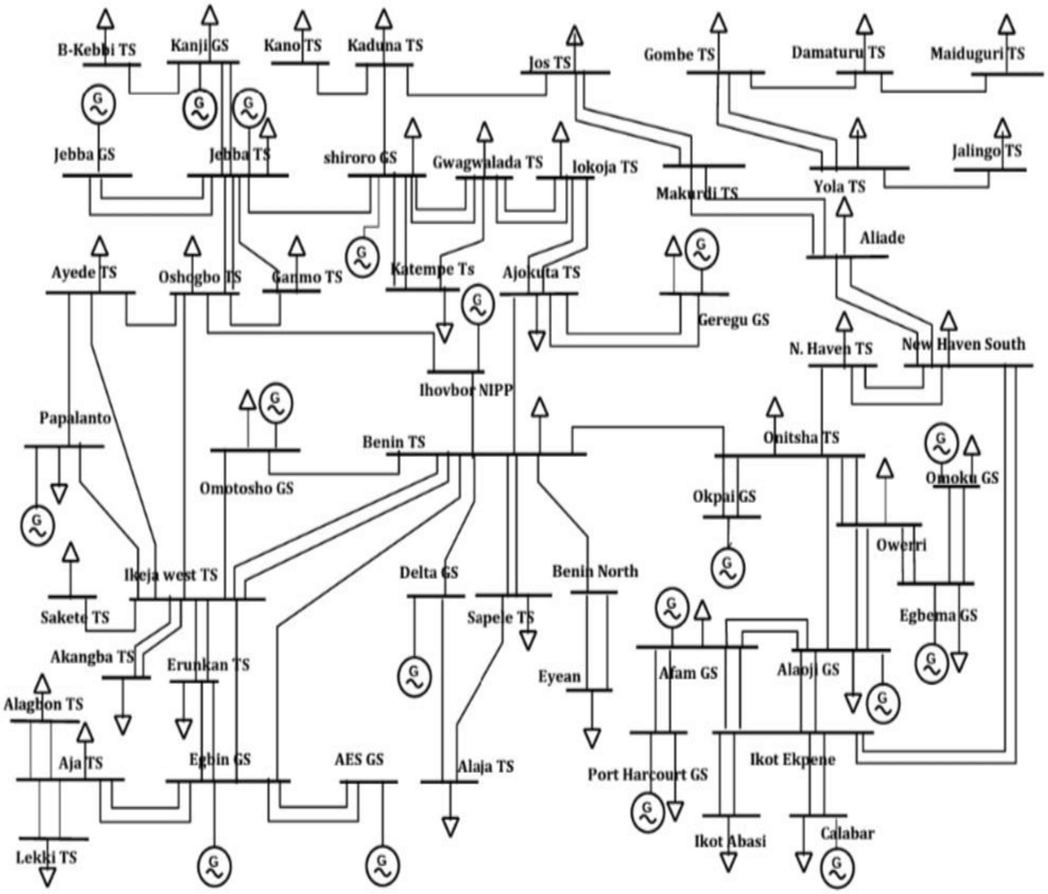

Figure 1: One Line Diagram of Nigerian 54-bus Transmission Network

Step 1: Prepare the models
Step 2: Input transmission network line data and bus data
Step 3: Run the Newton-Raphson power flow

Step 4: Run the eigenvalue analysis
Step 5: Check for positive eigenvalues
Step 6: If positive eigenvalues exist, then find the weakest bus, apply STATCOM controller to the bus and tune the parameters of STATCOM controller.
Step 7: Run the power flow
Step 8: Check for positive eigenvalues
Step 9: If positive eigenvalues exist, repeat steps 6-8
Step 10: If positive eigenvalues do not exist, the system is stable
Step 11: End the process

STATCOM controller parameters tuning involves adjusting regulation gain to match system's response, time constant to determine the speed of response, and voltage level of the controller to match the power system's voltage level at the point of connection.

