© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1722769

Real-Time System Monitoring for Stability and Optimization of Port Harcourt Transmission Substation

AMADI, PROMISE CHIME[1], CHIZINDU STANLEY ESOBINENWU[2]
[1]*Engineering Management Programme, University of Port Harcourt*
[2]*Department of Electrical and Electronic Engineering, University of Port Harcourt, Rivers State, Nigeria*

Abstract- The dependability and reliability of transmission substations are vital for the delivery of safe and steady electricity across the Transmission Company of Nigeria (TCN) National Grid. The research undertakes real-time system monitoring for stability and optimization of the Port Harcourt Transmission Substation applying Electrical Transient Analyzer Program (ETAP) simulations and supplemented and optimized by Python-based Genetic Algorithm (GA). To achieve this, a model of the Port Harcourt Transmission Substation was developed in ETAP to conduct load flow, contingency and transient stability analyses. The model identified baseline weaknesses including voltage dips, feeder overloads, and frequency deviations. The simulation results were exported to a Python Genetic Algorithm (GA), where control parameters of turbine governor droop, Automatic Voltage Regulator (AVR) gain, Power System Stabilizer (PSS) settings, and Synchronous condenser capacity were then optimized iteratively through a fitness function to reduce voltage deviations, frequency instability, and thermal overloading from the ETAP simulations. Results indicated that prior to the optimization, the system was vulnerable to voltage instability, line overloads exceeding thermal limits, and oscillatory frequency deviations. But after utilization of the optimization model, all bus voltages were able to stabilize near 1.0 pu, loadings were balanced within safe voltage limits (i.e. 1.02 pu +/−) and the frequency oscillations were damped in a more consistent manner with better settling times. The Genetic Algorithm (GA) fitness evolution curve indicated progressive improvements, as seen with the fitness moving from approximately, 0.55 to 0.93. The conclusion of this study is that the ETAP – Python-Based Generic Algorithm (GA) integration provides an efficient, effective and resilient platform for monitoring and optimizing the stability of the System in real time and proves that it is possible to leverage a deterministic simulation, combined with evolutionary optimization, into an improved approach for increasing flexibility at the Port Harcourt Transmission Substation level in giving added value to Transmission Company of Nigeria (TCN) operations and contributing to the advancement of Smart Grid development in Nigeria.

Keywords: Transmission substation, ETAP, Genetic Algorithm, voltage stability, contingency analysis, transient stability, real-time monitoring, power system optimization, Nigeria power grid, load flow analysis

I. INTRODUCTION

In the electrical power network, the transmission substations form the basis or backbone as they facilitate bulk power wheeling or transportation from the moment power is generated at the various generating stations to distribution networks where power finally gets to the consumers. For system stability to be maintained, reliable operation is important for continuity of power supply and good quality. As a result of the critical position of the transmission substations, any disturbance along the line of transmission will create instability that will propagate across the entire transmission network. This disturbance if not checked the very moment it occurs has the capacity to cause cascaded tripping which could lead to possible system collapse and widespread blackouts. To avoid this worse scenario as the power system continues to grow and expand in size and complexity with very high demand of consumer loads, the need to employ a more advanced or intelligent control mechanisms for real-time system monitoring for stability optimization has become increasingly crucial if we must meet or provide power supply required to drive the economic, industrial, commercial and residential activities on daily basis.

In Nigeria for instance, the transmission power sector is still experiencing persistent operational and technical challenges ranging from frequency and voltage instability, frequent system collapses, transformer overloading, line congestion as well as lack of spare parts. These challenges are largely attributed to aging transmission infrastructure, vandalism, poor funding and corruption, rapid load growth, limited redundancy and insufficient integration of modern automation and optimization technologies and poor planning. Although the conventional

Supervisory Control and Data Acquisition (SCADA) systems have provided basic monitoring functions in the Nigerian transmission power network, yet they often lack advanced analytical and on-the-spot decision-support capabilities needed for proactive system operation for system stability.

The Electrical Transient Analyzer Program (ETAP) is one of the modern power system analysis tools that provide detailed modelling and simulation capabilities for evaluating system behaviour under various operating and contingency conditions. Yes, while ETAP is effective for system analysis, however, it does not inherently provide adaptive optimization of control parameters in real time. As a result of this intelligent optimization techniques, particularly Genetic Algorithms (GAs), provide a promising solution due to their ability to handle nonlinear, multi-objective optimization problems that is peculiar to power system operation.

