Journal of Newviews in Engineering and Technology, Vol. 7(1), (2025) 143–152.

Journal of Newviews in Engineering & Technology
Faculty of Engineering
Rivers State University, Port Harcourt, Nigeria.
ISSN: 2795-2215
Email: rsujnet@gmail.com | Homepage: https://rsujournal.com

Impact of Dynamic Response on Generator Rotor Angle of an Island Generating Plant in the Nigerian Grid Network

A.E. Airoboman[a, *], A. Ibrahim[a], O.A. Ogunleye[a], R.N. Okparanma[b]

[a] *Department of Electrical/Electronic Engineering, Nigerian Defence Academy, Kaduna, NIGERIA.*
[b] *Department of Agricultural and Environmental Engineering, Rivers State University, Nkpolu-Oroworukwo, PMB 5080, Port Harcourt, NIGERIA.*

**Corresponding Author:* airobomanabel@nda.edu.ng

ARTICLE INFO

Article History
Received: 8 January 2025
Received in revised form: 24 April 2025
Accepted: 27 April 2025
Available online: 31 July 2025

Keywords
Transient stability, Generator rotor angle, Dynamic load response, Artificial Neural Network (ANN), Nigerian grid network

ABSTRACT

This study investigated the impact of varying load demand and dynamic response on the generator rotor angle in the Nigerian grid network. Data spanning 7 years (2015 to 2022), including generator, transformer, line, cable, busway, energy flow, and single-line diagram information were collected from Shiroro Hydroelectric Power Station, Transmission Company of Nigeria (TCN), Mando and Kaduna Electricity Distribution Company (KAEDCO). Transient stability analysis was conducted using MATLAB 2020a, focusing on a 10-second window after disturbances. Results from power flow analysis showed high transformer loading, notably GWAGWADA at 124.7% and undervoltage issues in several buses, including Bus847 (93.94 V) and Bus1306 (84.06 V). The lowest undervoltage value was 84.06 V while the highest was 94.96 V (Bus758). The highest rotor angle deviation occurred during ADDL3-DROPL3 events, with a value of 9.785 degrees at 7.5 seconds. Compared with the IEEE 14 Bus system, which showed 3.907 degrees under similar conditions, the Shiroro Generator had a 5.878-degrees stability advantage. Artificial Neural Network (ANN) modelling of Shiroro Generator Units 2-4 was based on initial operating conditions. The ANN demonstrated satisfactory training, with regression values exceeding 0.9 and best validation performances of 64.12 and 1261.19 at early iterations. This study underscored the need for targeted interventions to enhance the transient stability of the Nigerian grid.

1. Introduction

Maintaining power system stability has long been a critical concern in system operation and remains a priority today. Modern electrical power systems have become increasingly complex due to increasing interconnections, installation of large generating units, and extra high voltage tie-lines etc. (Aligbe et al., 2021). Power system stability is the ability to return to normal or stable operating conditions after being subjected to some form of disturbance (Araga & Airoboman, 2021). Conversely, instability means a condition denoting loss of synchronization or falling out of step. Furthermore, stability is the tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain a state of equilibrium. The system is said to remain stable (stay synchronized) if the forces tending to hold machines synchronized with one another are sufficient to overcome the disturbing forces.

Dynamic stability is the ability of the power system to maintain stability under continuous small disturbances also known as small-signal stability. These small disturbances occur due to random fluctuations in loads and generation levels. The system can regain synchronization with the inclusion of automatic control devices including Automatic Voltage Regulators (AVR) and frequency controls. This is the extension of the steady state stability, which takes a longer time to clear the disturbances (Gupta & Sasry, 2019). As a result, power industries worldwide are moving towards deregulation, which allows for competition, even though it makes electrical power systems more complicated.

Stability problem is concerned with the behaviour of the synchronous machine after disturbances. Consequently, the monitoring of electric power system dynamics becomes vital to evaluate and enhance the performance of system operation at all levels of loading due to excessive number of possible contingencies. Dynamic stability problems associated with power generating systems have been widely documented (e.g., Ariyo et al., 2013; Barus and Pranomo, 2013; Mahmud et al., 2013; Airoboman et al., 2015; Okakwu and Ogujor, 2017; Adress and Millanovic, 2018; Gupta et al., 2019; Khan *et al*., 2020; Ahmed et al., 2020; Charafeddine et al., 2021; Ahmed et al., 2021).

Central to these prior studies is the vast amount of concentration on the dynamic stability challenges of individual generating units without focusing on the dynamic impact of system connectivity. Currently, there is little information in the literature on the significance of interlinking electricity systems (e.g., Nahas et al., 2023).

Consequently, there is a need for comprehensive dynamic studies of the systems to assess the influence of interconnectivity on system parameters including (but not limited to) generator rotor angle while accounting for power growth. In the Nigerian grid network, available records show that studies have focused more on either the Kaduna Electricity Distribution Company (KAEDCO) Town 1 Injection Substation 132/33kV Network or KAEDCO Town 2 Injection Substation 132/33kV Network without considering recent network expansion and the prospects of interlinking the two systems. Therefore, there is a need to holistically analyse a potential hybrid KAEDCO Towns 1 and 2 Networks to comprehensively examine the impact of varying load demand and dynamic response on the generator rotor angle island Nigerian grid network. This study focused basically on the Artificial Neural Network (ANN) modelling and ETAP simulation of the system to monitor the effect of varying/dynamic load on the stability of generation for a long period of time.

2. MATERIALS AND METHODS

2.1 Materials/Data

The data used for this study were obtained from Shiroro Generating Station and Kaduna Town 1 transmission station. The data from Shiroro Generating Station and the single-line diagram of KAEDCO 132/33kV Kaduna Town 1 transmission station are presented in Table 1 and Figure 1, respectively.