3. RESULTS AND DISCUSSION

The models of synchronous machine, AVR, TG, and STATCOM were prepared as shown in figure 2. The power flow analysis was carried out and the result obtained showed that buses Damaturu, Gombe, Jalingo, Maiduguri and Yola violated the voltage limit of ±10%. This implies the system is weak with reactive power losses. Maiduguri was the weakest bus with the lowest voltage of 0.82488 p.u.

Eigenvalue analysis was carried out after the power flow analysis. Figure 3 shows the plot of imaginary parts against the real parts of the eigenvalues. Seven of the eigenvalues fall on the positive real axis, this denotes that the system is small-signal unstable.

STATCOM controller was connected to Maiduguri bus, the weakest bus with the lowest voltage magnitude. The power flow results for without and with incorporation of STATCOM controller are presented in table 1.

Figure 4 shows the voltage magnitudes of each buses with and without STATCOM controller's incorporation. The result shows that the voltages of the buses with voltage limit violation has improved and has been brought within limit implying that the controller has injected reactive power into the network to compensate for the losses.

The eigenvalue analysis was also carried out after the incorporation of the controller. Figures 5 shows the plot of imaginary parts against the real parts of the eigenvalues after the controller's incorporation. The positive eigenvalues has changed from 7 to 0. Hence, the system has become small-signal stable after incorporating STATCOM controller.