On this note, this paper proposes a real-time system monitoring and stability optimization framework that in cooperates ETAP simulation with a Python-based Genetic Algorithm. This framework is a practical case study that is applied to the Port Harcourt 132/33 kV Transmission Substation. The objective is to demonstrate how intelligent optimization can improve voltage and frequency stability, reduce equipment loading and enhance transient stability performance in a real-world transmission network. This study addresses this gap by presenting a practical framework that combines ETAP-based monitoring with Genetic Algorithm optimization to enhance real-time stability monitoring and operational decision support.

II. METHODOLOGY

2.1 Description of the Study Substation

The Port Harcourt 132/33 kV Transmission Substation is a major transmission node within the Nigerian power grid due to its significant position in the major industrial area of the country. The substation is saddled with the responsibility of supplying ten number 33 kV distribution feeders serving industrial, commercial and residential consumers within and outside the city metropolis. Also, the substation consists of three number 60 MVA 132/33kV power transformers, bus bars, four 132 kV incoming transmission lines from Afam, Omoku, and Trans-Amadi Generating stations. The substation is highly sensitive to operational disturbances as a result of its high load demand and strategic importance. Appendix A is a typical diagram of the Port Harcourt 132/33kV Transmission Substation.

2.2 Substation Configuration and Modelling

For the purpose of this work, the single line diagram of Port Harcourt 132/33 kV transmission substation was modelled in Electrical Transient Analyser Program (ETAP). The actual operational parameters used for this model were obtained directly from the Transmission Company of Nigeria (TCN) records which include line parameters, transformer ratings, feeder load data, impedance characteristics and voltage control settings. The purpose is to ensure that the simulation results accurately reflect real operating conditions. A typical representation of the ETAP model of the Port Harcourt 132/33Kv is shown in appendix B.

2.3 ETAP System Modelling

After developing an accurate ETAP design or model of the Port Harcourt 132/33kV substation to represent a network topology by obtaining equipment parameters from the operational data of the substation like transformer ratings, feeder parameters and load characteristics, tripping reports and so on simulation began although these operational parameters were verified in order to ensure real simulation outcomes. In the event of this, load flow analysis was carried out to evaluate or analyse the steady -state, voltage profile, loading of equipment such as lines, transformers and outgoing 33kV feeders under normal operating condition and power flows.

Also, N-1 criteria were used to perform Contingency analysis in order to analyse or assess the system behaviour whenever there is transformer outages and feeder tripping. Again, in a bid to analyse system response to large disturbances, for instance, sudden loss of generator or load and three phase faults at critical bus section, transient stability simulation was conducted.

2.4 Genetic Algorithm Optimization Framework

A Python-based Genetic Algorithm was developed to optimize key operational parameters using ETAP simulation outputs. The Genetic Algorithm (GA) employed a population-based evolutionary approach consisting of selection, crossover and mutation operations. A multi-objective fitness function was defined to minimize voltage deviations, reduce line and transformer loading and improve transient stability indices.

Table 1: Genetic Algorithm Parameters Used for Optimization

Parameter	Value
Population Size	50.0
Number of Generations	100.0
Crossover Probability	0.80
Mutation Probability	0.05
Selection Method	Tournament Selection
Fitness Objective	Minimize voltage deviation and system losses

In a view to implementing the optimization process, the Genetic Algorithm (GA) tool was employed with a population size of 50.0 and a maximum generation limit of 100.0. In the process of implementation, a 0.80 crossover probability and 0.02 mutation rate were adopted in order to balance the exploitation and exploration in the search space. While maintaining system operational constraints, the objective function reduced bus voltage deviation across the transmission network.

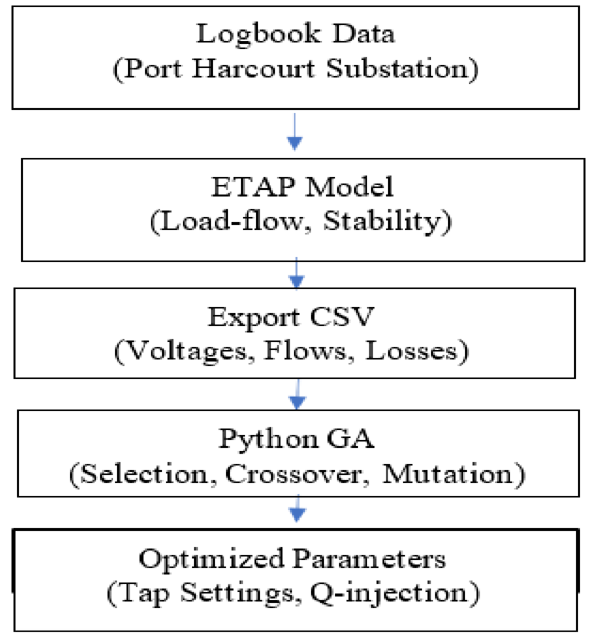

Figure 1: ETAP and Python-based Generic Algorithm Flowchart

For the optimization process to happen, there must be data iterative exchange between ETAP and the Genetic Algorithm (GA) in order to enable a continuous refinement of control parameters until convergence was attained.

