ELECTRICAL SOLAR SYSTEM

Adaptive Neuro-Fuzzy Inference System (ANFIS)-Based Controller for a Unified Power Quality Conditioner (UPQC) in an Islanded Microgrid

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Abstract

This study investigates the development and performance of an ANFIS-controlled Unified Power Quality Conditioner (UPQC) integrated into a solar photovoltaic-battery islanded microgrid for voltage regulation, harmonic mitigation, transient stability, and active-power balancing in the Tende-Ama Ogu/Bolo distribution system, Rivers State, Nigeria. The study first assessed the solar energy resource at Tende-Ama Community using Global Horizontal Irradiance (GHI) data obtained from the NASA POWER database for January 2024 to August 2026. An average daily GHI of 4.13 kWh/m^2/day was obtained, with PV capacity factors of 62.79%, 60.24%, and 60.19% for the assessed 2024, 2025, and 2026 periods, respectively. A MATLAB/Simulink model of the solar-battery islanded microgrid was subsequently developed, comprising a PV array, MPPT-controlled boost converter, DC-AC inverter, BESS with bidirectional boost-buck converter, balanced load, and nonlinear rectifier load. Load-flow analysis of the Tende-Ama Ogu/Bolo distribution system established the baseline voltage profile under heavy loading and identified Bus 5, Bus 10, Bus 13, Bus 14, and Bus 18 as voltage-weak buses, with voltage magnitudes of 93.25%, 92.77%, 93.50%, 91.59%, and 90.72%, respectively. A UPQC was then integrated at the point of interconnection to provide series and shunt compensation. Harmonic assessment showed that the total harmonic distortion of 20.62% was reduced to 1.15% following UPQC compensation. Under transient voltage disturbances, the UPQC dynamically compensated for voltage sag and swell while maintaining a stable load voltage. Under heavy loading, integration of the ANFIS-controlled UPQC improved all bus voltages to within the 0.95–1.05 pu acceptable operating range, with the previously weak buses improved to 99.327%, 99.091%, 99.945%, 99.500%, and 99.536%, respectively. The findings demonstrate that the integrated ANFIS-controlled UPQC and coordinated PV-BESS control strategy provides an effective approach for improving voltage regulation, mitigating harmonic disturbances, supporting transient stability, and maintaining active-power balance in a solar-battery islanded microgrid.

Keywords: ANFIS controller; DC-AC inverter; load flow; MATLAB/Simulink; microgrid; MPPT-controlled boost converter; photovoltaic (PV)-battery

1 Introduction

Energy remains a fundamental driver of economic growth, industrial development, and socio-political stability in every nation. Virtually all aspects of modern life ranging from education, healthcare, and telecommunication to transportation and manufacturing depend on the availability of reliable and affordable energy supply. As a result, global energy demand remains a growing demand due to population expansion, fast industrialization and enhancement of living standards (Oyedepo, 2024). Energy sources today are still dominated by fossil fuels and nuclear energy with less than 10 per cent of the world's energy coming from renewable and environmentally friendly sources [4]. The use of renewable energy technologies such as solar, wind, hydro and biomass energy are being

viewed as a promising development to mitigate the negative environmental impacts of traditional energy sources. Of these, solar photovoltaic (PV) is particularly prominent because of its abundance, modular deployment, and ability to be used both as a grid-connected energy source as well as a standalone energy source [8]. Solar radiation in Nigeria is available year-round, making it a practical solution to meeting the country's chronic electricity shortages, particularly in remote and rural communities. But, the intermittent and stochastic nature of solar energy often leads to voltage and frequency fluctuations, which makes the performance of the systems based on solar energy unstable when the irradiance and loads change over time [8].

To overcome these challenges, solar photovoltaic-battery hybrid systems have been developed to enhance energy reliability and maintain continuous power supply in both grid-connected and islanded or off-grid modes as seen in [9]. During islanded operation, the microgrid operates autonomously disconnected from the main utility grid thereby requiring advanced control strategies to manage power flow, maintain voltage and frequency within acceptable limits, and ensure high power quality. In such conditions, maintaining the integrity of power quality becomes paramount, as nonlinear loads and converter-based interfaces introduce harmonic distortions, voltage sags, swells, and other dynamic disturbances that can degrade system performance (Khalid *et al*., 2022).

A Unified Power Quality Conditioner (UPQC) is an advanced power electronic device capable of simultaneously mitigating both current and voltage-related disturbances. The UPQC combines a series and shunt compensator to improve the voltage profile, eliminate harmonics and control the reactive power in the network. It forms part of renewable-based systems to provide stable, clean and reliable power supply to critical loads. Proportional Integral (PI) and Conventional fuzzy logic controllers have fixed control parameters and are unable to adapt to a dynamic and nonlinear environment [2]. The Adaptive Neuro-Fuzzy Inference System (ANFIS) is one of those, which is a hybrid computational method combining the self-learning ability of the Artificial Neural Network (ANN) with linguistic reasoning of Fuzzy Logic (FL). The dual capabilities of its adaptation and interpretation make ANFIS a suitable tool for adjusting the control parameters in real time when there are changes in the system [3]. Secondly, the proposed intelligent control system aims at optimizing the power flow, efficient battery energy management, and voltage and frequency stability during the islanded operation. Besides, it is designed to mitigate the power quality problems including harmonics, voltage sag and swell, reactive power imbalance. The adaptive learning and fuzzy reasoning components of the ANFIS-UPQC control scheme offer an efficient, robust, and intelligent way to ensure stability and reliability in renewable energy systems, helping to pave the way for the global shift towards sustainable and resilient energy sources.