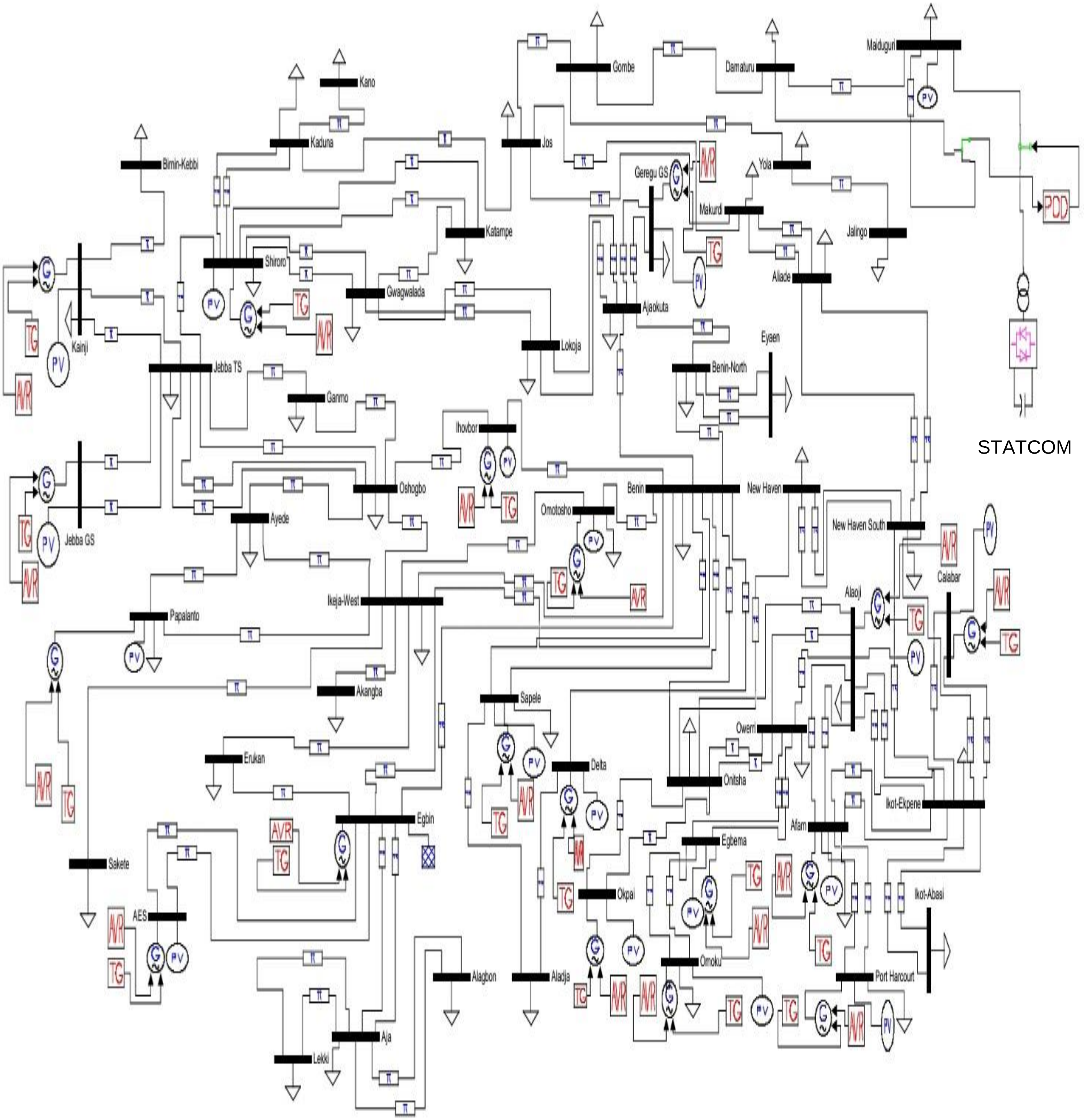

Figure 2: PSAT preparation of the Nigerian transmission system

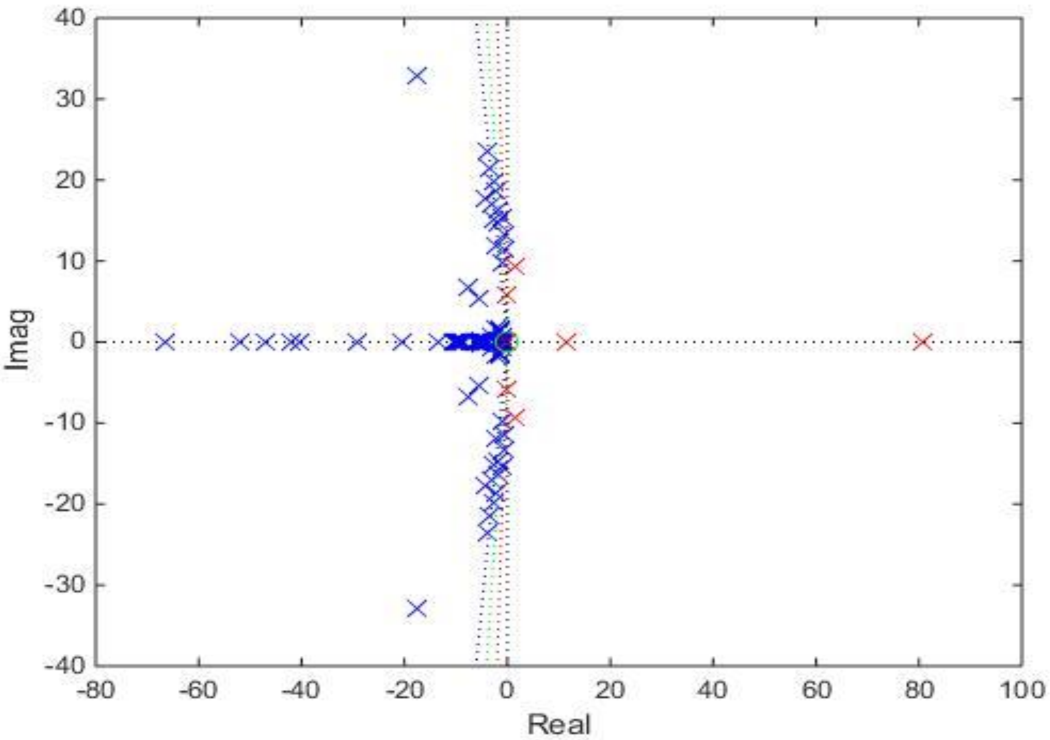

Figure 3: Nigerian Transmission Network Eigenvalues Plot

Table 1: Power Flow Results of Nigerian Transmission System without and with STATCOM