2.5 ETAP–Python Integration Framework

This structure that was proposed enables a two-way or bidirectional communication between ETAP and a Python-based Genetic Algorithm (GA) module. The bus voltages, transformer loading and frequency which are real-time system state variable deviation were exported from ETAP to the Python environment through an application interface. The function of the Genetic Algorithm (GA) is to process all of these system inputs by analysing system fitness and deciding the adjustments of optimal control parameters. Again, these parameters that were upgraded are iteratively re-engaged to the ETAP design in order to achieve convergence criteria. The combination of both ETAP and Genetic Algorithm (GA) create opportunity that enhances dynamic system monitoring and real-time operational optimization despite the fluctuating load and contingency conditions.

© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1722769

2.6 Simulation Scenarios

In a bid to completely analyse this proposed framework, many real life or practical operating situations or scenarios as regard to system operations were taken into consideration. Some of these scenarios included the base case scenario, N-1 contingency conditions as well as the transient fault incidents that were applied at certain critical buses within the Port Harcourt transmission substation. Simulations were done for each of the scenarios aforementioned before and after optimization in order to ensure objective resemblance or correlation within the National grid.

Table 2: Summary of simulation scenarios and disturbance conditions

Scenario ID	Operating Condition	Disturbance Type	Location	Objective
S1	Base-case operation	None	Entire substation	Steady-state load flow assessment
S2	Contingency case	Transformer outage (N−1)	132/33 kV transformer	Voltage stability evaluation
S3	Fault condition	Three-phase fault	132 kV bus	Transient stability assessment
S4	Load variation	Sudden load increase	33 kV feeders	Dynamic response analysis
S5	Optimized operation	Same as S2–S4	Same locations	Before/after optimization comparison

III. RESULTS AND DISCUSSION.

3.1 Load Flow and Voltage Profile Analysis

The Port Harcourt 132/33kV transmission substation steady-state performance was evaluated under the base-case operating conditions using the ETAP load flow analysis. Results obtained showed that the buses operated within the permissible voltage limits of 0.95 – 1.05p.u. Nevertheless, the industrial, commercial and residential heavily loaded 33kv distribution feeders supplied by many critical 33kV buses operated close to the lower acceptable range which suggests that reactive power margin was minimal and due to the stressed conditions voltage was suppressed.

The steady-state bus voltage profile under normal and N-1 contingency conditions are as shown in figure 3 below. During normal operating condition voltage remains within the permissible range while reductions in voltage across the various buses is observed in the contingency scenario results. Refinery 2, 33kv feeder experiences the most significant voltage drop to 0.95p.u showing that voltage stability is weak under outage conditions. Although the system does not negate operating limitations or restrictions, the minimized voltage margins show susceptibility or exposure and this justifies the need to enhance system resilience through strategic optimization procedures.

3.2 Contingency Performance Assessment

For the purpose of analysing the robustness of the system, N-1 contingency analysis was conducted by simulating the outage of Afam- PH Line 1 transmission line. By subjecting the system under stress operating condition, load increase was noticed on the parallel transmission lines and along the downstream 33kV distribution load feeders. Accordingly, it was observed that many of the buses experienced voltage depression and the Refinery 2 bus suffered the most significant decrease put at 0.95p.u. Despite the fact that voltage remained within the operating limits, the decreased stability margins show increased vulnerability to continued or many contingency events. These observations or findings corroborate the need for system strengthening using intelligent optimisation tools in order to improve the reliability and stability of the power system thereby minimizing the potential of cascaded tripping.