2 Statement of the problem

Tende-Ama is a community in Ogu/Bolo Local Government Area of Rivers State that faces inadequate and unreliable electricity supply, which affects domestic, commercial, and community activities thereby limiting the local socio-economic advancement. Thus, the proposed solar PV–battery system under islanded operation offers an alternative electricity supply; however, this proposed operation constitutes some specific technical challenges resulting from variations in solar power generation and consumer demand that can cause generation-load imbalance, voltage deviations, and frequency fluctuations in the absence of utility-grid support. Furthermore, the nonlinear loading can introduce harmonic distortion, voltage disturbances, and reactive-power imbalance, thereby reducing the power quality and stability of electricity supplied to consumers. The challenges of maintaining

acceptable voltage profile, frequency, reducing harmonic distortion, and improve reactive-power levels in the proposed Tende-Ama islanded microgrid are paramount in this research. Conventional UPQC controllers have limited adaptability to nonlinear and time-varying conditions. Thus, this study therefore proposes an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based controller infuse into the Unified Power Quality Conditioner (UPQC) to provide adaptive voltage and current compensation while improving the power quality and operational stability that affect positively on the supply system, better support for socio-economic activities; thus, reducing dependency on unreliable grid electricity in Tende-Ama community. This study is to design an adaptive neuro-fuzzy inference system-based controller for unified power quality conditioner in islanded microgrid operation.

3 Objectives

The objectives of this study are as follows:

1. To assess the solar energy resource potential for the photovoltaic power generation, and the power distribution network data of the Tende-Ama Community in Ogu/Bolo LGA, Rivers State.
2. To model the distribution network with Solar PV-Battery inclusive and evaluates the bus voltage profile, etc., of the Tende-Ama distribution system but without UPQC and identify voltage-weak buses; however, investigate the capability and applicability of the UPQC before fully used.
3. To model the solar photovoltaic-battery with UPQC system into the Tende-Ama community power distribution network via MATLAB/Simulink software for simulation while ascertaining the enhanced power quality and system power stability.
4. To develop an ANFIS-based controller that coordinates the photovoltaic-battery energy storage system (PV-BESS) for voltage and frequency regulation under the islanded microgrid distribution operation.
5. To simulate the entire system for voltage-current compensation performance of the ANFIS-controlled PV-Battery-UPQC in the Tende-Ama community distribution system.

4 Literature review

[4] presented an effective hybrid renewable energy system that employed an artificial intelligence technique to ascertain the optimal power generation and management of power flow within the system. The system utilizes photovoltaic (PV) and wind energy conversion system (WECS) as the primary energy sources while the battery energy storage system (BESS), the hydrogen energy storage system (HESS), and the supercapacitor energy storage system (SESS), as backup sources from providing reliable simultaneous power supply. The study compared Hybrid ZOA-ANFIS based MPPT and hybrid GTO-ANFIS-based MPPT techniques for optimal power extraction from PV and wind turbines system. Upon comparing the two methods, the result obtained shows that both hybrid methods exhibit high levels of performance. However, the hybrid ZOA-ANFIS-based MPPT technique demonstrates relatively superior performance in terms of reduction in computational time of 26.172 % compared to the GTO algorithm for the PV system. Similarly, in the case of the wind energy conversion system, there was a substantial decrease of 35.5 % in computational time when compared to the GTO algorithm.

[5] presented a research work, Optimization and Management Strategy of Grid Connected Hybrid Renewable Energy Sources capable of supplying electricity to about 26-30 houses for a selected appliance. The research was aimed at designing an efficient energy management strategy based on

fuzzy logic algorithm that will optimize the cost and minimize the power loss from renewable energy sources.

[2] designed a fuzzy logic decision on various energy sources. This was done to avoid load shedding. Input signals from three (3) different sources were considered as the author implemented the design system. The inputs were voltage range, irradiance and battery state of charge. The outputs were linear constraints as the authors applied Takagi's fuzzy inference system. The result showed that the designed system took decisions regarding the conditions and obtained load feeding signal behaviour.

[2] presented an energy management technique for the isolated micro-grids. A master- slave topology was utilized wherein local controllers were effectively managed, controlled and maintained through a middle controller. The authors investigated the performance of the microgrid under fault and steady state condition. Results obtained validated the proposed system showed consistency when compared with IEEE 1547.

Shravani *et al*. (2023) focus on addressing power quality issues, particularly current variations caused by harmonics generated from nonlinear loads, which can degrade power system stability. The study explores the role of active power conditioners, including Shunt Active Power Filters (SAPFs), Series-Enhanced Active Power Filters (SEAPFs), Unified Power Quality Conditioners (UPQCs), and Intelligent Power Quality Conditioners (IPQCs) in mitigating these harmonics.

4.1 Fuzzy logic

The use of Fuzzy logic based MPPT is based on fuzzy set theory, which helps overcome the uncertainties and non-linearity associated with PV systems. Fuzzy logic controllers are used to determine the best operating point without using a mathematical model of PV array. This is especially suitable for applications with partially shaded PV arrays or where the sun's path and its intensity change quickly. The main advantage of fuzzy logic is its adaptability to different operating conditions without the need of a precise model of the system. However, the design of an effective fuzzy logic controller can be difficult, depending on the set of rules and membership functions that are selected and tuned, which may require a lot of trial and error or expertise [2]. The study found that FLC was effective to keep the hybrid DG system stable, especially in controlling the voltage regulation and the power flow of the system under varying renewable energy sources. There is a need for further research on optimizing fuzzy rules for real-time applications, especially for large-scale systems with complex networks.

4.2 Artificial neural networks (ANN)

ANN-based MPPT techniques involve data driven models to learn and predict the complex nonlinear relationship between environmental variables and PV system output to estimate the MPP [4]. The ANN is trained during the training phase with historical data from the various operating conditions. After this training, the network can estimate the optimum operating point for the current conditions in a short time [3]. One advantage of ANN is that it is able to generalize and predict the MPP even in the presence of noise and partial shading in different situations. The output of ANN based MPPT,

4.3 Adaptive neuro-fuzzy inference system (ANFIS)

ANFIS is a hybrid method of combining human-like reasoning of fuzzy logic and learning ability of neural networks. In ANFIS based MPPT controller, fuzzy inference system is designed in such a manner that it can fine-tune its rules and membership functions by training data . This leads to an MPPT technique capable of effectively coping with the uncertainties and nonlinear behaviors of PV

systems and providing high tracking performance under dynamic conditions [5]. The ability to adapt to the environment with the help of previously collected data makes ANFIS systems more capable of adapting to the surrounding environment, especially when there are partial shading and unpredictable weather changes. Similar to ANN, ANFIS also needs a large amount of data for training purposes and proper system design to optimize complexity and performance [6].