Table 1: Values of Shiroro Generator Modelling Parameters.

Parameter	Value
Pole (P)	4
Frequency (f)	50 Hz
Power Factor	0.85
Rated Voltage	330 kV
Rated Power	155 MW
Inertia Constant (H)	7.5 MJ/MVA
RPM	1,800

2.2 Methods

Figure 2 shows the process flow chart for this study while equation 1 is the summarized equation of the Newton-Raphson Algorithm. Correspondingly, equations 2–6 show the modelling of the Shiroro plant. The values in Table 1 were substituted into the appropriate equations to get the required model results. MATLAB version 220a (The MathWorks Inc., USA) was used to implement ANN on the ETAP simulation results (Table not shown). Figure 3 shows custom neural view of Shiroro Generator7 (PV Unit 2-4) having the following parameters and values: input:1; hidden layer:14; output layer:7 and output: 8. Figure 3 also shows ANN training view having a training algorithm of Levenberg-Marquardt because of its result. However, the following transfer functions were implemented in the hidden layers: Layer 1: LOGSIG; Layer 2; TANSIG; and Layer 3: PURELIN. These combinations of transfer functions were executed for multiple training to get a regression as close to unity as possible. The ANN-based supervised learning architecture (Figure 3) was employed on the post-fault values of generator rotor angle trajectory as input and predicted the final values of the rotor angle trajectory and time for a period of one year at which critical generator crossed the system stability.

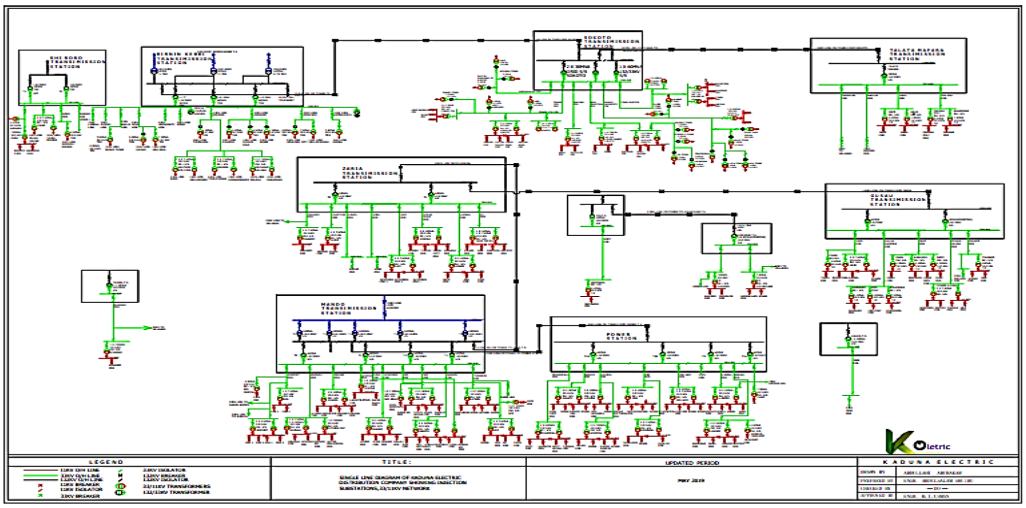

Figure 1: Single-Line Diagram of Kaduna Electricity Distribution Company (KAEDCO) 132/33kV Kaduna Town 1 Injection Station.

$$\begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_N} & |V_2|\frac{\partial P_2}{\partial |V_2|} & \cdots & |V_4|\frac{\partial P_2}{\partial |V_4|} \\ \vdots & \mathbf{J11} & \vdots & \vdots & \mathbf{J21} & \vdots \\ \frac{\partial P_N}{\partial \delta_2} & \cdots & \frac{\partial P_N}{\partial \delta_N} & |V_2|\frac{\partial P_N}{\partial |V_2|} & \cdots & |V_N|\frac{\partial P_N}{\partial |V_N|} \\ \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_N} & |V_2|\frac{\partial Q_2}{\partial |V_2|} & \cdots & |V_4|\frac{\partial Q_2}{\partial |V_4|} \\ \vdots & \mathbf{J12} & \vdots & \vdots & \mathbf{J22} & \vdots \\ \frac{\partial Q_N}{\partial \delta_2} & \cdots & \frac{\partial Q_N}{\partial \delta_N} & |V_2|\frac{\partial Q_4}{\partial |V_2|} & \cdots & |V_4|\frac{\partial Q_4}{\partial |V_4|} \end{bmatrix} \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_N \\ \frac{\Delta|V_2|}{|V_2|} \\ \vdots \\ \frac{\Delta|V_N|}{|V_N|} \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_N \\ \Delta Q_2 \\ \vdots \\ \Delta Q_N \end{bmatrix} \quad (1)$$

$$\text{MVA rating of Shiroro Generator (S)} = \frac{\textit{Rated Power}}{\textit{Power Factor}} \quad (2)$$

$$\text{S} = \frac{155}{0.85} = 182.35MVA$$

$$\text{Stored K. E.} = \text{H}\left(\frac{MJ}{MVA}\right) \times S\ (MVA) \quad (3)$$

$$\text{Stored K. E.} = \frac{7.5MJ}{MVA} \times 182.353MVA = 1367.64MJ$$

$$\text{Synchronous Speed of Generator (RPS)} = \frac{2f}{P} \quad (4)$$

$$\text{Synchronous Speed of Generator (RPS)} = \frac{2 \times 50}{4} = 25rps$$

$$Moment\ of\ Inertia = \frac{2H}{MVA} \times \frac{S}{2\pi f/_P} \quad (5)$$

$$\therefore Moment\ of\ Inertia = \frac{2 \times 7.5}{MVA} \times \frac{182.353MVA}{2 \times 3.142 \times 50/_4} = 34.8$$

Generator Acceleration Swing equation is given by equation 6.

$$P_s - P_e = \frac{H}{\pi f} \times \frac{d^2\delta}{dt^2} \quad (6)$$

$$\therefore \text{Acceleration } (\alpha) = \frac{d^2\delta}{dt^2} = \frac{\frac{\pi f}{H}(P_s - P_e)}{S} \quad (7)$$

Substituting, $\alpha = \frac{d^2\delta}{dt^2} = 0.00098011$ (electrical degrees/sec^2).