DOI: https://doi.org/10.64388/IREV10I3-1722769

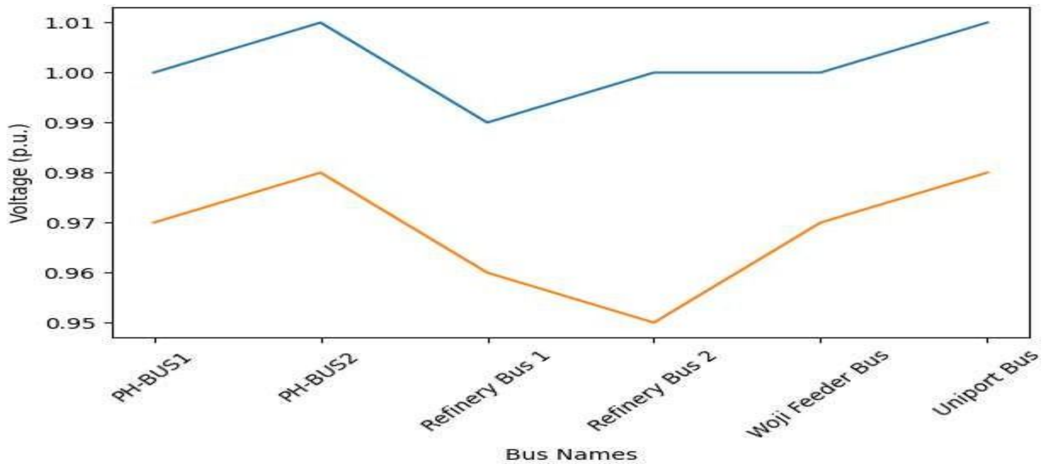

Figure 2: Bus Voltage profile under normal and N-1 contingency conditions

Transient Stability Analysis

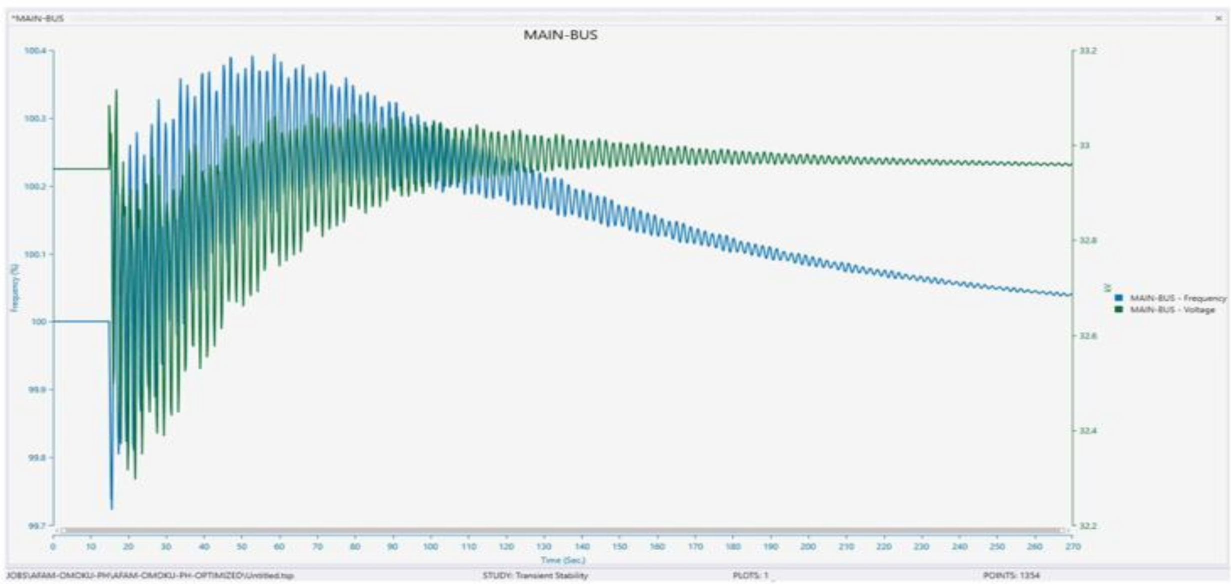

Figure 3: Response of Voltage and Frequency: Before Genetic Algorithm-Based Optimization

In a bid to evaluate the dynamic behaviour of the Port Harcourt 132/33kV transmission system when subjected to distortions, transient stability analysis was carried out. Monitoring the changes in the bus voltage magnitude and frequency of the system as a result of the distortions or disturbances in the network the dynamic response of the system was analysed. The ETAP dynamic analysis module was used to carry out the simulation in a view to observe or monitor the characteristics of the system stability before and after optimization using Genetic Algorithm. For the case of before- optimization dynamic response shown in figure 3 above, it was observed that the system showed visible vibrations in both system voltage magnitude and frequency just after the disturbance happened. There was a temporary drop in voltage before a gradual recovery to its usual steady-state level while the frequency of the system displayed transient variations before stabilising back to its nominal value of operation. These observed vibrations showed that the system had very minimal damping ability under the initial operating states.