4.4 Overview of the unified power quality conditioner (UPQC)

In modern power distribution systems, there are several power quality (PQ) disturbances which could be tackled by a single device called the Unified Power Quality Conditioner (UPQC) a custom power device designed to compensate for both voltage and current related disturbance simultaneously. Unlike conventional compensation devices that target either voltage or current disturbances independently, UPQC integrates both functionalities into a single coordinated system, making it particularly suitable for networks with high penetration of power electronic converters and renewable energy sources [3].

4.5 Operating principle of the UPQC

The UPQC operates based on the coordinated action of two voltage source converters (VSCs) connected through a common DC-link capacitor. The series VSC is connected in series with the distribution line and is primarily responsible for mitigating voltage-related disturbances such as voltage sags, swells, flicker, and unbalance by injecting a compensating voltage [1]. The shunt VSC is connected in parallel with the load and compensates for current-related issues, including harmonic currents, reactive power demand, and load imbalance. The common DC-link allows real power exchange between the two converters, enabling effective and simultaneous voltage and current compensation [6]

4.6 Power quality improvement capabilities of the UPQC

UPQC provides comprehensive power quality enhancement by simultaneously addressing voltage and current disturbances, which are commonly observed in modern distribution systems with nonlinear and inverter-based loads. It effectively mitigates voltage sags, swells, harmonics, and unbalanced conditions, while also compensating reactive power and improving power factor [4].

Many studies have shown that total harmonic distortion (THD) can be decreased considerably at both the source and load side, when using UPQC. UPQC helps in complying with the power quality standards by blocking the propagation of load generated harmonics to the rest of the grid and maintaining the regulated voltage supply to sensitive equipment. These features render UPQC ideal for industrial, commercial and renewable energy based power systems [5].

4.7 Configuration and components of the UPQC

A typical UPQC system includes a series coupling transformer, a shunt coupling inductor, voltage source converters and energy storage element in the DC-link. The series transformer is used to inject voltage to the distribution system without breaking the circuit, and the shunt inductor is used to inject current into the distribution system under control (Yin et al., 2020). During compensation, the DC-link capacitor is a key component for ensuring energy balance and operating stability of the converter. Voltage, current and voltage of the DC-link are monitored by control and sensing circuits. For renewable energy and microgrid systems, the DC-link can be backed by battery or supercapacitor

to improve the compensation capability and buffer the additional energy during transient and steady state condition [8].

5 Materials and methods

5.1 Materials

The materials employed for the modelling and simulation of the proposed solar photovoltaic –battery islanded power system with Unified Power Quality Conditioner (UPQC) includes:

Solar photovoltaic (PV) array serving as the primary renewable energy source, Battery Energy Storage System (BESS) for energy backup and islanded operation, DC-DC boost converter for PV voltage regulation and maximum power extraction, Unified Power Quality Conditioner (UPQC) comprising series and shunt voltage source converters, DC-Link Capacitor shared by the series and shunt converters of the UPQC, Injection Transformers for series voltage compensation, Passive Filters (LC/Low-Pass Filters) for harmonic attenuation, Nonlinear and Linear Loads representing practical load conditions, MATLAB/Simulink Software Environment for system modelling and performance evaluation

5.2 Methods

This study applied both simulation and analytical based approach for an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based controller for a Unified Power Quality Conditioner (UPQC) in an islanded microgrid system. The proposed system consists of a solar photovoltaic (PV) array, DC-DC boost converter, battery energy storage system (BESS), and UPQC connected at the point of common coupling (PCC). The UPQC comprises a series voltage source inverter (VSI) for voltage disturbance compensation and a shunt VSI for current harmonic and reactive power compensation. The system is operated under fully islanded conditions, with the BESS providing power support during reduced or zero solar generation. An ANFIS-based controller is developed to generate the appropriate control signals for the UPQC. The proposed system is subjected to different operating conditions, including nonlinear loads, load variations, voltage disturbances, and reduced or zero solar generation. The performance of the ANFIS-based UPQC controller was evaluated using the network voltage profile, current total harmonic distortion (THD), and reactive-power compensation. Figure 2 shows the Proposed model of the Islanded Solar PV-Battery Microgrid with ANFIS-Based UPQC Controller (un-simulated).

The existing Tende-Ama community distribution system comprises eighteen (18) of 11/0.415 kV distribution transformers located along the streets. The loads supplied by these transformers were represented in the distribution network model as equivalent three-phase loads connected to their respective 11 kV buses. The model includes balanced loads representing the normal electrical demand and a nonlinear rectifier load for assessing harmonic disturbances. The resulting load model provides the baseline operating condition for evaluating voltage deviations, harmonic distortion, and the compensatory performance of the proposed UPQC. Figure 1 presents the Simulink model of Tende-Ama community distribution network, with load model comprises of the eighteen distribution transformers. Also, Table 1 shows the Tende-Ama community distribution load bus data indicating the connected distribution transformers.

