ENHANCEMENT OF ADAPTIVE POWER FACTOR CORRECTION FOR IMPROVED PERFORMANCE IN DYNAMIC AND COMPLEX POWER SYSTEMS USING AN INTELLIGENTLY CONTROLLED ULTRACAPACITOR

***Emeasoba, A. B.[1], Ezeonye, C. S.[2], Adeyi, A. A.[3], Obi, P. I.[4]**

[1]Department of Electrical/Electronic Engineering, Caritas University, Amorji-Nike, Enugu State.
[2]Department of Electrical & Electronic Engineering, University of Agriculture and Environmental Sciences, Umuagwo, Imo State.
[3]Department of Electrical/Electronic Engineering, Maritime Academy of Nigeria, Oron, Akwa Ibom State
[4]Department of Electrical/Electronic Engineering, Michael Okpara University of Agriculture, Umudike, Abia State.

*Corresponding Author: chinonso.ezeonye@uaes.edu.ng,

ABSTRACT

Modern power systems are increasingly exposed to more changing loads and nonlinear operating conditions, which can affect the performance of conventional power factor correction systems. This study presents an enhancement of an adaptive power factor correction method for improved performance in dynamic and complex power systems using an intelligently controlled ultracapacitor. The study had established six performance constraints related to the adaptive power factor correction system; response latency, compensation error, harmonic resonance, step resolution, voltage stability, and thermal working temperature. A quantitative analysis of the conventional and the improved systems was carried out for response latency, step resolution, and thermal operating temperature using the results of the simulations. A conventional Simulink model was developed to establish the baseline performance of the system. A fuzzy inference-based rule base was subsequently developed to determine appropriate corrective actions based on the identified system conditions, after which an artificial neural network was trained using the developed rules. An ultracapacitor model was then developed and integrated with the intelligent control scheme and the conventional adaptive power factor correction model. Simulation results showed that the response latency decreased from 55 ms for the conventional system to 48.28 ms with the intelligently controlled ultracapacitor, representing an improvement of approximately 12.2%. The step resolution decreased from 14 kVA to 12.28 kVA, corresponding to an improvement of approximately 12.3%, while the thermal operating temperature decreased from 58 ^{0}C to 50.8 ^{0}C, representing an improvement of approximately 12.4%. The results indicate that integrating intelligent control with an ultracapacitor can improve selected dynamic and operating characteristics of the adaptive power factor correction system. The proposed approach therefore provides a promising simulation-based framework for improving adaptive power factor correction performance under dynamic operating conditions.

Keywords: Adaptive power factor correction, dynamic power systems, intelligent control, neural network, fuzzy logic, ultracapacitors.

1.0 INTRODUCTION

Modern electric power systems are increasingly characterized by dynamic operating conditions, nonlinear loads, and the growing integration of renewable energy resources. In particular, the integration of renewable energies brings about dynamic operating conditions, which make the active and reactive power flows management an interesting item. The impact of solar integration on active power transfer, reactive power transfer and available transfer capability has been investigated on the Nigerian 330 kV transmission system under varying system conditions (Akinuli *et al*., 2024; Ezeonye *et al*., 2025). In Nigeria, the frequent power grid disturbances and collapse have equally demonstrated the significance of voltage stability and sufficient reactive power provision for an efficient power system (Obi *et al*., 2026). Hence, power factor correction (PFC) is essential to enhance the utilization of electrical energy, minimize the undue demand for reactive power, improve the voltage profiles, and the efficiency and reliability of power system as a whole (Sadiq & Antar, 2024; Samuel *et al*., 2025; Espin & Téllez, 2026).

Conventional power factor correction methods usually involve fixed or switched capacitor banks and other devices to compensate reactive power (Galadima, 2025). In power distribution systems, capacitor compensation, when appropriately applied, can bring about power factor improvement and active and reactive power losses reduction, which further indicates the practical value of reactive power compensation on the performance of the network (Obi *et al*., 2022). Variations in power factor have also been linked with changes in the technical losses in a Nigerian distribution system, with results that predict the necessity for a dynamic reactive power compensation under fluctuating loading conditions (Oyedoh, 2023). While these methods are capable of achieving reasonable compensation for quasi-stationary operating condition, their performance may deteriorate as a result of rapidly varying loads, nonlinear current wave shape, harmonic interference, and transient operating condition of the system. When the reactive power demand changes significantly, fixed capacitor bank may cause either under compensation or over compensation. They may also become the source of resonances when their characteristic curves cross with system impedance or harmonic curves. These constraints have heightened the demand for power factor correction methods with improved adaptability to dynamic system conditions (Coman *et al*., 2020; Adragna *et al*., 2024; Lu *et al*., 2023).

Adaptive power factor correction methods are a way of tuning the compensation level to the operating conditions of the system. Adaptive methods have the potential to be more flexible than fixed compensation schemes by continually adapting to the changes in reactive power demand. The accuracy of the measurement, control, switching and energy compensation units determines how well an adaptive power factor correction system works. Hence, response time, compensation error, harmonic resonance, step size, voltage stability, and temperature should be considered when evaluating the performance of the system, particularly in the case of rapidly changing operation conditions. Voltage stability is an important aspect of power network operation as evidenced by investigation into under voltage and load shedding strategies to improve the network voltage profiles in the South Eastern Nigerian network (Chukwulobe *et al*., 2022). The role of adaptive control and enhanced compensation schemes in power quality maintenance in modern electrical networks has recently been brought forth (Zhang *et al*., 2023; Ezeonye *et al*., 2026; Tipán *et al*., 2026).

Ultracapacitors have been the subject of intense research for applications with fast energy exchange needs due to their high-power density, fast charging and discharging, high efficiency and long cycle life (Bijarniya & Kumar, 2016). This also allows them to be used for compensation and transient power support such as in power quality applications. Unlike conventional batteries, which tend to have lower power density and slower response times, ultracapacitors can provide or uptake power at high efficiency for brief periods of time. These features could enable them to be compatible to assist adaptive PFC schemes working in dynamic scenarios (Obi *et al*., 2013; Kumar *et al*., 2022; Shah *et al*., 2022; Maribe, 2025; Herrera-Jaramillo *et al*., 2026).