Having applied the optimization approach, the result obtained after- optimization as indicated in figure 4 below proved a substantial enhancement or improvement in system stability. The deviations in two of the system variables; voltage and frequency were reduced and their vibrations were significantly suppressed out speedily as when compared with the before-optimization scenario as shown in figure 3 above. The ability of the system to maintain stability and suddenly return to steady-state operation after disturbances was improved upon by the optimized control parameters. This validates that the structure proposed for optimization substantially improved the transient stability performance of the Port Harcourt transmission network

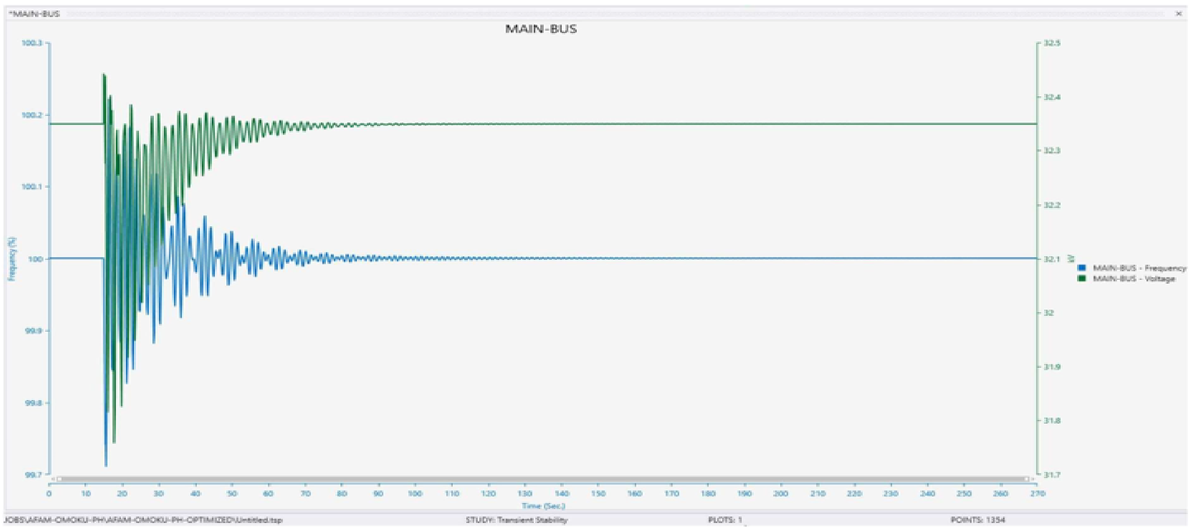

Figure 4: Response of Voltage and Frequency: After Genetic Algorithm-Based Optimization

3.3 Optimization Performance Evaluation

In order to evaluate the proposed Genetic Algorithm (GA) effectiveness, convergence characteristics and fitness improvement trend were analysed. The essence of implementing the Genetic Algorithm (GA) is to optimize key system control parameters like regulation of voltage settings, reactive power allocation variables with the intention of reducing voltage deviation and improving the performance of transient stability. The convergency curve showed constant reduction in fitness value across successive generation. The population initially exhibited relatively high fitness results, showing a poor stability margins and extreme voltage variation. The Genetic Algorithm (GA) efficiently searched and verified the solution space and identified enhanced parameters combinations as the generations progressed, leading to a substantially reduced final fitness result. In comparing the optimized and unoptimized case, the optimized solution demonstrated a faster dynamic response, minimized overshoot and enhanced vibration characteristics unlike the unoptimized case. Again, the settling time was reduced significantly and voltage recovery due to system disturbances occurred swiftly. From the results obtained they prove that the Genetic Algorithm (GA) successfully improved both the steady-state and transient performance of the Port Harcourt substation.

© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1722769

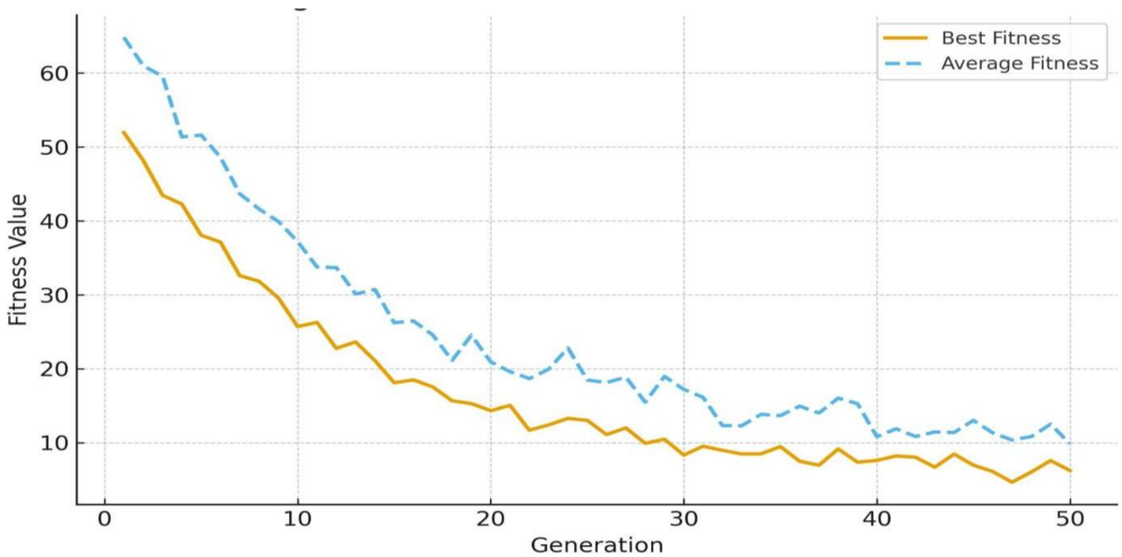

Figure 5: Genetic Algorithm (GA) fitness Evolution curve

From figure 5 above, the dynamic response shows clearly from the optimized case the improvement achieved using the proposed Genetic Algorithm (GA) based optimization tool. For the case of the unoptimized, three phase fault led to a sever voltage dip and significant frequency variations having a relatively long stabilizing time before attaining equilibrium state. The delay in recovery of amplitude of oscillations show dampening ability and fragile transient stability margins. On the other hand, the optimised system shows reduced voltage drop magnitude, enhanced vibration damping and quick return to nominal frequency. Significantly, the settling time was shortened even as frequency deviation remain within the allowable limits. As a result of this, the improvements of the Genetic Algorithm validate its effectiveness in enhancing the dynamic stability performance of the Port Harcourt 132/33kv transmission substation. The steady-state and dynamic performance improvements noticed have made the Port Harcourt substation to have practical significance for system operation. Considering the Port Harcourt 132/33kv transmission substation and other similar substations within Nigeria, this optimization structure that have been proposed can improve voltage regulation, minimise the risk of cascaded tripping during contingency conditions and enhance the overall reliability and stability of system operation. This proposal leverages on intelligent control optimization to provide an economic strategic option needed for the reinforcement of system infrastructure.

34. Comparative Performance Summary.

Comparatively, the results shown in table 3 below clearly explain the efficiency and effectiveness of the Genetic Algorithm (GA)-based optimization framework that is proposed to improve performance of operation of the Port Harcourt 132/33kv transmission substation. Before the optimization, the system exhibited visible and obvious voltage dips, that is, bus voltage dropping to 0.95p.u as minimum under contingency conditions. Just immediately after system optimization, the voltage profile significantly improved. The minimum bus voltage rose from 0.95p.u to 0.98p.u and the general voltage change across the various buses becomes symmetrical. Again, the optimised system showed minimised deviation in frequency and quicker voltage recovery as a result of the system disturbances. By these achieved improvements, the proposed optimization approach has proved to enhance system voltage reliability and stability, strengthen resilience, enforce compliance within the acceptable operational limit.

Table 3: Comparative Performance of the Power System Before and After Optimization

Performance Indicator	Before Optimization	After Optimization
Minimum Bus Voltage	0.95 p.u.	≈0.98 p.u.
Voltage Range	0.96 – 1.02 p.u.	0.98 – 1.01 p.u.
Maximum Voltage Deviation	0.05 p.u.	<0.02 p.u.
Frequency Deviation	±0.5 Hz	±0.2 Hz
Voltage Recovery	Slower	Faster
System Stability Margin	Limited	Improved

IV. CONCLUSION

This research is a presentation of an operational model for real-time system monitoring for stability and optimization of Port Harcourt Transmission substation using Electrical Transient Analyser Program (ETAP) simulation combined with a Python-based Genetic Algorithm (GA). This designed ETAP model activated a holistic assessment of the steady-state load flow, contingency conditions and the behaviour of transient stability of the Port Harcourt Transmission substation under real or actual operating scenarios. Results obtained after simulations revealed that during normal operating condition the system voltage level was maintained within the acceptable limits although contingency conditions like transmission line outages caused voltage reduction and increase on critical components indicating reduction in stability margins. Significantly, the application of Genetic Algorithm (GA) optimization improved system performance by reducing voltage deviations, enhancing recovery of voltage during disturbances and improving the damping of frequency vibrations during fault situations. Looking at the comparative analysis of key system performance indicators validated the optimised operating condition provided a more steady and resilient system response. The outcomes prove that combining intelligent optimization structures with real-time monitoring tools can significantly improve the operational reliability, stability and resilience of the Port Harcourt transmission substation. This proposed optimization structure provides a realistic data-driven approach for modernizing power system operation within the Transmission Company of Nigeria. Further work may concentrate on the integration of real-time supervisory control and data acquisition (SCADA) measurements with the optimization structure to activate automatic corrective control in the transmission network. This proposed framework can also include other essential substations in the Transmission Company of Nigeria (TCN) in a bid to further improve system reliability and operation effectiveness.