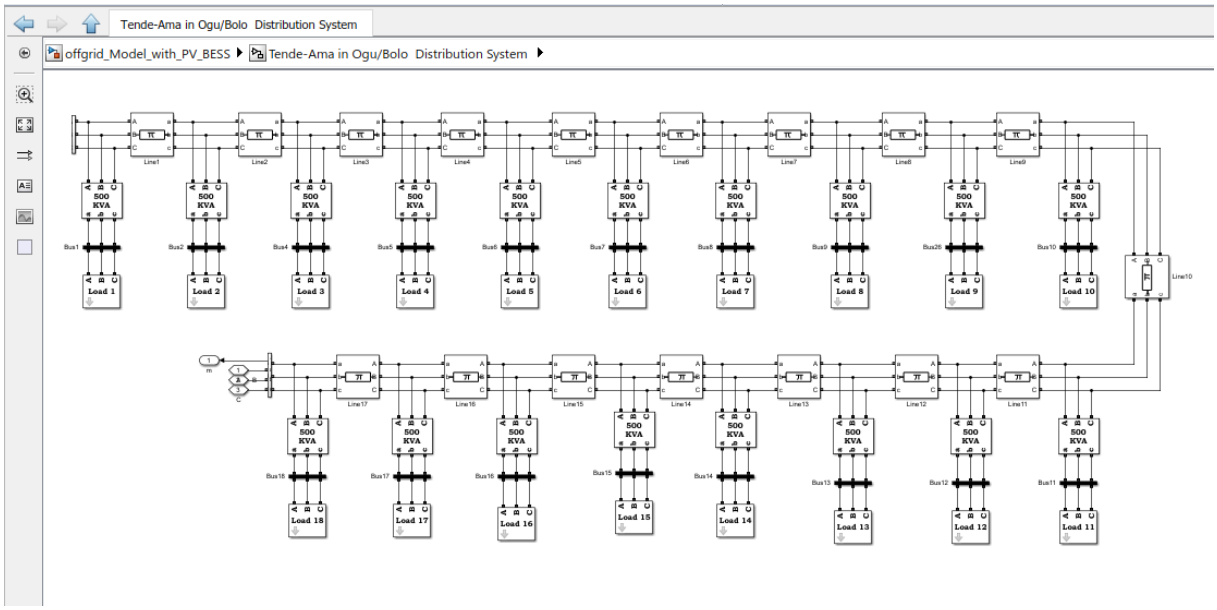


Figure 1. Simulink model of the Tende-Ama Ogu distribution network (un-simulated; model developed in this research).

Table 1. Distribution load bus data of the Tende-Ama community, Ogu/Bolo.

Bus ID	Bus name	Rated voltage (kV)	Transformer (kVA)	Load (kVA)	Load (kW)	Load (kvar)	PF	Current (A)
1	Bus1	11	500	308.0	261.8	162.3	0.85	428.5
2	Bus2	11	500	140.5	119.4	74.03	0.85	195.5
3	Bus3	11	500	224.0	190.4	118.0	0.85	311.6
4	Bus4	11	500	262.0	222.7	138.0	0.85	364.5
5	Bus5	11	300	278.0	236.3	146.4	0.85	386.8
6	Bus6	11	500	188.5	160.2	99.28	0.85	262.2
7	Bus7	11	500	300.0	255.0	158.0	0.85	417.4
8	Bus8	11	500	261.5	222.3	137.8	0.85	363.8
9	Bus9	11	500	302.0	256.7	159.1	0.85	420.1
10	Bus10	11	300	288.0	244.8	151.7	0.85	400.7
11	Bus11	11	500	199.5	169.5	105.1	0.85	277.5
12	Bus12	11	500	268.5	228.2	141.4	0.85	273.5
13	Bus13	11	300	270.0	229.5	142.2	0.85	375.6
14	Bus14	11	500	262.0	222.7	138.0	0.85	364.5
15	Bus15	11	300	278.0	236.3	146.4	0.85	386.8
16	Bus16	11	500	188.5	160.2	99.28	0.85	262.2
17	Bus17	11	500	300.0	255.0	158.0	0.85	417.4
18	Bus18	11	500	300.0	241.6	149.7	0.85	417.4
Total			8,200	4,619.0	3,912.6	2,424.8		6,326

Source: Port Harcourt Electricity Distribution Company (2026).

Table 1 show the Tende-Ama Community in Distribution Load Bus Data in the Ogu/Bolo LGA. Data adapted from the Port-Harcourt Electricity Distribution Company, 2026.

The distribution network is represented using 17 Three-Phase PI Section Line blocks in MATLAB/Simulink. All feeder sections are assumed to use the same 150 mm^2 ACSR overhead conductor in a horizontal phase arrangement, operating at 11 kV and 50 Hz.

Table 2. Positive- and zero-sequence parameters of the 11 kV distribution lines for Simulink PI-section line modelling.

S/N	Electrical parameter	Positive sequence	Zero sequence	Unit
1	Resistance	0.2053	0.4265	Ω/km
2	Inductive reactance	0.3990	1.5164	Ω/km
3	Inductance	0.001270	0.004827	H/km
4	Capacitance	[to be supplied]	[to be supplied]	F/km

Table 2 shows the positive, and zero-sequence parameters of the 11kV distribution lines for Simulink PI section line modelling. The feeder lengths are based on the values provided, giving a total modelled line length of 29.80 km.

Figure 2 presents the proposed Simulink model of Tende-Ama community distribution network with load model comprises of the eighteen distribution transformers, UPQC, Solar photovoltaic and Battery energy storage system (un-simulated)