Nonetheless, the sole employment of an ultracapacitor does not imply an ideal compensation response. A suitable control strategy is needed to decide at what moment and in what manner the stored energy must be used according to the system variation. Intelligent control, artificial neural networks and fuzzy logic are more suited for nonlinear systems and time-varying system conditions. These methodologies can also be applied to measured system data to compute appropriate control actions, which enables enhancement of the adaptiveness of power electronic devices and reactive power modules (Govil *et al*., 2025; Uwagboe & Saha, 2026). By combining intelligent control with ultracapacitor energy storage, there is promising prospect to further enhance the dynamic performance of an adaptive power factor correction. The intelligent controller describes which corrective action to take for the current given system state, and the ultracapacitor delivers a source of energy to execute the required compensating action. This type of confluence is expected to be increasingly important for future power systems with fluctuating loads, distributed generation, renewable energy interfaces and so forth (Mariasiu, 2025; Aranizadeh *et al*., 2025).

Although adaptive power factor correction methods have been proposed and intelligent control and ultracapacitor technologies are widely used, there still exists a question on their combined use for enhancing the dynamic performance of power factor correction systems. Especially, intelligent integration of ultracapacitor for enhancing response latency, compensation error, harmonic resonance, step resolution, voltage stability, and thermal operation temperature is interesting for future work. Considering these performance traits can help to better predict the potential strength and weakness of the suggested scheme. It is thus the adaptation of power factor correction based on an intelligent controlled ultracapacitor for enhanced performance in dynamically changing and complex power system that is of concern in this paper. This work analyzes the recognized performance constraints, derives a conventional adaptive power factor strategy, develops a fuzzy inference-based control rule base, trains a neural network applying the derived rules, and couples the ultracapacitor model with the intelligent control and the conventional system. The resulting design is then tested via simulation by comparing the known numerical values of the response latency, step resolution, and temperature of operation of a conventional and an enhanced system.

2.0 METHODOLOGY

2.1 Characterization of Performance Limitations in the Adaptive Power Factor Correction System

The first phase of the investigation was the description of the performance constraints of the adaptive power factor correction system in dynamic and complex operating conditions. Six features of performance were considered: response latency, compensation error, harmonic resonance, step resolution, voltage stability, and thermal operating temperature. The conventional system served as the benchmark to compare the identified traits.

Response latency was analyzed as a function of the response time of the control system to changes in the environmental conditions. Compensation error is the deviation introduced in a reactive power compensation scheme. Harmonic resonance was evaluated in terms of the compensation and harmonic interaction components. Step resolution was the size of the smallest effective compensation step that the system can use. Voltage stability was evaluated as the voltage fluctuation caused by reactive power compensation and thermal operating temperature was defined as the temperature increment induced by running the compensating system. The characterized values and the corresponding root causes are shown in Table 1.

Table 1: Characterized performance limitations and identified root causes of the adaptive power factor correction system

Performance characteristic	Unit	Conventional value	Identified root cause
Response latency	ms	55	Controller processing delay or slow mechanical switching relative to load cycles
Compensation error	%	6	Low resolution current transformers or quantization errors in the analogue to digital conversion process
Harmonic resonance	%	6.2	Lack of detuning reactors and possible amplification of system resonance frequencies by compensation capacitors
Step resolution	kVA	14	Coarse switching granularity under small and highly variable load conditions
Voltage stability	%	12	Rapid reactive power injection resulting in transient voltage variation
Thermal operating temperature	^{0}C	58	High equivalent series resistance or inadequate cooling during rapid switching cycles

2.2 Development of the Conventional Adaptive Power Factor Correction Model

Following the characterization of the identified performance limitations, a conventional adaptive power factor correction model was developed in MATLAB/Simulink. The model incorporated the electrical system and control components required to represent the baseline adaptive power factor correction arrangement. The six identified performance characteristics were incorporated into the model through monitoring and display blocks. These included response latency, compensation error, harmonic resonance, step resolution, voltage stability, and thermal operating temperature. The outputs of the monitoring blocks provided the baseline values against which the performance of the enhanced system was subsequently evaluated. Figure 1 presents the developed conventional Simulink model for adaptive power factor correction. The model contains the conventional control panel and the monitoring sections used to obtain the values of the identified performance characteristics.

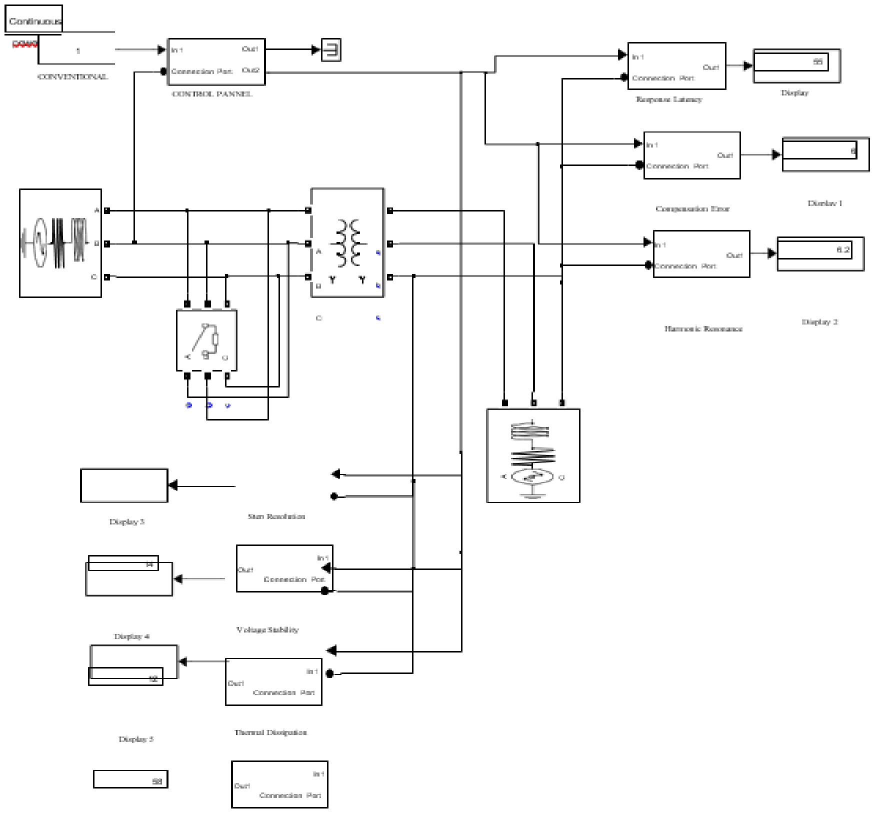

Figure 1: Developed conventional Simulink model for adaptive power factor correction

2.3 Development of the Intelligent Ultracapacitor Rule Base

In the next step, fuzzy inference-based rule was established to find the corrective action of related performance conditions. The fuzzy inference system was established with the aid of a Mamdani based inference structure, which provides a rule-based method for processing system conditions and generating the control responses. Recent works have demonstrated the use of fuzzy controllers for power quality enhancement and reactive power control in power systems (Miron *et al*., 2024; Mohan *et al*., 2026).