REFERENCES.

[1] Abubakar, M., & Salami, B. (2022). PLC-based real-time breaker monitoring in a 132/33 kV substation. Nigerian Transactions on Electrical and Electronic Engineering, 10(2), 91–99.

[2] Adebayo, T., Ojo, K., & Abiodun, M. (2024). Design and implementation of an automated real-time power distribution line monitoring system: A case study of Nigerian power system. International Journal of Recent Technology and Innovation, 10(2), 45–52.

[3] Adeniran, O. O., & Alabi, R. A. (2021). Real-time web-based interface for monitoring high-voltage equipment in Nigeria. International Journal of Electrical and Computer Engineering, 11(5), 3987–3996.

[4] Adzua, Peter Terseer. "Resolving the incredible Nigerian national power grid collapse frequency through reliable SCADA/EMS deployment." Global Scientific Journal 9, no. 5 (2021): 1452–1457. https://www.globalscientificjournal.com/resea

rchpaper/Resolving_the_incredible_Nigerian_National_Power_Grid_Collapse_Frequency_through_Reliable_SCADA_EMS_Deployment.pdf.

[5] Afolabi, F., & Okonkwo, C. (2023). Cloud-based SCADA and IoT integration for real-time breaker control in microgrids. Nigerian Journal of Power Systems and Smart Grid, 7(1), 23–34.

[6] Afolabi, O. J., & Okonkwo, E. C. (2023). Development of an IoT-based real-time SCADA monitoring framework for Nigerian transmission substations. International Journal of Smart Grid and Sustainable Energy, 12(1), 25–38.

[7] Anonymous. (2023). Distributed thermal monitoring of high-voltage power lines: An optimized sensor deployment strategy. International Journal of Grid Reliability and Thermal Safety, 6(2), 58–66.

[8] Baltin, A., Samoilov, V., & Makarov, D. (2025). Digital monitoring of emergency 35Journal of Smart Grid Applications, 9(1), 66–75.

[9] Chika, I. F., & Omorogiuwa, E. (2020). Real-time line fault detection in Nigerian transmission grid using GSM-based modules. International Journal of Engineering Research in Africa, 47, 120–129.

[10] El Mrabet, A., Benkaddour, R., & El Houssine, R. (2025). Real-time monitoring and optimization of power networks using advanced control algorithms. International Journal of Power Systems, 12(3), 45–63.

[11] El Mrabet, H., Ait El Cadi, A., & Benamar, N. (2025). Real-time cyber-physical substation monitoring using SDN and edge intelligence. IEEE Transactions on Smart Grid Technologies, 16(3), 812–820. https://doi.org/10.1109/TSG.2025.3254768

[12] El Mrabet, R., Berrada, K., & Zine-Dine, K. (2025). A real-time monitoring framework for resilient transmission grids. Journal of Modern Power Systems and Clean Energy, 13(2), 455–468.

[13] Hannon, D., Gómez, J. C., & Zhang, Z. (2019). Real-time smart grid monitoring using IoT and fog computing.

[14] IEEE Transactions on Smart Grid, 10(6), 6705–6714.

[15] Hannon, J., Smith, R., & Thompson, L. (2019). Real-time monitoring techniques for transmission substations.

[16] Journal of Electrical Power Systems, 15(2), 101–118.

[17] Hannon, M., Stewart, D., & Clark, R. (2019). Wide-area monitoring and control using synchro phasors in the UK transmission network. International Journal of Electrical Power & Energy Systems, 113, 165–175. https://doi.org/10.1016/j.ijepes.2019.05.009

[18] Hao, S., Kou, Y., & Zeng, X. (2023). IoT-based intelligent sensing framework for real-time monitoring of high-voltage transmission lines. Sensors and Actuators A: Physical, 354, 114219. https://doi.org/10.1016/j.sna.2023.114219

[19] Idris, M. A., & Oyedepo, S. O. (2019). Real-time monitoring architecture for Nigerian 132 kV grid system.

[20] Journal of Electrical Systems and Information Technology, 6(1), 13–21.

[21] Kartika, D., & Muwardi, A. (2025). Real-time monitoring of a 150 kV substation using multi-platform notification and visualization systems. International Journal of Smart Grid Technologies, 10(1), 12–28.

[22] Kartika, E. A. Y., & Muwardi, R. (2025). Design and implementation of a real-time monitoring system for a 150 kV substation with multi-platform notification and visualization. Journal of Electrical Systems and Smart Grid Technologies, 15(1), 55–70.