Considering that the machine is a 4-pole machine (i.e., 2 pairs of poles), acceleration in mechanical degrees/sec was calculated as follows.

$$\alpha = \frac{d^2\delta}{dt^2} = 0.00098011/\text{Pole pairs}$$

$$\alpha = \frac{d^2\delta}{dt^2} = 0.00098011/2 = 0.000490055$$

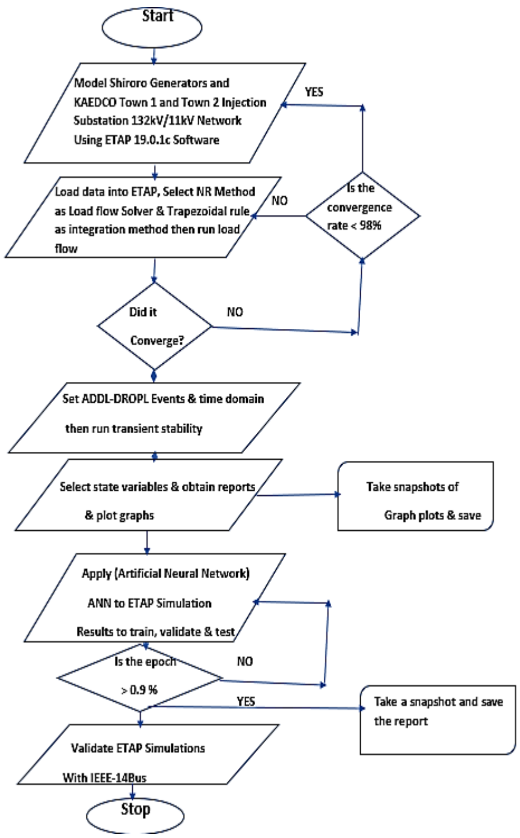

Figure 2: Flow-Chart of Impact of Varying Load Demand and Dynamic Response on the Generator Rotor Angle of Island Nigerian Grid Network.

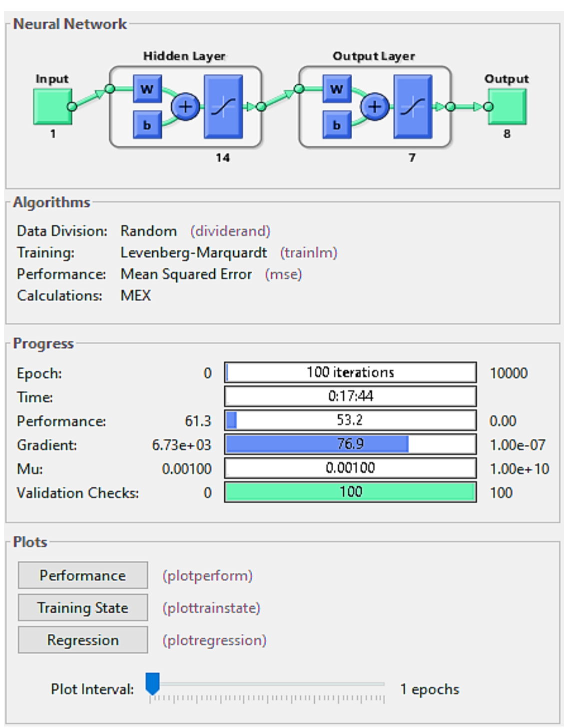

Figure 3: ANN training Network View of Shiroro Generator 7 (PV (Unit 2-4)).

3. RESULTS AND DISCUSSION

3.1 Load Flow Analysis

Load flow study as an essential analysis for power system was executed to calculate the sinusoidal steady state of system voltage, the generated and absorbed active power, P (MW) and reactive power, Q (MVAr), as well as power losses. The voltage magnitude of each bus and its angle was calculated when the power generators and loads are predefined. Then with the following event ID (ADDL1-DROPL1; ADDL2-DROPL2; ADDL3-DROPL3) and time (1.00:1.300; 3.00:3.200; 7.00:7.500) linked with a simulation time range of 10s, the platform to ascertain and view the behaviour of the system at the time of normal and emergency operating conditions was obtained. Table 2 displays the summary of load flow analysis.

Table 2: Summary of Load Flow Analysis

Study ID	Description
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	678
Branches	672
Generators	4
Power Grids	0
Loads	193
Load-MW	207.861
Load-MVAr	20.225
Generation-MW	215.428
Generation-MVAr	64.11
Loss-MW	7.567
Loss-MVAr	43.885
Mismatch-MW	0
Mismatch-MVAr	0

From Tables 1 and 2 and Figure 4, the following parameters: Bus (ID, kV), Voltage (% Magnitude, Angle), Generator (MW, MVAr), Load (MW, MVAr), and Load Flow (ID, MW, MVAr, Amplitude, %PF, %Tap) that provide important information to reduce or minimize kW and KVAr losses, optimized circuit usage, transformer tap setting identification, pragmatic voltage profile development as well as equipment specification guidelines were ascertained.