The model incorporated two input variables, the aggregated PFC condition index and the monitoring sensor condition, and the output was the related corrective control state. The aggregated PFC condition index defines a sum of severity among identified performance conditions for adaptive power factor correction: response latency, compensation error, harmonic resonance, step resolution, voltage stability, and thermal operating temperature. These situations were encapsulated in a single supervisory index, as the executed simulation model did not have separate streaming measurements for each attribute. Hence, the fuzzy inference mechanism acted as a supervisory decision module to select the suitable corrective control state given the detected operating conditions. Figure 2 illustrates the proposed fuzzy inference system, while Figure 3 shows the associated rule implementation.

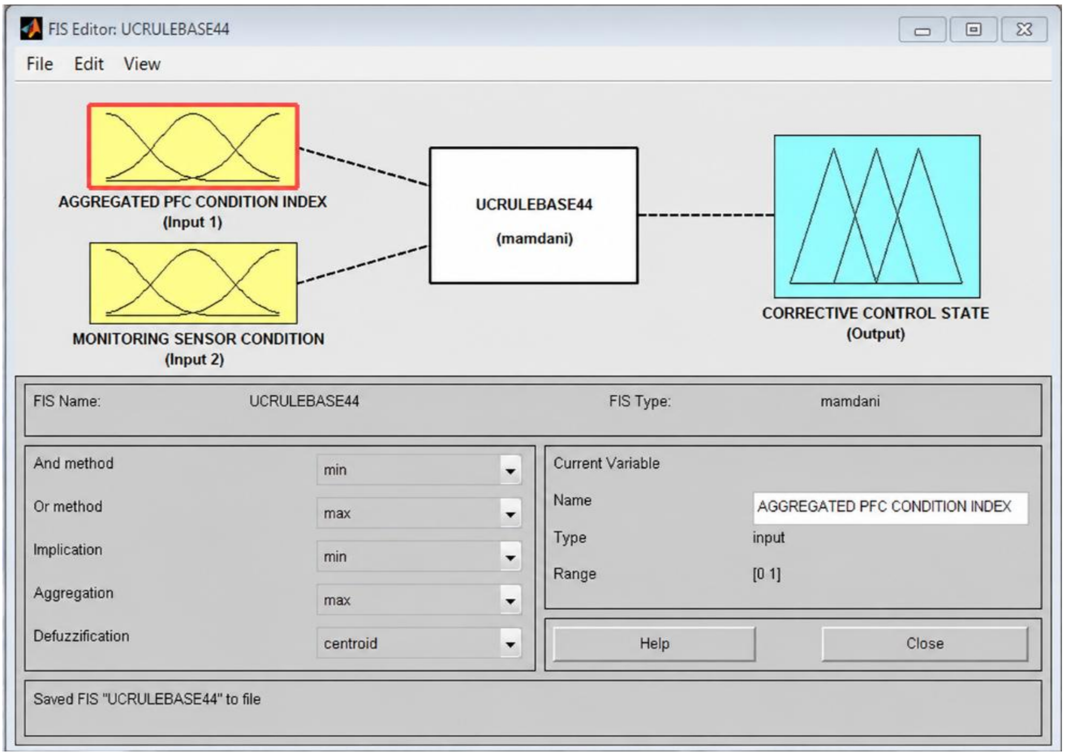

Figure 2: Developed fuzzy inference system for intelligent adaptive power factor correction

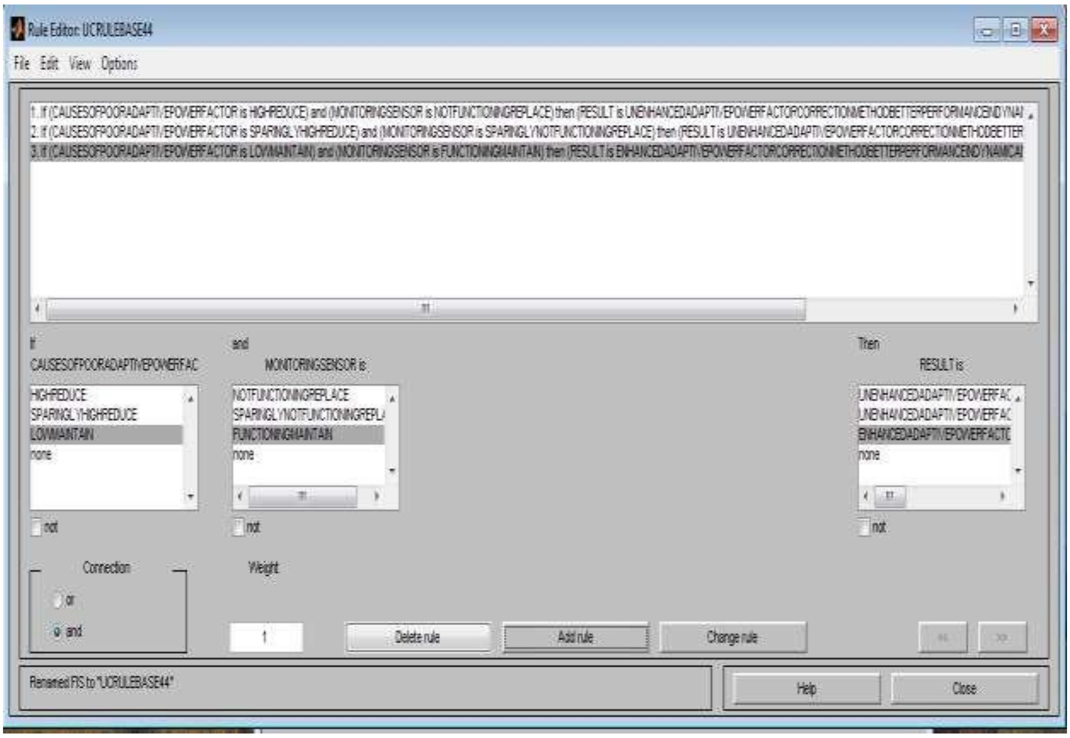

Figure 3: Implementation of the developed fuzzy inference rule base

2.4 Fuzzy Rule Base

The rule set consisted of three main rules that relate the aggregated PFC condition index and the condition of the monitoring sensor to the specific corrective control state.

The rules developed in the study were:

Rule 1: A high aggregated PFC condition index and non-functioning monitoring sensor leads to a high corrective intervention.

Rule 2: A moderately high aggregated PFC condition index, and a moderately nonfunctional monitoring sensor, result in a moderate corrective intervention.