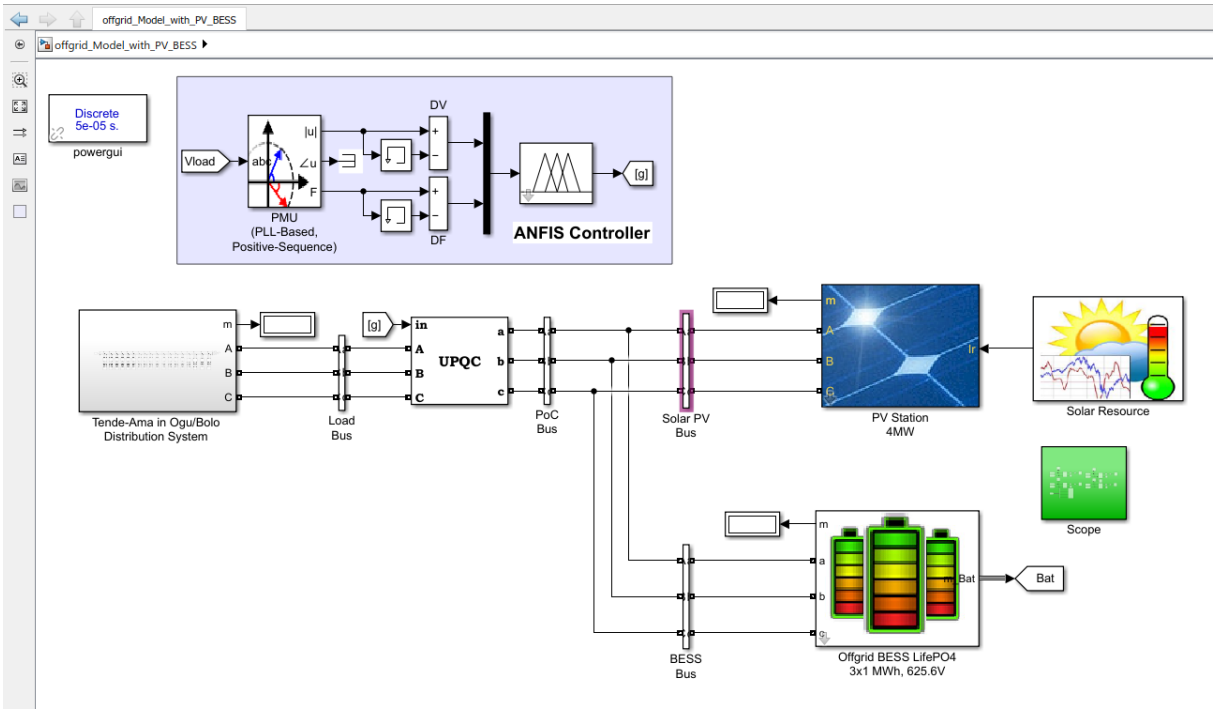


Figure 2. Proposed islanded solar PV–battery microgrid with ANFIS-based UPQC controller (un-simulated model developed for this research).

6 Results and discussion

6.1 Solar energy resources

Table 3 provides the annual solar resources and corresponding photovoltaic (PV) energy performance for the development of the proposed Solar Photovoltaic-Battery modelled islanded microgrid. The annual global horizontal irradiance (GHI) results assessed reveals the availability of solar energy throughout the assessment period as shown. In 2024, a total GHI of 1,551.33 kWh/m^2 was recorded over 366 days, corresponding to an annual solar energy yield of 2,482.13 kWh. Resulting to an average solar energy yield of 6.596kWh/day.

Table 3. Annual solar resource and PV performance.

Year	Days Available	Annual GHI (kWh /m^2)	Annual Yield (kWh)	Capacity Factor (%)	Performance Ratio (%)
2024	366	1551.332	2482.131	62.794	88.89
2025	365	1484.253	2374.804	60.244	88.89
2026	243	987.227	1579.563	60.188	88.89

Source of GHI and yield data: NASA POWER (2026).

In 2025, the annual GHI decreased slightly to 1,484.25 kWh/m^2, with an associated solar energy yield of 2,374.80 kWh. For 2026, the available data covered 243 days, from January to August, during which a cumulative GHI of 987.23 kWh/m^2 and an estimated solar energy yield of 1,579.56 kWh were obtained. The lower 2026 values are therefore attributable partly to the shorter assessment period and should not be interpreted as a full-year reduction in solar potential. Figure 3 shows the annual GHI (kWh/m^2) versus year.

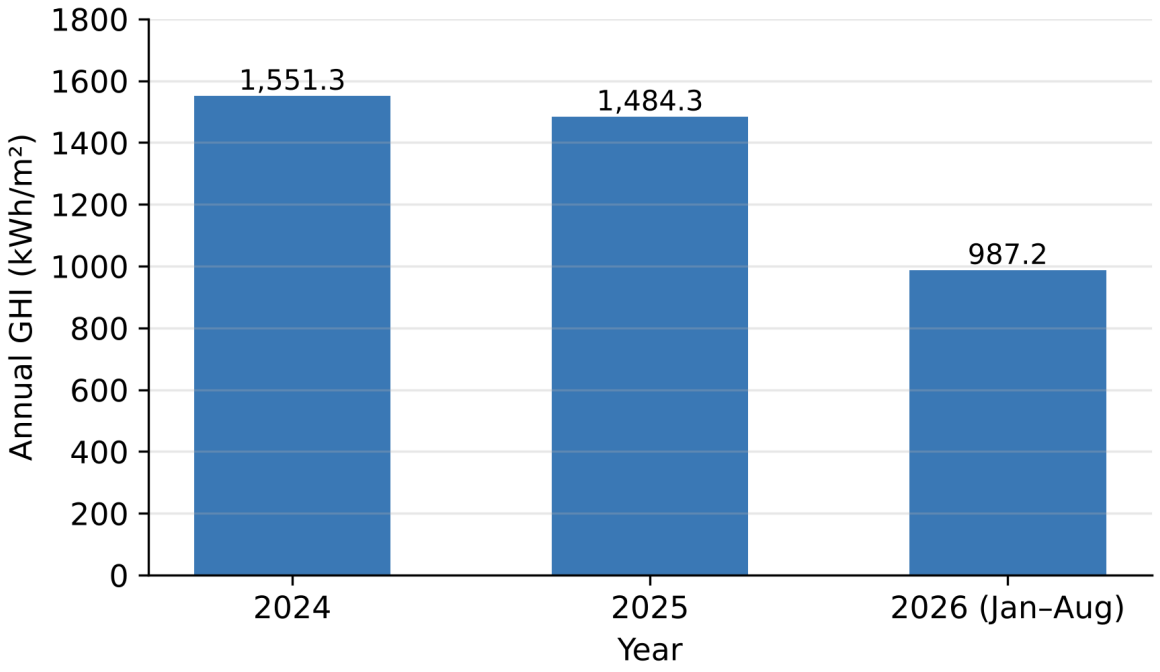


Figure 3. Annual GHI (kWh/m^2) by year (2026: January–August only).

As seen in the Table 3 and Figure 3 above, the PV performance assessment indicates a favourable energy conversion characteristic. The calculated capacity factor was 62.79% in 2024, 60.24% in 2025, and 60.19% for the available period in 2026. The relatively close values across the years suggest that the PV system can maintain reasonably consistent energy production despite annual variations in solar irradiation. Furthermore, the calculated performance ratio of 88.89% for all three periods indicates that a substantial proportion of the available solar resource is converted into useful electrical energy under the assumed PV-system conditions.