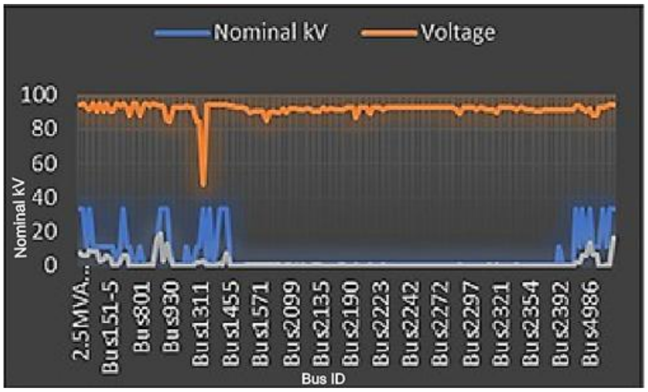

Figure 4: Bus Load-Flow Analysis

As observed in Table 2, there was a complete absence of mismatch since Mismatch-MW = 0 and Mismatch-MVAr = 0, suggesting that the load flow analysis was successful. Table 3 displays branch load-flow analysis. The % loading in column five indicates 14 scenarios with high percentage loading. As observed in Table 4, the Shiroro generating station has four units, which have been arbitrarily tagged as Gen5, Gen7, Gen8, and Gen9. It is essential to state that Gen5 is the Swing/slack Generator because it is fundamentally presumed to generate power necessary for losses in the system; while Gen7, Gen8, and Gen9 are PV Generators. For bus load-flow analysis, percent loading showed 163 scenarios with observed undervoltage (Table not shown). For instance, in Figure 4, the portion decoded as: Bus ID: 2.5MVA water board; nominal kV: 33; voltage: 94.61; and MW loading: 19 is an indication of undervoltage on 2.5MVA water board. Similarly, another portion was decoded as: Bus ID: Bus847; nominal kV: 33; voltage: 93.94; and MW loading: 19. 126, an indication of undervoltage on Bus847. Furthermore, it was observed that bus1306 and bus1311 had the same undervoltage value of 84.06V, which was the lowest value. Moreover, the highest undervoltage value was 94.96V possessed by Bus758.

Table 3: Branch Load Flow Analysis

ID	MW Flow	MVAr Flow	Amp Flow	% Loading
11kV High cost	6.61	4.097	462.9	143.1
11kV Leventis	5.394	2.842	345.8	106.9
11kV Narayi village	6.739	4.205	473.3	146.3
Cable2-2	7.681	0.0063	418.8	138.2
Cable2-2-1	6.389	0.0043	347.3	114.6
Cable7	6.739	4.205	473.3	158.9
Cable13-2	8.05	0.0069	439	144.8
Cable13-2-1	6.241	0.0041	339.3	111.9
Cable13-2-4	5.67	0.0035	313.6	103.4
GWAGWADA	0.313	0.205	7.128	124.7
JAJI T1	8.167	0.659	156.3	109.3
RAGASA T-2	15.914	1.111	285.9	106.4
S/GARI 2	0.772	0.518	17.55	185.8
Zaria3	15.056	2.226	278.4	101.5

Table 4: Shiroro Generator Simulation Data.

ID	Rating/Limit	Rated kV	MW	MVAr	Amp	% PF	% Generation
Gen5 (Unit-1)	155 MW	330	215.428	64.11	393.2	95.85	139
Gen7 (Unit-2)	155 MW	330	0	0	0	0	0
Gen8 (Unit-3)	155 MW	330	0	0	0	0	0
Gen9 (Unit-4)	155 MW	330	0	0	0	0	0

3.2 Rotor Angle Stability

In this study, rotor angle transient stability was also examined. As shown in Figure 5, Gen5 (Swing) simulation result, which is a slack bus has consecutive rotor angle of 0° and excitation voltage (Efd) of 2.5pu. Additionally, from the MATLAB ANN simulation result (Table not shown), Gen5 (Swing) at time 0 sec has a rotor angle of 0° with a mechanical power of 218.198MW and electrical power of 215.427MW. Since the mechanical power is greater than the electrical power, the system is unstable for the time being and the accelerating power is a positive value of 2.7704 MW. Similarly, Gen5 possesses constant excitation voltage (Efd) of 2.59pu because it is a swing generator alongside an adjustable excitation current (Ifd) to have a persistent excitation voltage (Efd). Also, due to instability, the percentage impedance (%Z) had a low value of 81.13% but gradually increased to 87.94% at 0.16 sec due to stability. The mechanical/electrical power ratio at 0 sec was 101.29%: a clear-cut proof of their close relationship. While the percentage change in mechanical power was fast to be constant at 1.6% from 0 to 0.3 sec, the percentage change in electrical power had a slow starting value of 0.3%, which became stable at 0.2 sec downwards with a value of 1.2%.