Rule 3: When monitoring sensor is functioning and the aggregated PFC condition index is low, the corrective control is to keep the current compensation state.

Table 2: Developed fuzzy inference rules for adaptive power factor correction

Rule	Aggregated PFC Condition Index	Monitoring Sensor Condition	Corrective Control State
1	High	Not functioning	High ultracapacitor corrective support
2	Moderately high	Moderately nonfunctional	Moderate ultracapacitor corrective support
3	Low	Functioning	Maintain existing compensation level

The control commands of Table 2 constitute the supervisory control states of the ultracapacitor compensation subsystem. A high level gets a high level of corrective ultracapacitor support, a moderately high level gets a moderate level of corrective support, and a low level keeps the current compensation level. Since the provided simulation results do not contain experimentally obtained threshold values, the proposed model represents these actions as fuzzy control states instead of fixed numerical switching thresholds. The true compensation action is later calculated through the fuzzy inference system (FIS) and integrated intelligent control system.

2.5 Operational Mechanism of the Fuzzy Rule Base

The proposed FIS takes the aggregated PFC condition index and monitoring sensor condition as its inputs, then processes them with the defined membership functions and rules and outputs the corrective control state. The operational mechanism involves fuzzification of the input variables, application of the fuzzy rules, aggregation of the rule outputs, and defuzzification to obtain the final control output. Figure 4 illustrates the operational mechanism of the developed fuzzy inference rule base used in the study.

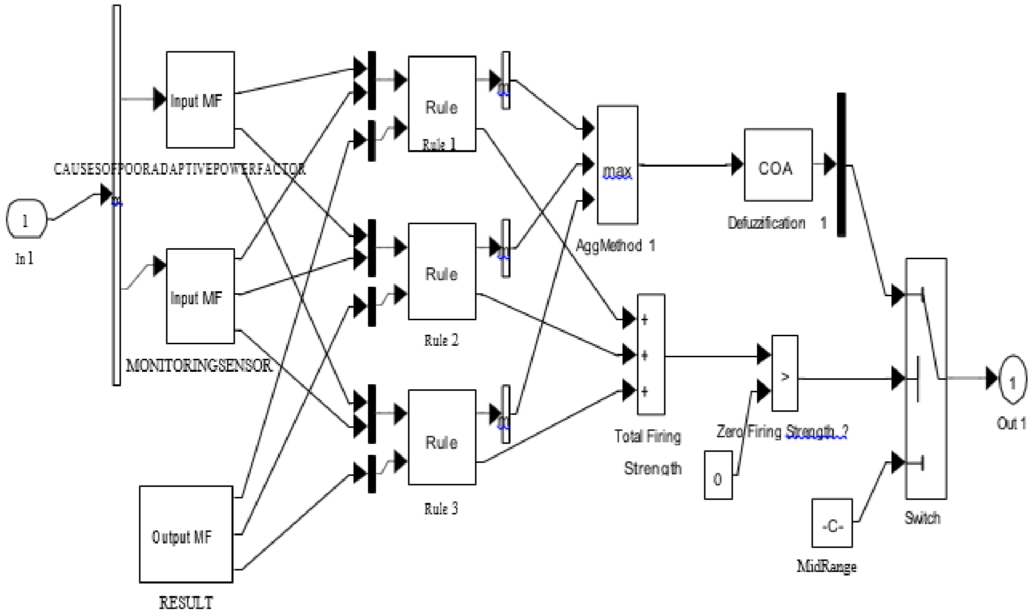

Figure 4: Operational mechanism of the developed fuzzy inference rule base for adaptive power factor correction

2.6 Neural Network Mapping of the Fuzzy Control Rules

After development the fuzzy rule base, a neural network mapping phase was employed to map the fuzzy-rule input conditions to their corrective control states. The neural network was trained with the three developed fuzzy rules input conditions and its control responses for over twenty training cycles.

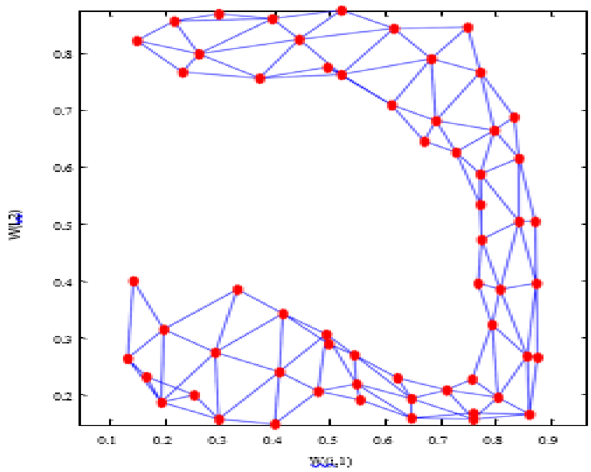

Figure 5: Neural-network weight topology obtained from the fuzzy-rule training data

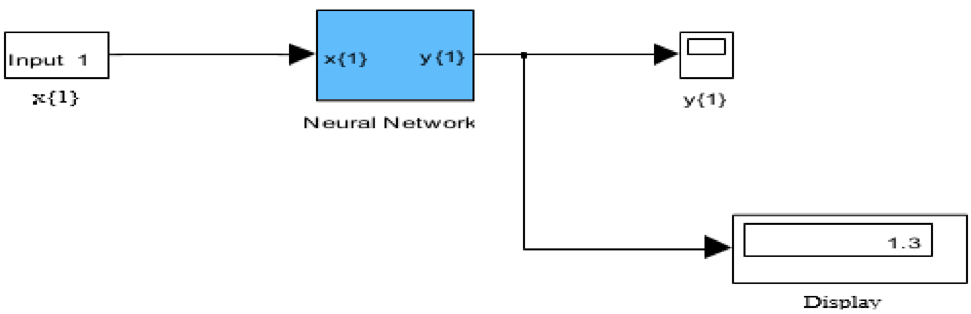

Figure 6: Output of the trained neural network based on the developed fuzzy control rules

Figure 5 shows the resulting neural-network weight topology, and Figure 6 shows the corresponding neural-network output. The weight topology is a pattern-based representation of the relation from the fuzzy-rule data and acts as intelligent mapping module in the proposed control framework. In our current realization, the neural network was presented to be the resulting fuzzy control conditions and thus not as a separately validated feedforward backpropagation or ANFIS controller. The obtained simulations results did not include a standalone numerical training-error metric, detailed layer-by-layer architecture, or activation function specification for the neural-network mapping stage. As such they are not given as empirically backed attributes of the proposed framework. The neural-network module is in turn embedded into the intelligent supervisory mapping framework to model the response of fuzzy control rules. The neural-network output was then interpreted in the supervisory control framework as the associated corrective control state for the ultracapacitor compensation subsystem. Thereby the fuzzy rule base defines the corrective states, and the neural-network module supplies its pattern mapping representation of those states to be used in the intelligent compensation framework proposed.