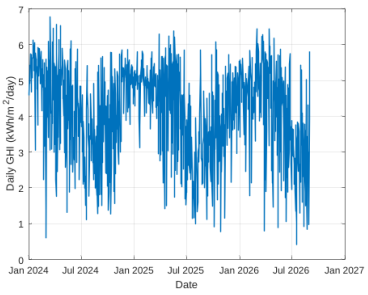


Figure 4. Daily GHI of Tende-Ama in Ogu/Bolo, Rivers State, January 2024–August 2026 (data: NASA POWER, 2026).

6.2 Distribution network with the PV–battery model and bus voltage profile without UPQC

Figure 5 shows the distribution network with solar photovoltaic-battery islanded microgrid model without the addition of Unified Power Quality Conditioner (UPQC). Since no UPQC was incorporated in it, the resulting voltage and current characteristics represented the uncompensated baseline condition. Thus, this model therefore provides back-up, and power injection from the solar photovoltaic system as a reference case for evaluating subsequent improvements in voltage regulation, current quality, and harmonic distortion.

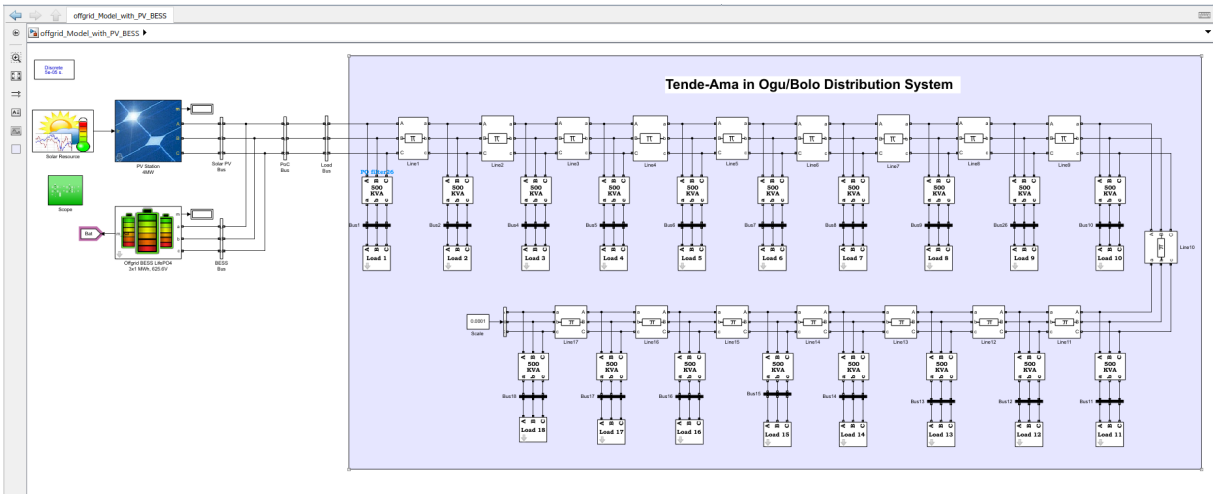


Figure 5. MATLAB/Simulink model of the solar PV–battery islanded microgrid without UPQC.

6.3 Load-bus voltage profile without UPQC

Figure 6 represents the load-bus voltage profile of the Tende-Ama distribution system without UPQC compensating. This assessment establishes the baseline voltage condition and identifies buses susceptible to voltage degradation for subsequent compensation. From the load flow simulation Bus5: 93.25%, Bus10: 92.77%, Bus13: 93.50%, Bus 14: 91.59% and Bus18: 90.72% are heavily impacted buses in the network under overload condition. The identified

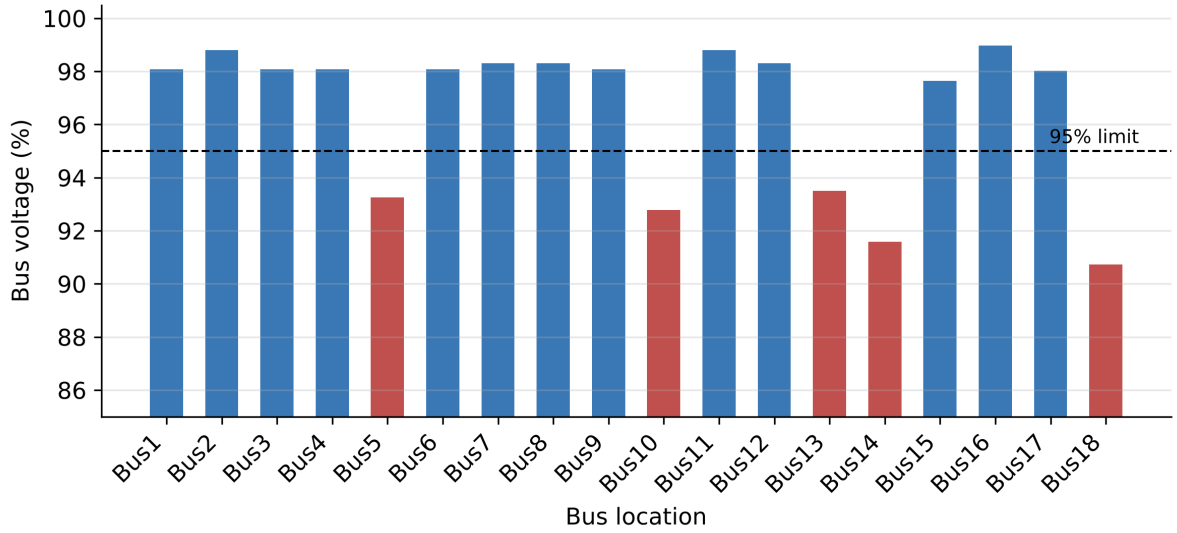


Figure 6. Bus voltage profile of the existing Tende-Ama community distribution system (buses below the 95% limit in red).