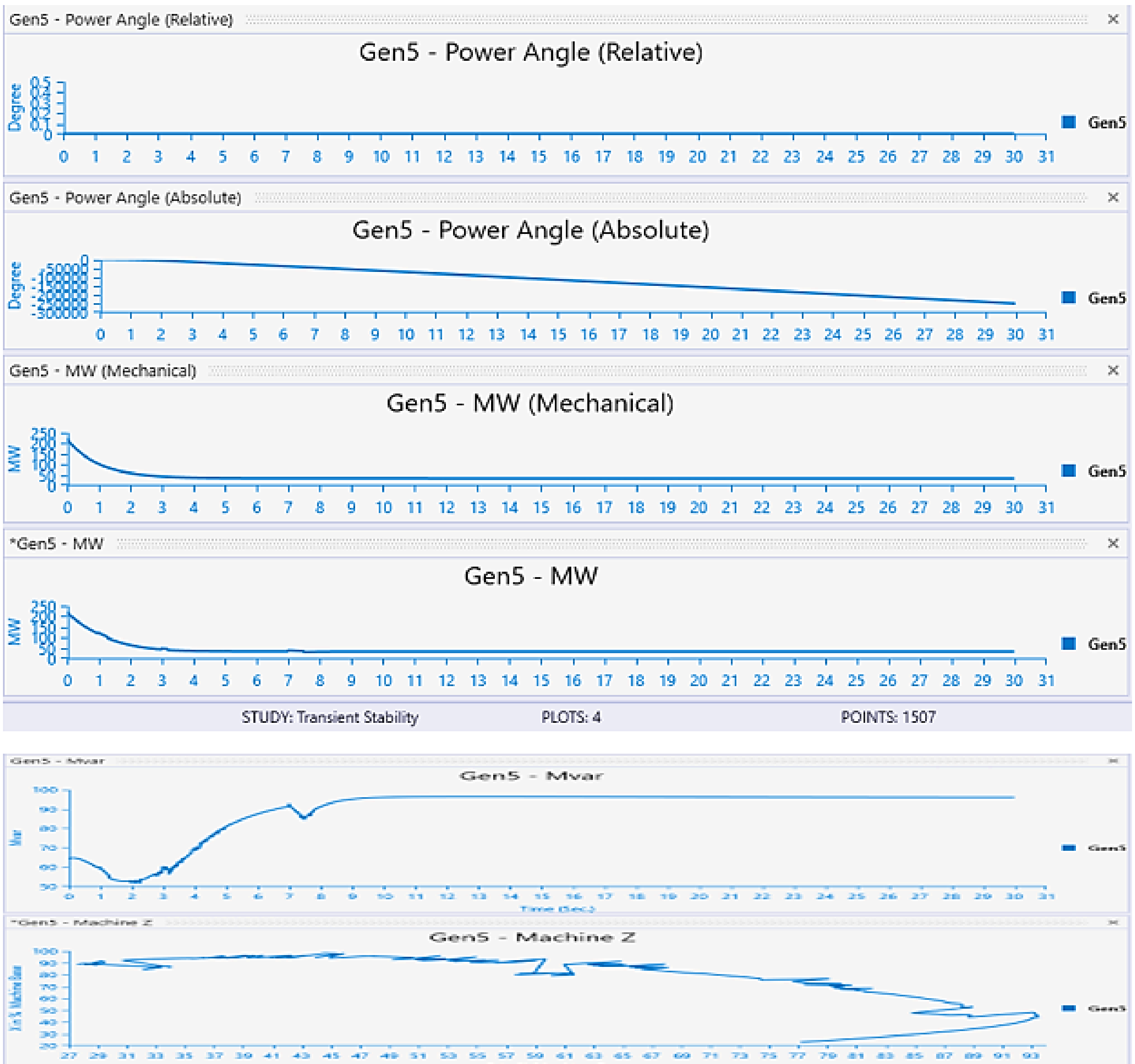

Figure 5: Shiroro Generator ((swing) Gen5 Unit-1) Transient Stability Plots.

A holistic analysis of Figure 6, Shiroro Generator Gen7 (Unit2 PV), Gen8 (Unit3 PV), and Gen9 (Unit4 PV) simulation result, showed that at 0 sec, the rotor angle was -49.208 degrees with a mechanical and electrical power of 0 MW, respectively, indicating steady state stability. Moreover, percentage impedance (%Z), mechanical/electrical power ratio (%), percentage change in mechanical power (%), percentage electrical/mechanical variation ratio (%), accelerating power (MW) and percentage frequency variation (%) have a value of 0; yet excitation voltage (Efd) had a steady value of 1.0657pu. However, excitation current (Ifd) changed transiently at same value of 1.0657pu. At 0.02 sec, percentage impedance (%Z) skyrocketed to 78537.95%, possessing current of 0.406A, electrical power of 0.2282 MW, holding mechanical/electrical ratio of 0.00%, and percentage change in mechanical power of 0%; however, with a percentage change in electrical power of -426.31%. Correspondingly, a mechanical power of 0 MW that is lower than electrical power of 0.2282 MW: resulting in accelerating power of -0.2282 MW, a sign of deceleration and system stability. Nonetheless, frequency variation increased slightly to 0.01%.