2.7 Development of the Ultracapacitor Model

An ultracapacitor model was then developed in MATLAB/Simulink and incorporated with the intelligent control. The model was designed to deliver the needed fast energy response of the adaptive compensation. Additional parameters and signal generators were added in order to simulate certain conditions of the model without setting the time scale of the transient compensation. The proposed model for the ultracapacitor in Simulink is shown in Figure 7.

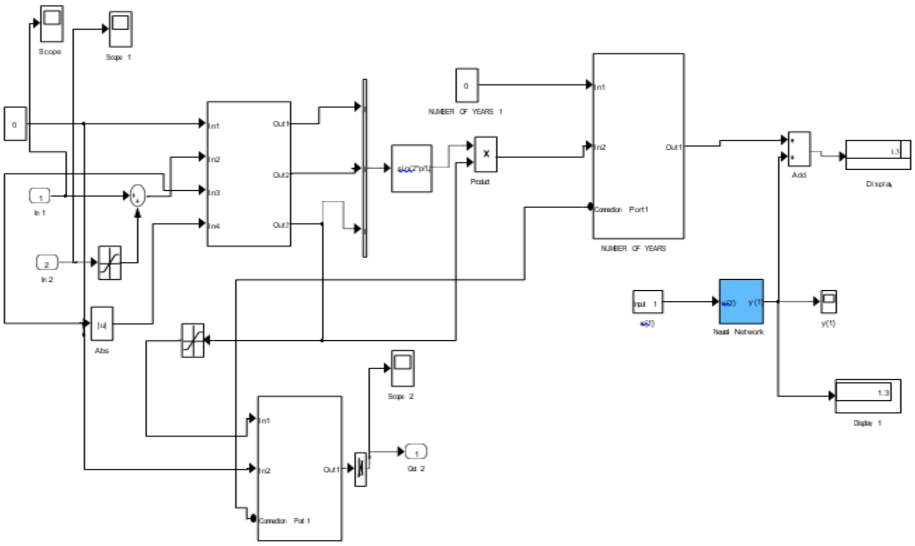

Figure 7: Developed Simulink model of the ultracapacitor

The number of years shown in Figure 7 is a secondary aging parameter added to the model of the ultracapacitor to capture long-term drift of the characteristics of the approximated device. It is not the time scale of the transient process of load reactive power compensation. Also, the sinusoidal signal and product block are part of the internal signal generation used in the model, and not to be interpreted as a direct low frequency control command to the ultracapacitor. The compensation response during transient is dominated by the intelligent control and ultracapacitor subsystem, while these auxiliary model elements offer additional model inputs and parameter variation.

2.8 Algorithm for the Proposed System

The algorithm developed in the study was used to integrate the conventional adaptive power factor correction model, fuzzy inference rule base, neural-network, and ultracapacitor model. The process consisted of characterization of the identified performance limitations, development of the conventional model, development of the intelligent control rule base, neural-network training, development of the ultracapacitor model, and integration of the individual components.

The algorithm followed these general stages:

i. Characterize the performance limitations associated with the adaptive power factor correction system.
ii. Identify response latency.
iii. Identify compensation error.
iv. Identify harmonic resonance.
v. Identify step resolution.
vi. Identify voltage stability.
vii. Identify thermal operating temperature.
viii. Develop the conventional Simulink model and incorporate the identified performance characteristics.
ix. Develop the ultracapacitor fuzzy inference rule base.
x. Train the ANN using the developed rules.
xi. Develop the ultracapacitor Simulink model.
xii. Integrate the fuzzy rule base, ANN, and ultracapacitor model.
xiii. Integrate the intelligent ultracapacitor subsystem with the conventional adaptive power factor correction model.
xiv. Evaluate whether the identified performance limitations are reduced after integration.
xv. If the required improvement is not achieved, return to the integration and control adjustment stage.
xvi. If improvement is achieved, obtain the enhanced adaptive power factor correction system.

For the comparison, response latency and step resolution were regarded as scalar performance metrics of the simulation models, rather than as variables over the calendar-time scale. Hence, the results of the comparison are given directly for the standard and neural-based ultracapacitor designs.

2.9 Integration of the Proposed System

The final stage of the methodology involved integrating the intelligent control system and ultracapacitor model with the conventional adaptive power factor correction system. The resulting Simulink model combined the conventional compensation arrangement with the developed fuzzy inference rule base, trained neural network, and ultracapacitor subsystem. The physical connection of the proposed compensator can be traced by its electrical connection; from the 330 kV input to the 330/11 kV transformer, then to the 11 kV side, where the power factor correction unit is connected. The bidirectional power converter serves at the connection between the electrical system and the ultracapacitor bank, enabling the ultracapacitor to provide or absorb the required compensation power. Figure 8 illustrates the coupling of the intelligent control, converter interface and the ultracapacitor subsystem with the conventional adaptive power factor correction scheme.