6.4 Assessment of UPQC capability for mitigating harmonic disturbances

Figure 7 presents the instantaneous source voltage, load voltage, and injected voltage over the 0 -1s simulation period, demonstrating the response of the UPQC to harmonic disturbances in the islanded microgrid. From 0 to 0.2 s, the source voltage exhibits a relatively regular three-phase sinusoidal waveform, representing the normal operating condition. At 0.2 s, harmonic distortion is introduced into the source voltage and persists until about 0.8 s, as indicated by the increased waveform distortion and amplitude variation. During the disturbance interval of 0.2 - 0.8s, the injected voltage

of the UPQC becomes active, producing the compensating voltage required to counteract the distortion present in the source. The injected waveform demonstrates that the series compensation unit responds dynamically to the disturbance and the load voltage remains sinusoidal and balanced throughout the disturbance interval, despite the distortion observed in the source voltage. This indicates that the UPQC effectively isolates the sensitive load from the distorted source voltage.

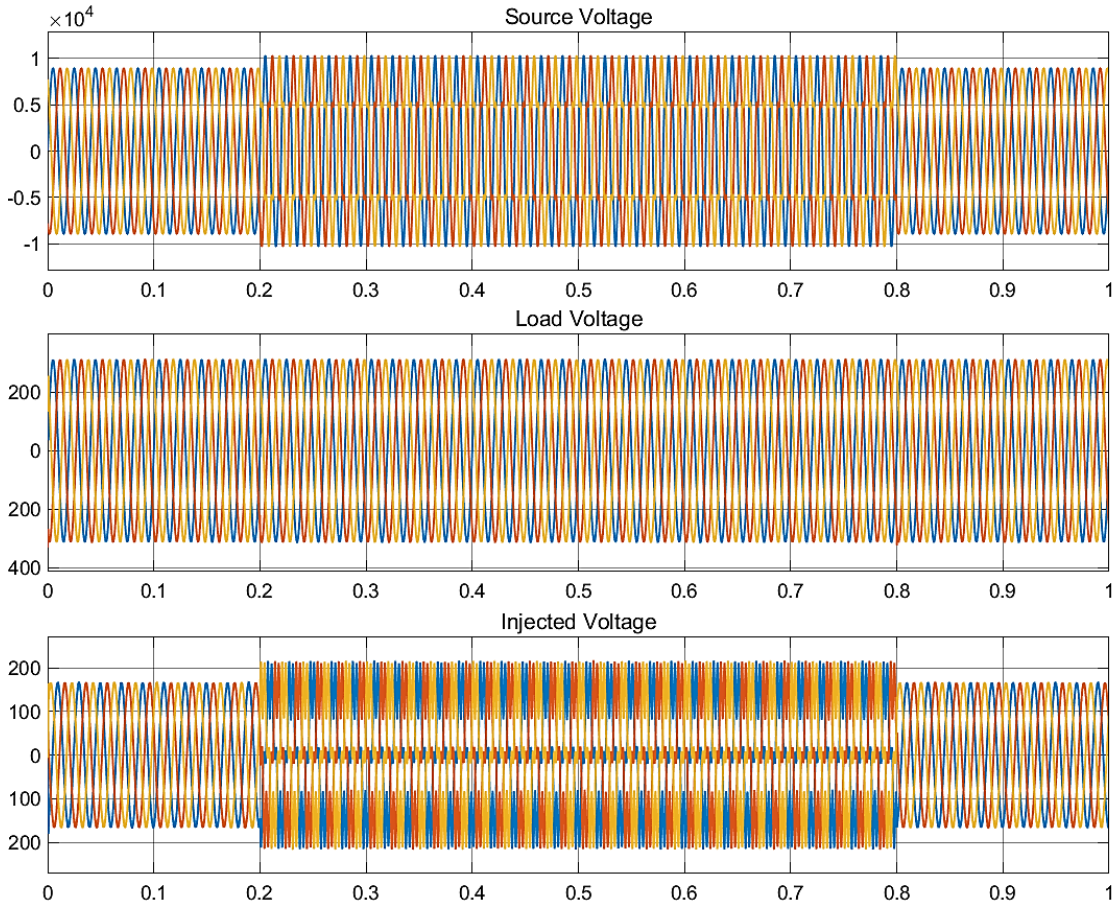


Figure 7. Instantaneous source, load and injected voltage waveforms before, during and after the disturbance.

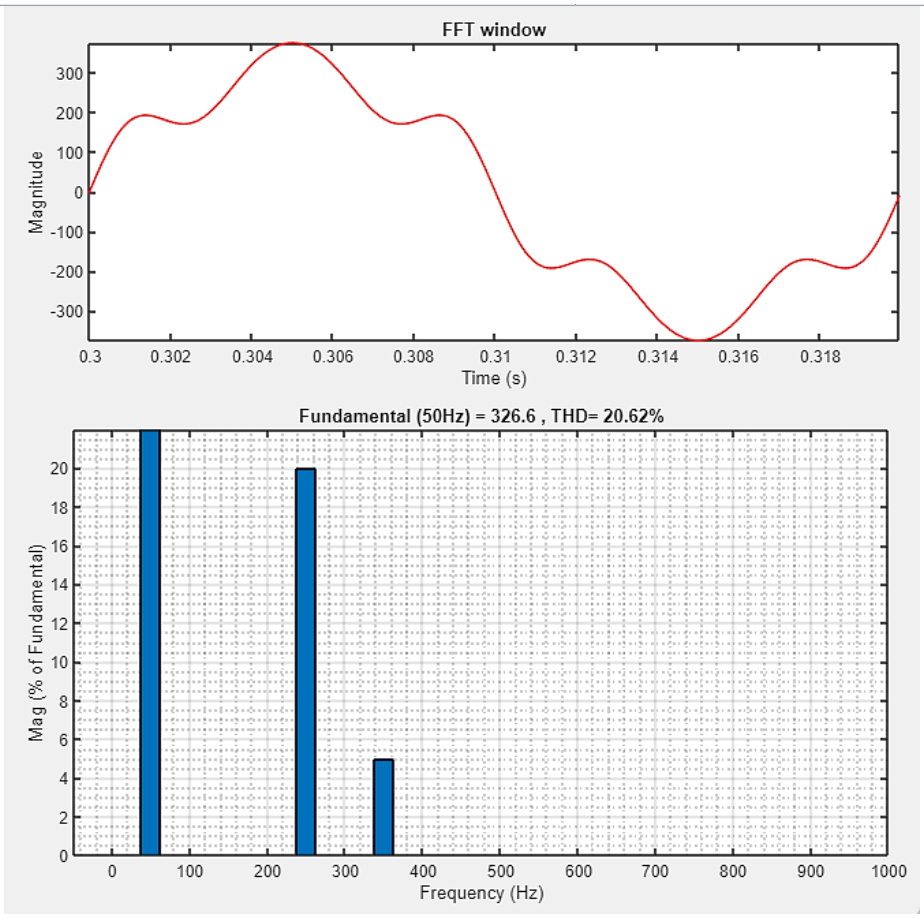


Figure 8. FFT of the harmonic voltage spectrum without UPQC (THD = 20.62%).