[23] Klauber, M., Rosenqvist, L., Johnson, P., & Lelic, M. (2020). Real-time monitoring applications for the power grid under geomagnetic disturbances. Space Weather, 18(5), e2020SW002501.

[24] Li, W., Deka, D., Chertkov, M., & Wang, M. (2018). Real-time faulted line localization and PMU placement in power systems through

convolutional neural networks. arXiv preprint arXiv:1810.05247. https://arxiv.org/abs/1810.05247

[25] Li, W., Deka, D., Chertkov, M., & Wang, M. (2019). Real-time wide-area monitoring and control for power systems: Concepts and case studies. Proceedings of the IEEE, 107(1), 68–91.

[26] Liu, H., Zhang, Y., & Sun, K. (2023). Real-time fault prediction and generation adjustment based on GRU deep learning algorithms. Applied Energy, 344, 121116.

[27] Lorenz-Meyer, M., Hoffmann, R., & Schaefer, D. (2022). Real-time wide-area state estimation using PMU measurements in substation testbeds. Electric Power Components and Systems, 50(7–8), 673–685.

[28] Masisani, W. M., & Adabara, I. (2022). Monitoring with communication technologies of the smart grid.

[29] International Journal of Electrical and Electronic Engineering, 8(4), 55–72.

[30] Mbeke, P. C., & Ilo, F. U. (2023). Improving the real-time fault monitoring in 330 kV power transmission network using wide area monitoring technique. International Journal of Electrical Power and Energy Systems, 145, 108607.

[31] Mufana, M. W., & Ibrahim, A. (2022). Monitoring with communication technologies of the smart grid.

[32] International Journal of Electrical Engineering and Applications, 9(4), 110–125.

[33] Musa, A., & Alimi, R. (2023). A real-time smart grid monitoring system using IoT and cloud services. Nigerian Journal of Electrical and Control Engineering, 11(2), 77–84.

[34] Nwosu, E. K., & Audu, J. S. (2018). Deployment of a real-time remote monitoring system for TCN 132/33 kV substations. Nigerian Journal of Electrical Engineering, 17(2), 89–101.

[35] Ogunleye, T. A., & Salami, T. T. (2020). Real-time wireless sensor deployment in grid substations for condition-based monitoring. Sensors and Transducers, 244(9), 15–23.

[36] Okorie, C. F., & Jimoh, B. S. (2022). Real-time energy management using SCADA and smart sensors.

[37] International Journal of Energy Systems, 12(4), 220–233.

[38] Okoro, C. E., Ugwuanyi, P. I., & Eneh, B. (2021). AI-based fault diagnosis using SCADA logs in Enugu transmission zone. International Journal of Artificial Intelligence Applications in Power Systems, 5(3), 101–109.

[39] Oluseyi, P. O., Adelaja, T. S., & Akinbulire, T. O. (2017). Analysis of the transient stability limit of Nigeria's 330 kV transmission sub-network. Journal of Energy Systems and Power Engineering, 6(3), 23–39.

[40] Onyema, M. O., & Bakare, A. A. (2022). Real-time transmission line condition monitoring using fiber optic sensors. Journal of Electrical Infrastructure and Grid Operations, 4(4), 56–65.

[41] Picallo, I., Latorre, J. M., & Kirschen, D. (2019). Dynamic state estimation and real-time optimal power flow using neural networks. IEEE Transactions on Power Systems, 34(6), 4600–4609.

[42] Uche, A. I., & Olumide, M. T. (2023). Real-time grid load monitoring using Python and open-source SCADA. Journal of Power and Energy Engineering, 11(2), 45–58.

[43] XXXZVan der Merwe, J., Kruger, H., & Pretorius, P. (2022). AI-enhanced SCADA systems for fault detection in African transmission networks. IEEE Transactions on Power Delivery, 37(4), 2956-2968. https://doi.org/10.1109/TPWRD.2022.3214567.

[44] Wang, L., He, Y., & Zhang, F. (2025). Real-time EMI-hardened monitoring of high-voltage substations using transient sensors. IEEE Access, 13, 101021–101031. https://doi.org/10.1109/ACCESS.2025.3348712

[45] Wang, L., Xu, J., & Chen, Z. (2024). Development of PMU-based transient stability detection using CNN-LSTM considering time

series data measurement. IEEE Access, 12, 55620–55633.

[46] Wang, Y., Chen, H., & Zhao, Q. (2025). Real-time monitoring and fault diagnosis of power transformers using deep learning. Electric Power Systems Research, 226, 109636.

[47] Yahaya, S., & Obiora, T. (2023). ZigBee-based wireless sensor network for real-time monitoring of 11 kV feeders in Nigeria. Journal of Energy and Electrical Systems, 8(1), 35–44.