Bus Number	Bus Name	V [p.u]	Phase [rad]	V [p.u] (STATCOM)	Phase [rad] (STATCOM)	$P_{(gen)}$ [p.u]	$Q_{(gen)}$ [p.u]	$P_{(load)}$ - [p.u]	$Q_{(load)}$ [p.u]
1	AES	1	0.0766	1	0.0766	2.452	-1.2769	0	0
2	Afam	1	-0.60379	1	-0.60304	7.2	3.8245	5.34	4.01
3	Aja	1.0264	-0.00671	1.0264	-0.00671	0	0	1.15	0.86
4	Ajaokuta	0.98389	-0.4617	0.98389	-0.46091	0	0	1.2	0.9
5	Akangba	0.97223	-0.10125	0.9722	-0.10118	0	0	2.03	1.52
6	Aladja	0.98813	-0.26642	0.98813	-0.26618	0	0	2.1	1.58

7	Alagbon	1.0237	-0.00955	1.0237	-0.00955	0	0	1.2	0.9
8	Alaoji	1	-0.6039	1	-0.60315	2.5	3.6042	4.67	2.7
9	Aliade	1.0119	-0.75728	1.0388	-0.75555	0	0	0.95	0.56
10	Ayede	0.95599	-0.15938	0.956	-0.15921	0	0	1.74	1.31
11	Benin	0.98774	-0.27207	0.98782	-0.27183	0	0	1.44	1.08
12	Benin-North	0.97714	-0.30441	0.97721	-0.30414	0	0	0.8	0.6
13	Birnin-Kebbi	0.96885	-0.32586	0.96885	-0.32535	0	0	1.52	1.22
14	Calabar	1	-0.56143	1	-0.56059	6.18	-1.6496	0	0
15	**Damaturu**	**0.83123**	**-0.89005**	**1.02**	**-0.88485**	**0**	**0**	**0.24**	**0.18**
16	Delta	1	-0.25154	1	-0.25129	3.41	1.8601	0	0
17	Egbema	1	-0.57805	1	-0.57736	2.5	0.85026	0	0
18	Egbin	1.033	0	1.033	0	3.3745	1.8378	0	0
19	Erukan	1.0031	-0.04787	1.0031	-0.04784	0	0	1.2	0.9
20	Eyaen	0.97397	-0.30921	0.97403	-0.30894	0	0	4.4	2.2
21	Ganmo	0.9786	-0.28828	0.97861	-0.28783	0	0	1	0.75
22	Geregu GS	0.985	-0.46103	0.985	-0.46024	4.85	5.3888	2	1.5
23	**Gombe**	**0.8529**	**-0.86305**	**0.97675**	**-0.85664**	**0**	**0**	**0.68**	**0.51**
24	Gwagwalada	0.95312	-0.63606	0.95315	-0.63485	0	0	2.2	1.65
25	Ihovbor	1	-0.26465	1	-0.26439	1.166	1.8212	0	0