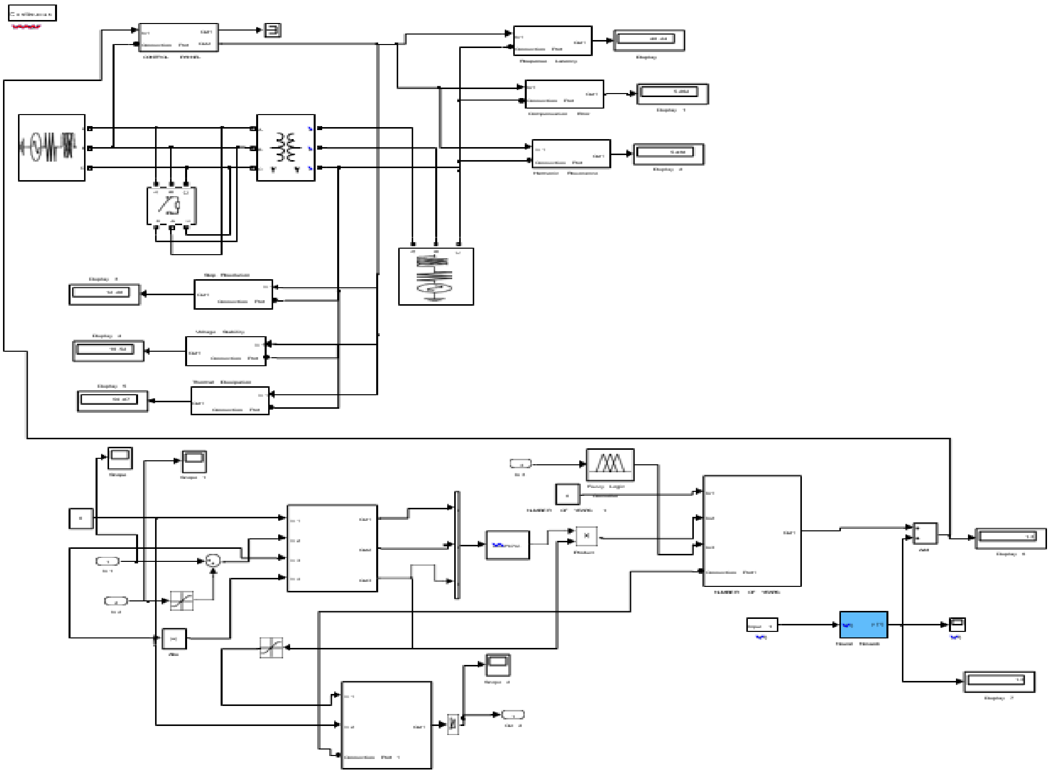

Figure 8: Integrated Simulink model showing the connection of the adaptive power factor correction system and ultracapacitor compensation subsystem

3.0 RESULTS AND DISCUSSION

The simulation results obtained from the conventional adaptive power factor correction model and the proposed intelligent controlled ultracapacitor model were compared to determine the effect of the proposed enhancement on selected performance characteristics. The comparison focused on response latency, step resolution, and thermal operating temperature, for which numerical results were obtained for both the conventional and enhanced systems. The results provide an indication of the effect of integrating intelligent control and ultracapacitor support into the adaptive power factor correction system.

3.1 Response Latency

Table 3 presents the comparison between the conventional adaptive power factor correction system and the system incorporating the intelligent controlled ultracapacitor.

Table 3: Comparison of response latency between the conventional and intelligent controlled ultracapacitor based adaptive power factor correction systems

System	Response latency (ms)
Conventional adaptive power factor correction system	55.00
Intelligent controlled ultracapacitor based system	48.28

The conventional adaptive power factor correction system had a response latency of 55 ms and the intelligent controlled ultracapacitor based system was 48.28 ms. The lower value obtained with the improved setup indicates a decrease in the stated response latency. The percentage decrease was about 12.2%.

This is in line with the role of the ultracapacitor in the proposed system. Intelligent control system, on the other hand, decides the suitable corrective action. Consequently, the two together minimizes the response time involved in the compensation process. Figure 9 shows a direct comparison of the reported response latency for the two system architectures.

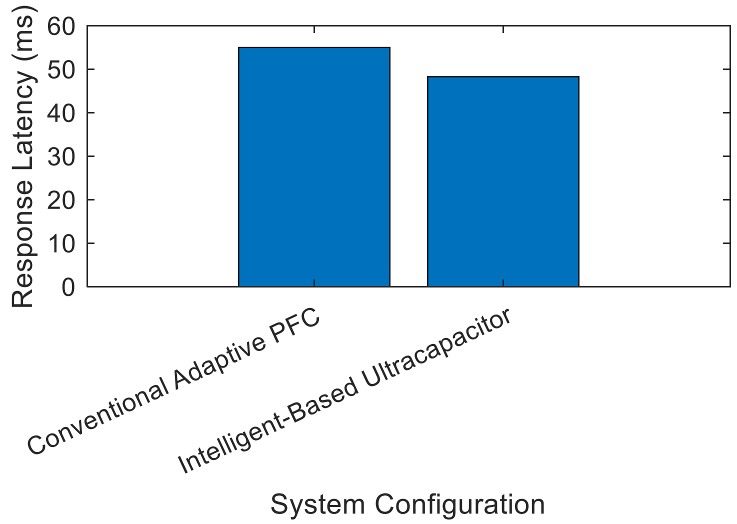

Figure 9: Comparison of response latency between the conventional and intelligent controlled ultracapacitor based adaptive power factor correction systems

Figure 9 illustrates that the intelligent controlled ultracapacitor based topology delivers the shortest response latency among the conventional adaptive power factor correction system. The response latency shows a reduction from 55.00 ms for the conventional approach to 48.28 ms for the improved design. This demonstrates that the reconfigurable system can deliver a quicker corrective response in simulated operating condition. The decrease of the response latency agrees with the rapid energy exchange capability of the ultracapacitor, and the supervision of the intelligent control system.

3.2 Step Resolution

Table 4 presents the simulated step resolution of the conventional and intelligent controlled ultracapacitor systems.

Table 4: Comparison of compensation step resolution between the conventional and intelligent controlled ultracapacitor based adaptive power factor correction systems

System	Step resolution (kVA)
Conventional adaptive power factor correction system	14.00
Intelligent controlled ultracapacitor based system	12.28

The conventional adaptive power factor correction system recorded a step resolution of 14 kVA. Following integration of the intelligent controlled ultracapacitor configuration, the reported step resolution decreased to 12.28 kVA. This represents a calculated reduction of approximately 12.3%.
The percentage improvement was calculated as:

$$\text{Percentage reduction} = \frac{\text{Conventional value} - \text{Enhanced value}}{\text{Conventional value}} \times 100 \qquad (1)$$

$$\therefore \text{ Percentage reduction} = \frac{14 - 12.28}{14} \times 100 = 12.29\% \quad (2)$$

Thus, the step resolution improved by approximately 12.3%.

The reduction from 14 kVA to 12.28 kVA is relevant to the operation of an adaptive power factor correction system because a smaller compensation step provides finer adjustment of the compensation level. This can be particularly useful where the reactive power requirement varies with operating conditions. Figure 10 presents a direct comparison of the reported step resolution for the two system configurations

Figure 10 shows the simulated comparison. The conventional system remains at 14 kVA, while the intelligent controlled ultracapacitor system remains at approximately 12.28 kVA during the reported simulation period.