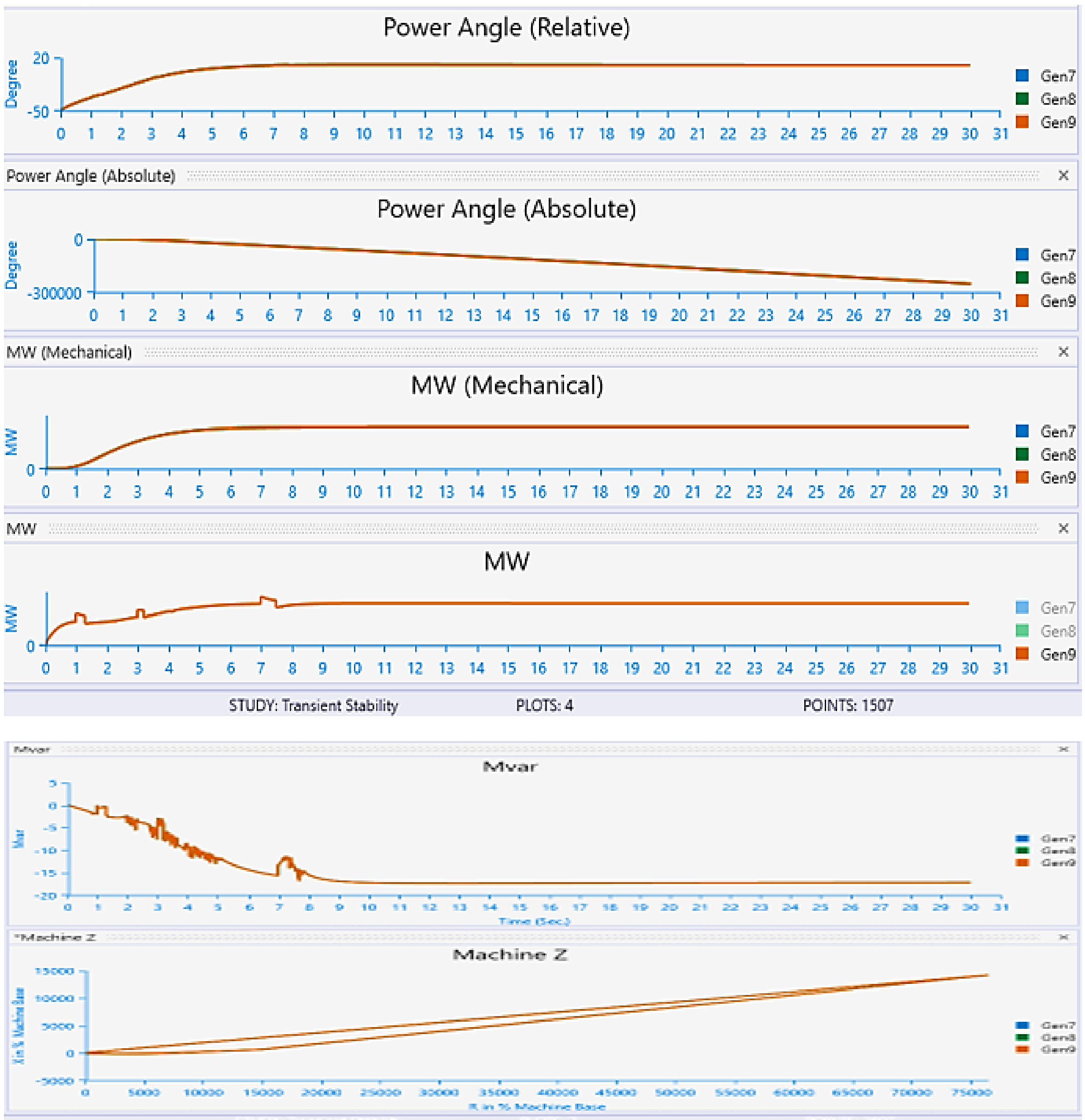

Figure 6: Shiroro Generator (PV) Gen7 Uni-2, Gen8 Uni-3, and Gen9 Uni-9 Transient Stability Plot.

Figure 8, the epoch (iteration) was changed from default value of 6 to 100 for efficient training. Similarly, Figure 9 displays ANN performance, the best validation performance was 1261.1906 at epoch (iteration) of 237. There were four legends tagged as: blue: Train; green: Validation; red: Test; and dotted grey: best. Figure 10 outputs ANN training state, possessing the following parameters and values: gradient: 76.8389 at epoch 100; Mu: 0.001 at epoch 100 and validation checks: 100 at epoch 100.

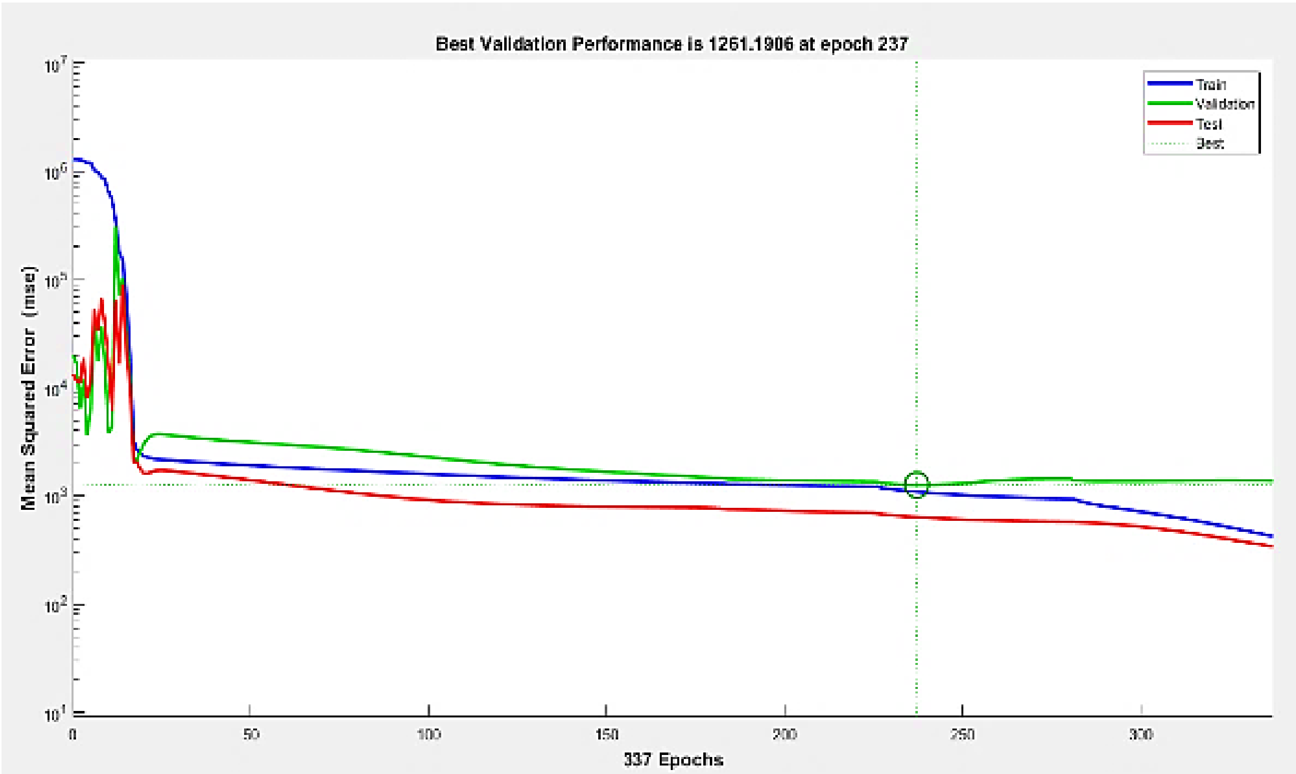

Figure 8: ANN Training Performance Epoch Shiroro Generator 7 (PV (Unit 2-4))