26	Ikeja-west	0.98095	-0.09217	0.98095	-0.0921	0	0	8.47	6.35
27	Ikot-Abasi	0.98025	-062612	0.98104	-0.62544	0	0	2.27	1.7
28	Ikot-Ekpena	0.99977	-0.60578	1.0005	-0.60513	0	0	1.4	0.5
29	**Jalingo**	**0.82987**	**-0.89122**	**0.95684**	**-0.87798**	**0**	**0**	**0.2**	**0.15**
30	Jebba GS	1	-0.29759	1	-0.29706	4.03	4.6967	0	0
31	Jebba TS	0.99422	-0.30138	0.99423	-0.30087	0	0	2.6	1.95
32	Jos	0.92496	-0.78518	0.97558	-0.78393	0	0	0.72	0.54
33	Kaduna	0.93933	-0.737	0.96009	-0.736	0	0	1.43	0.98
34	Kainji	1	-0.29565	1	-0.29514	2.92	2.3488	0.89	0.67
35	Kano	0.90639	-0.7734	0.92794	-0.77078	0	0	1.94	1.46
36	Katampe	0.94196	-0.68275	0.94198	-0.68145	0	0	3.03	2.27
37	Lekki	1.0237	-0.00949	1.0237	-0.00949	0	0	1.15	0.86
38	Lokoja	0.96972	-0.50391	0.96974	-0.50303	0	0	1.2	0.9
39	**Maiduguri**	**0.82488**	**0.89936**	**1.05**	**-0.89469**	**0**	**0**	**0.31**	**0.2**
40	Makurdi	0.99333	-0.77104	1.0241	-0.77104	0	0	1.85	0.65
41	New Haven	1.0984	-0.69214	1.0990	-0.69161	0	0	1.96	1.47
42	New Haven South	1.0981	-0.69234	1.0990	-0.69181	0	0	1.75	1.31
43	Okpai	1	-0.52842	1	-0.52789	4.66	0.9245	0	0

							3		
44	Omoku	1	-0.57764	1	-0.57695	0.448	0.18241	0.3	0.2
45	Omotosho	1.0006	-0.20101	1.0006	-0.20084	1.655	3.1355	1.2	0.58
46	Onitsha	0.98815	-0.56551	0.9898	-0.56514	0	0	5.13	3.7
47	Oshogbo	0.97342	-0.26372	0.97343	-0.26334	0	0	1.27	0.95
48	Owerri	0.9969	-0.58503	0.99706	-0.58435	0	0	1.8	0.75
49	Papalanto	0.973	-0.09328	0.973	-0.09319	2.04	-0.1842	0.71	0.58
50	Port Harcourt	1	-0.61381	1	-0.61305	1.78	1.7618	3.16	1.58
51	Sakete	0.9485	-0.13814	0.9485	-0.13807	0	0	2.05	1.11
52	Sapele	1	-0.25932	1	-0.25908	3.45	2.8576	1	0.77
53	Shiroro	1	-0.65792	1	-0.65652	3	9.7053	1.7	0.98
54	**Yola**	**0.83433**	**-0.88556**	**0.96071**	**-0.87371**	**0**	**0**	**0.26**	**0.3**