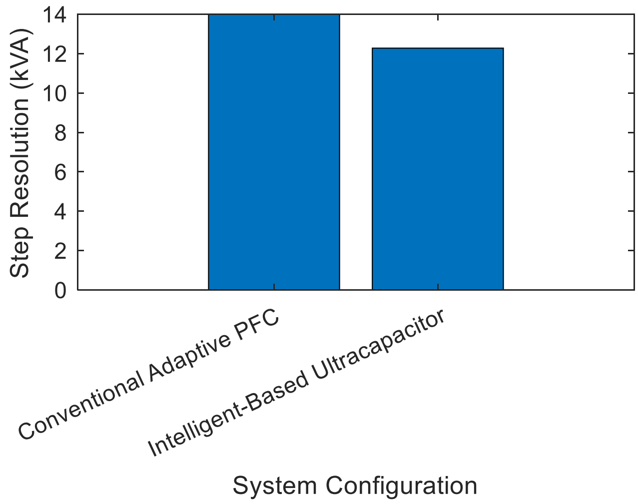

Figure 10: Comparison of compensation step resolution between the conventional and intelligent controlled ultracapacitor based adaptive power factor correction systems

Figure 10 demonstrates that the step resolution of the proposed intelligent controlled ultracapacitor based system is lower than that of the conventional adaptive power factor correction system. The step resolution is reduced from 14.00 kVA to 12.28 kVA. The lower step resolution means finer adjustment on compensation level and it is expected to be useful when reactive power demand varies in different working states. Thus, the result implies that the proposed scheme achieves a finer resolution in the compensation procedure under the simulated condition.

3.3 Thermal Operating Temperature

The third quantitatively evaluated characteristic was thermal operating temperature. The conventional system recorded a thermal operating temperature value of 58 °C, while the intelligent controlled ultracapacitor system recorded 50.8 °C. These values were used to determine the percentage improvement obtained from the proposed enhancement.

The percentage improvement was calculated using:

$$\text{Improvement} = \frac{\text{Conventional thermal value} - \text{Enhanced thermal value}}{\text{Conventional thermal value}} \times 100 \quad (3)$$

$$\therefore \text{ Improvement} = \frac{58 - 50.8}{58} \times 100 = 12.41\% \quad (4)$$

Hence, the thermal operating temperature decreased by approximately 12.4%.

3.4 Overall Comparison of the Simulated Results

The principal quantitative results obtained from the study are summarized in Table 5.

Table 5: Summary of simulated performance improvement

Performance characteristic	Conventional system	Intelligent controlled ultracapacitor system	Improvement
Response latency	55 ms	48.28 ms	12.2%
Step resolution	14 kVA	12.28 kVA	12.3%
Thermal operating temperature	58 °C	50.8 °C	12.4%

The results show that the integration of the intelligent controlled ultracapacitor produced lower reported values for all three quantitatively evaluated characteristics. Response latency decreased by approximately 12.2%, step resolution decreased by approximately 12.3%, and thermal operating temperature decreased by approximately 12.4%.

The obtained percentage reductions for response latency, step resolution, and thermal operating temperature are very close, from 12.4% to 12.2%. Such close numeric imply that the three reported outputs may be subject to a common scaling factor in the simulation model. Hence, the percentage reductions are considered as comparative outputs of the models and not as experimental measurements of three different physical enhancements. The results show the relative difference between the conventional and modified systems for the given simulation setup, but further time-domain and experimental studies are required for the static physical nature of each feature.

4.0 CONCLUSION

This work investigated the enhancement of adaptive power factor correction for improved performance in dynamic and complex power systems with an intelligent controlled ultracapacitor. The work characterized six performance limitations associated with the adaptive power factor correction system, namely response latency, compensation error, harmonic resonance, step resolution, voltage stability and thermal operating temperature. A conventional adaptive power factor correction model was developed in MATLAB/Simulink after which a fuzzy inference-based rule base and artificial neural network were developed and integrated with an ultracapacitor model to form the proposed enhanced system. The simulation results showed measurable improvements in the three performance characteristics for which comparative numerical results were available. Response latency decreased from 55 ms in the conventional system to 48.28 ms with the intelligent controlled ultracapacitor representing an improvement of approximately 12.2%. Step resolution decreased from 14 kVA to 12.28 kVA corresponding to an improvement of approximately 12.3%. The thermal operating temperature also reduced from 58 ^{0}C to 50.8 ^{0}C, showing an improvement of approximately 12.4%. The reduction in response latency indicates an improvement in the speed of the adaptive compensation response, while the reduction in step resolution indicates a finer compensation capability. The reduction in thermal operating temperature also indicates a more favourable simulated thermal condition for the proposed configuration. Collectively, these results demonstrate the potential of combining intelligent control with ultracapacitor support to improve selected performance characteristics of adaptive power factor correction under dynamic operating conditions. The study therefore concludes that the proposed intelligent controlled ultracapacitor approach provides a promising simulation-based method for enhancing the dynamic performance of adaptive power factor correction systems. However, the present results do not provide sufficient quantitative evidence to establish percentage improvements for compensation error, harmonic resonance, and voltage stability. These parameters were incorporated into the system characterization and simulation framework, but corresponding before and after numerical results were not presented. Consequently, the future work would be to quantitate these features and validate the suggested approach through experimental realization in the real practical operating conditions. Also, additional studies are needed to encompass other types of nonlinear and rapidly changing loads, other ultracapacitor values, and other intelligent control methods, in order to conclude on the robustness and practical usefulness of the proposed scheme.

REFERENCES

Adragna, C., Bianco, A., Gritti, G., & Sucameli, M. (2024). State-of-the-Art Power Factor Correction: An Industry Perspective. *Encyclopedia*, 4(3), 1324-1354. https://doi.org/10.3390/encyclopedia4030087

Akinuli, A. A., Akinola, O. A., Adebisi, O. I., Akinwale, A. T., Afolabi, S. A. & Etinosa, N. (2024). Hybrid Voltage Regulation of the Nigerian 330 kV Grid using Static Synchronous Compensator and Static Synchronous Series Compensator. *Engineering Review,* 44 (3), 147-166. https://doi.org/10.30765/er.26133

Aranizadeh, A., Mirmozaffari, M., & Farahani, B. K. (2025). Maximizing Wind Turbine Power Generation Through Adaptive Fuzzy Logic Control for Optimal Efficiency and Performance. *Wind*, 5(1), 1-25. https://doi.org/10.3390/wind5010004

Bijarniya, V. K. & Kumar, D. (2016). A Review Paper on Ultra Capacitor Technology and its Applications. *International Journal of Engineering Research & Technology*, 4(32), 1-3. https://doi.org/10.17577/IJERTCONV4IS32022

Chukwulobe, O. O., Obi, P. I., Amako, E. A. & Ezeonye, C. S. (2022). Improved Under-Voltage Load Shedding Scheme in Power System Network for South Eastern Nigeria. *NIPES Journal of Science and Technology Research*, 4(1), 212-223. https://doi.org/10.5281/zenodo.14520506

Coman, C. M., Florescu, A., & Oancea, C. D. (2020). Improving the Efficiency and Sustainability of Power Systems Using Distributed Power Factor Correction Methods. *Sustainability*, 12(8), 1-20. https://doi.org/10.3390/su12083134