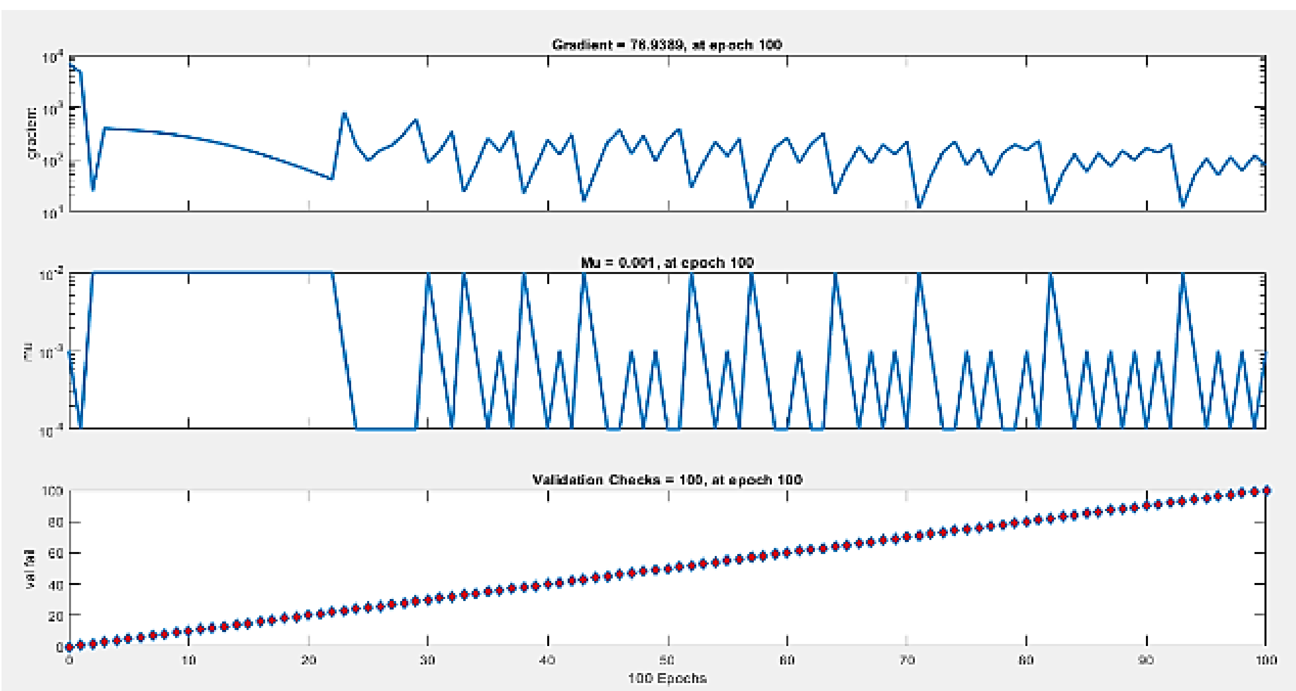

Figure 9: ANN Training State Shiroro Generator 7 (PV (Unit 2-4))

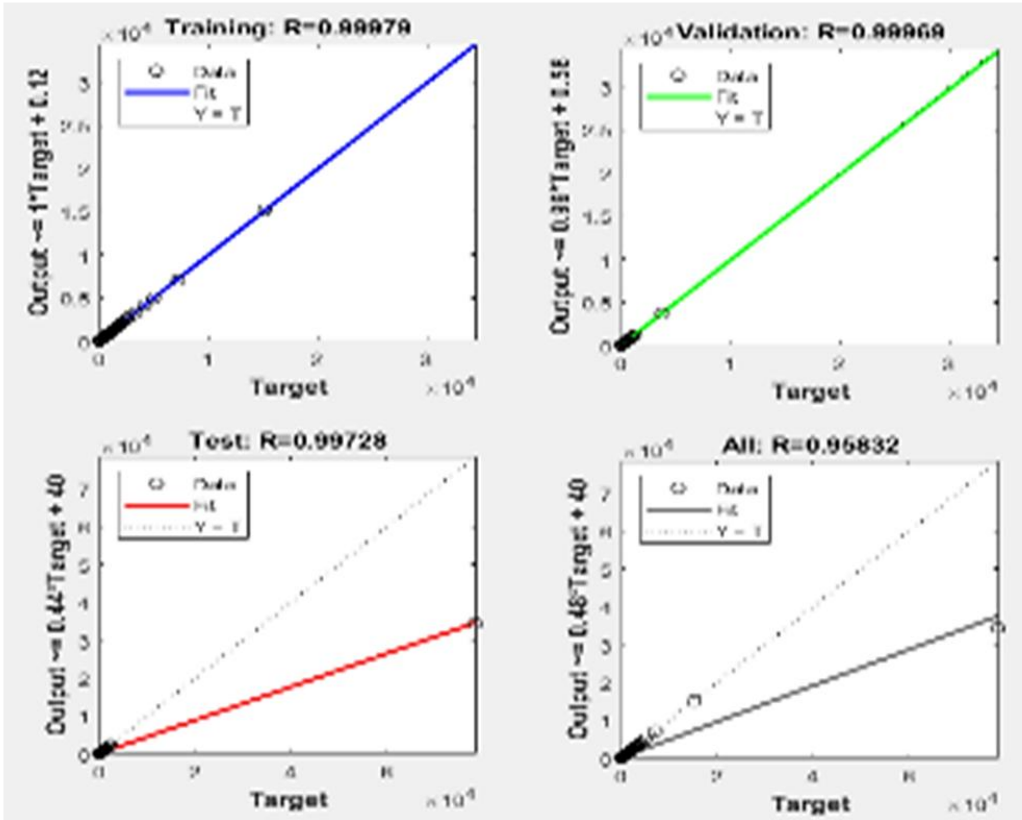

Figure 10: ANN Training Regression Shiroro Generator 7 (PV (Unit 2-4))