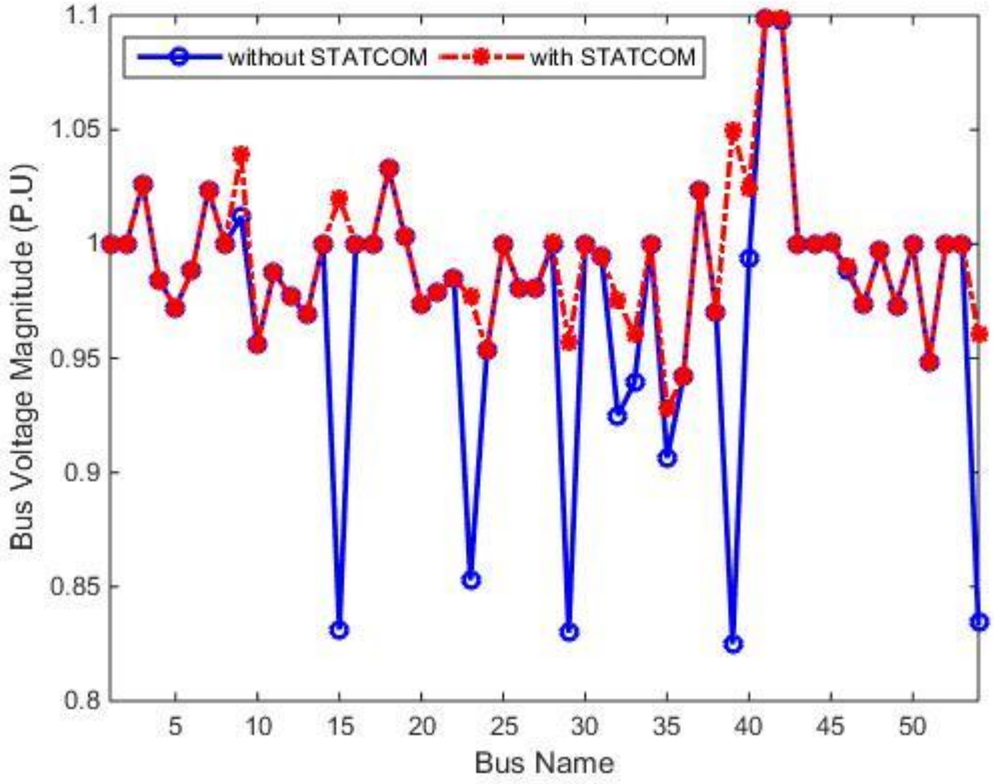

Figure 4: Voltage Profiles of Nigerian Transmission System without and with STATCOM Controller

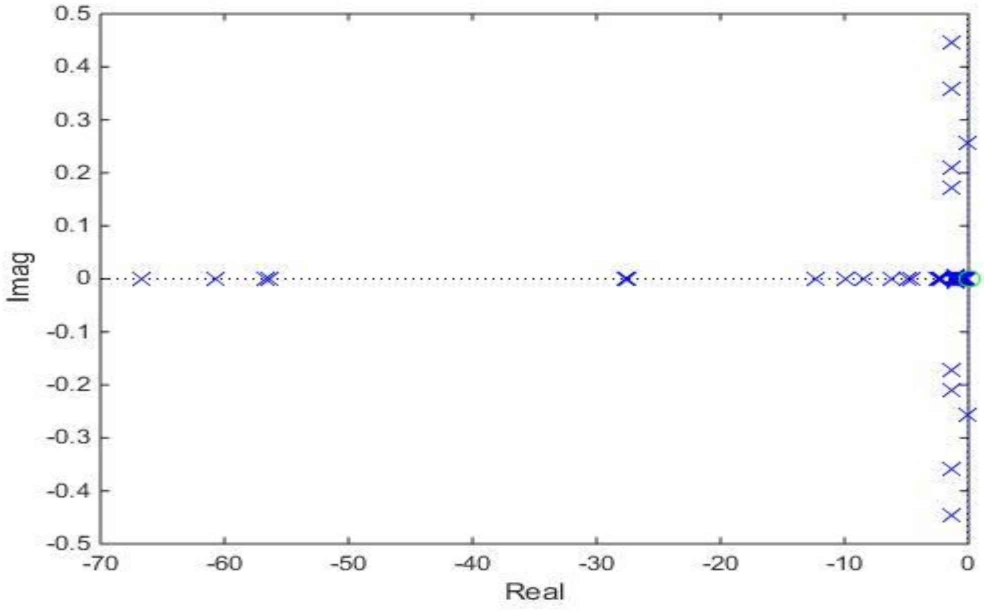

Figure 5: Nigerian Transmission Network with STATCOM Controller Eigenvalues Plot

4. CONCLUSION

The power flow and small-signal stability analyses of the Nigerian transmission system has been carried out. The power flow results of the simulation revealed that the network is weak with voltage limit violation which confirmed the work of previous researchers (Adepoju *et. al.,* 2011). The incorporation of STATCOM was able to bring the voltages within limit. The eigenvalues results revealed that the network is small-signal unstable confirming (Ogunjuyigbe and Gonoh, 2022). The enhancement of the system's stability was achieved using STATCOM controller. Therefore, STATCOM controller enhanced the small-signal stability of Nigerian transmission network.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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