Espin, A., & Téllez, A. A. (2026). Resonance-Aware Power Factor Correction in Transmission Networks Using Weighted Indices and Tuned Passive Filters for Harmonic Mitigation. *Energies*, 19(9), 1-58. https://doi.org/10.3390/en19092214

Ezeonye, C. S., Obi, P. I., Emeasoba, A. B., & Adeyi, A. A. (2026). Hybrid Energy Storage Systems for Improved Industrial Power System Performance. *4th International Engineering Conference (IECON 2026)*, Umudike, 25 – 26 March 2026, pp. 757-766. https://doi.org/10.5281/zenodo.21720122

Ezeonye, C. S., Oputa, O., Osuji, U., Onwuka, I. K. & Obi, P. I. (2025). Improvement of Power Transfer with Solar System Integration on Nigeria 330 kV Transmission Grid. *NIPES Journal of Science and Technology Research*, 7(1), 265-276. https://doi.org/10.37933/nipes/7.1.2025.21

Galadima, A. M. (2025). Reactive Power Compensation using STATCOM and Instantaneous Reactive Power Theory. *African Journal of Advances in Science and Technology Research, 18*(1), 1-23. https://doi.org/10.62154/ajastr.2025.018.010672

Govil, V. K., Tripathi, S. M. & Sahay, K. (2025). Real-Time Assessment of PV-DSTATCOM for Grid Power Quality Enhancement using an Indirect Current Control Strategy. *Scientific Report*, 15, 1-23. https://doi.org/10.1038/s41598-025-01078-z

Herrera-Jaramillo, D. A., Bastidas-Rodríguez, J. D., & Ramos-Paja, C. A. (2026). Power Converter-Based Impedance Spectroscopy for Supercapacitors: Theory, Simulation and Experimental Verification. *Batteries*, 12(8), 1-30. https://doi.org/10.3390/batteries12080286

Kumar, N., Kim, S. B., Lee, S. Y., & Park, S. J. (2022). Recent Advanced Supercapacitor: A Review of Storage Mechanisms, Electrode Materials, Modification, and Perspectives. *Nanomaterials*, 12(20), 1-36. https://doi.org/10.3390/nano12203708

Lu, Y., Ma, H., Wei, Y., Pan, Y., Chen, X., & Huang, Y. (2023). Research on Five-Level PFC Circuit Topology Based on Switch-Diode-Capacitor Network. *Electronics*, 12(6), 1-15. https://doi.org/10.3390/electronics12061286

Mariasiu, F. (2025). Control Algorithms for Ultra-capacitors Integrated in Hybrid Energy Storage Systems of Electric Vehicles' Powertrains: A Mini Review. *Batteries*, 11(11), 1-28. https://doi.org/10.3390/batteries11110395

Maribe, M. S. (2025) Power Factor Correction in Electrical Circuits. *International Journal of Applied Science*, 9(9), 326-330.

Miron, A., Cziker, A. C., & Beleiu, H. G. (2024). Fuzzy Control Systems for Power Quality Improvement: A Systematic Review Exploring their Efficacy and Efficiency. *Applied Sciences, 14*(11), 1-28. https://doi.org/10.3390/app14114468

Mohan, H., Kumar, A., Saxena, N. K., Mishra, S., Khetrapal, P., Azzopardi, B., & Jately, V. (2026). Fuzzy Logic Based Reactive Power Control for Power Factor Enhancement in EV Drives. *Scientific Reports, 16,* 1-22. https://doi.org/10.1038/s41598-025-34125-w

Obi, P. I., Amako, E. A. & Ezeonye, C. S. (2022). Comparative Financial Evaluation of Technical Losses in South Eastern Nigeria Power Network. *Bayero Journal of Engineering and Technology (BJET)*, 17(2), 41-51. https://doi.org/10.5281/zenodo.14520634

Obi, P. I., Ezeonye, C. S., Adeyi, A. A., Onwuka, I. K. & Oputa, O. (2026). Investigating Electricity Power Grid Collapses in Nigeria and Measures to Reduce its Effect during Occurrence. *NIPES Journal of Science and Technology Research*, 8(1), 197-211. https://doi.org/10.37933/nipes/8.1.2026.2312

Obi, P. I., Ulasi, J. A., Offor, K. J. & Chidolue, G. C. (2013). Improving Electric Power Quality in Nigerian Existing 330kV 28 Bus Electric Power System using Static VAR Compensator System. *International Journal of*

Engineering Research and Technology (IJERT), 2(8), 1060-1066.

Oyedoh, M. O. (2023). Evaluating Technical Losses Arising from Power Factor Fluctuations: A Case Study of the Nekpenekpen 33/11 kV Injection Substation. *NIPES Journal of Science and Technology Research, 5*(2), 367-377.

Sadiq, E. H., & Antar, R. K. (2024). Minimizing Power Losses in Distribution Networks: A Comprehensive Review. *Chinese Journal of Electrical Engineering, 10*(4), 20-36. https://doi.org/10.23919/CJEE.2024.000093

Samuel, I. A., Toyin, D. A., Somefun, T. E., Awelewa, A. A. & Abba-Aliyu, S. (2025) Evaluation and Improvement of Power Quality of Distribution Network: a Case Study of Covenant University, Ota. *Frontiers in Energy Efficiency*, 2, 1-14. https://doi.org/10.3389/fenef.2024.1389622

Shah, M. S., Mahmood, T. & Ullah, M. F. (2022) Power Quality Improvement using Ultra-Capacitor Based Dynamic Voltage Restorer with Real Twisting Sliding Mode Control. *Electrical Engineering & Electromechanics*, 1, 59-63. https://doi.org/10.20998/2074-272X.2022.1.08

Tipán, L., Barrera-Singaña, C., Carrión, D., & Jaramillo, M. (2026). Sustainable Power-Quality Enhancement and Loss Reduction in Radial Distribution Networks using a DCM Cuk-Based Power Factor Correction Scheme. *Sustainability*, 18(13), 1-23. https://doi.org/10.3390/su18136699

Uwagboe, J. O., & Saha, A. K. (2026). Enhanced Harmonic Mitigation and Reactive Power Support in Photovoltaic-Connected Power Filters Using a Robust Control Approach. *Engineering Proceedings*, 140(1), 1-12. https://doi.org/10.3390/engproc2026140059

Zhang, R., Liu, X., Zhou, S., Wang, C. & Zhou, Q. (2023) Boost Power Factor Correction Converter with Adaptive Harmonic Compensation Control. *Journal of Institute of Engineering & Technology (IET)*, 16(11), 1776-1795. https://doi.org/10.1049/pel2.12489