4. CONCLUSION

This study examined the impact of varying load demand and dynamic response on generator rotor angle of island Nigerian grid network and the following were obtained in terms of load flow analysis: GWAGWADA, Type: Transformer, MW Flow: 0.313, MVAr Flow: 0.205, Amp Flow: 7.128 and percentage loading: 124.7. This is an indication of high percentage loading on the GWAGWADA transformer having a value of 124.7%. Also, other portions were decoded including ID: JAJI T1, Type: Transformer, MW Flow: 8.167, MVAr Flow: 0.659, Amp Flow: 156.3 and percentage loading: 109.3. This is an indication of high percentage loading on the JAJI T1 transformer having a value of 109.3%. Bus ID: 2.5MVA WATER BOARD; Nominal kV: 33; Voltage: 94.61; and MW loading: 19 is an indication of under voltage in 2.5MVA WATER BOARD possessing a value of 94.61V. Also, another portion was decoded as: Bus ID: Bus847; Nominal kV: 33; Voltage: 93.94; MW loading: 19. 126, which is an indication of undervoltage on Bus847 having a value of 93.94. Furthermore, it was observed that Bus1306 and Bus1311 have the same undervoltage values of 84.06V, which was the lowest undervoltage value. Moreover, the highest undervoltage value was 94.96V recorded by Bus758. With respect to rotor angle stability, the lowest rotor angle recorded for Shiroro Generator (Gen7 (Unit-2), Gen8 (Unit-3), and Gen9 (Unit-4)), focusing on combined ADDL-DROPL events, was -33.0698 degrees and occurred at 1 sec, which was within 1-1.3 sec while the highest rotor angle occurred at 7.5 sec with a value of 9.785 degrees within 7-7.5 sec.

5. ACKNOWLEDGEMENTS

This research was sponsored by the Federal Government of Nigeria under the Tertiary Education Trust Fund (TETFUND) Institution-Based Research Grant number: TETF/DR&D/CE/NDA/IBR/2024/VOL. 1.

REFERENCES

Aligbe, A., Airoboman, A.E., Uyi, S.A., & Orukpe, P.E. (2021). Microgrid, Its Control and

Stability: The State of The Art" *International Journal of Emerging Scientific Research*. Vol. 3, pp. 1-12

Araga, I. & Airoboman, A.E. (2021). Enhancement of Voltage Stability in an Interconnected Network Using Unified Power Flow Controller. *Journal of Applied Science and Engineering (JASE)*. 4:65-74.

Adress A. & Millanovic, J. (2018). Effect of load models on angular and frequency stability of low inertia power networks. *The institute of Engineering and Technology, 13(19):1520-1526*.

Ahmed, A.H, Mohd. H.A., & Hamid, Y, (2020). Transient stability enhancement of power system with instability tolerant synchronous generator. *The Institute of Engineering and Technology,* 13(19):16-126.

Ahmed, Y., Sabry, W., & Hasanien, H.M. (2021). Enhancing rotor angle stability of power systems using marine predator algorithm based on cascaded PID control, *Ain Shams Engineering Journal, 12(2):1849-1857*.

Airoboman, A.E. Okakwu, I.K., Alayande, A., & Seun, O. (2015). On the Assessment of Power System Stability Using Matlab/Simulink Model, *International Journal of Energy and Power Engineering, 4(2):51-64*.

Ariyo, F.K., Fatunmbi, R.O., Lasabi, O.A., & Omoigui, M.O, (2013). Optimization of Distributed Generation on the Nigerian Electrical Grid. *Conference: ICIT 2013*.

Barus, D.H., & Pramono, E.Y. (2017). Dynamic System Monitoring and Control of Sumatera Power System Using PMU based on DFR. Proceedings of the International Conference on High Voltage Engineering and Power System, pp. 428-433.

Charafeddine, K., Ryzhkova, Y., & Matiunina, Y. (2021). Rotor Angle Stability of Synchronous Generator for Power Grid with Wind Energy. DOI: *10.1109/ICIEAM51226.2021.9446448*.

Gupta, A., Gurrala, G., & Sastry, P.S. (2019). An Online Power System Stability Monitoring System Using Convolutional Neural Networks**.** *IEEE Transactions on Power Systems***,** *34(2): 864-872*.

Khan, H.F., Hanif, A.H., & Anwar, N. (2020). Rotor Angle and Voltage Stability Analysis with Fault Location Identification on the IEEE 9 Bus System, *Eng. Technol. Appl. Sci. Res., 10(1):5259–5264*.

Mahmud, M.A., Hossain, M.J., & Pota, H.R. (2013). Effects of Large Dynamic Loads on Power System Stability. *International Journal of Electrical Power & Energy systems, 44(1):357-363*.

Nahas, A., Shalaq, M., & Chalah, M. (2023). Dynamic Stability of Synchronous Generators In Interconnected Power Systems: Case Study of Syria. *International Journal of Power Systems Research*, 12(4):325-340.

Nwohu, M.N., Isah, A.U., Usman, A., & Sadiq, A.A. (2016). Optimal Placement of Thyristor-Controlled Series Compensator (TCSC) on Nigerian 330kV Transmission Grid to Minimize Real Power Losses. *International Journal of Research Studies in Electrical and Electronics Engineering, 2(4):18-26*.

Okakwu, I.K., & Ogujor, E.A. (2017). Transient Stability Analysis of the Nigeria 330-kV Transmission Network. American Journal of Electrical Power and Energy Systems, 6(6):79-87.