Figure 9 presents the results of harmonic current mitigation in the Tende-Ama distribution system following the installation of the Unified Power Quality Conditioner (UPQC). The UPQC was deployed to mitigate harmonics caused by the presence of multiple frequency components in the voltage waveform, which caused the fundamental frequency to deviate from its ideal sinusoidal form. As shown in the Fast Fourier Transform (FFT) analysis' window, the compensated waveform became smoother, indicating a significant reduction in harmonic distortion and improved waveform quality. Total Harmonic Distortion (THD) was reduced to 1.15%, which is well within the acceptable limit and does not violate any predefined harmonic standards. This result demonstrates the effectiveness of the UPQC in enhancing power quality by suppressing harmonic disturbances and restoring the waveform closer to an ideal sinusoidal profile.

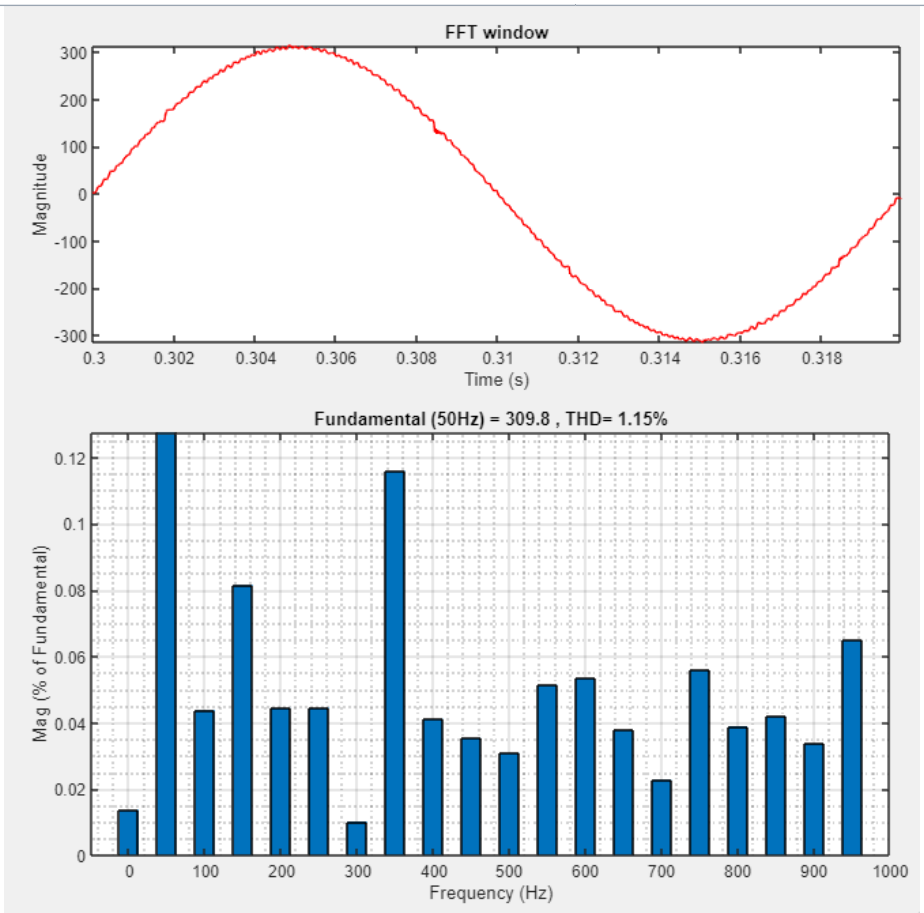


Figure 9. FFT of the harmonic voltage spectrum with UPQC (THD = 1.15%).

At 0.2s, the source voltage magnitude increases significantly and persists until about 0.5s, indicating a voltage swell condition. The magnitude of the source voltage drops at 0.5s and the voltage level is low until about 0.8s again, where the voltage condition is called a voltage sag. The source voltage slowly restores the normal operating voltage after 0.8 s. In the disturbance periods, the injected voltage of the UPQC can dynamically produce the required compensating voltage to compensate for the voltage changes of the source. When the voltage rises from 0.2 to 0.5 s, the injected voltage is adjustable so as to compensate the excessive voltage from the source; when the voltage drops from 0.5 to 0.8 s, the injected voltage is adjusted accordingly to compensate for the reduction of the source voltage. This results in the load voltage being essentially sinusoidal in nature and the voltage magnitude being very close to constant during the whole simulation time, notwithstanding the large difference between the source voltage and the load voltage. The UPQC's effective transient voltage regulation capacity is shown by the fact that the voltage of the load can be maintained within the desired range during load sag and swell. The results validate the effectiveness of the proposed UPQC in isolating the sensitive load from the source side voltage disturbances and ensuring power quality stability during transients in the solar PV-battery islanded microgrid.

6.5 ANFIS-based coordinated PV–BESS control for voltage and frequency regulation

Figure 10 shows the fuzzy logic designer representation of the developed ANFIS controller, confirming the functional relationship between the two measured-system error variables and the BESS control command. The control scheme is designed to coordinate the battery active-power response with voltage and frequency deviations to support stable operation of the islanded microgrid. The

controller uses Voltage Error and Frequency Error as its input variables and BESS Active Power Reference as the output variable, with a Sugeno-type fuzzy inference system adopted for the controller formulation. The membership functions associated with the input variables provide the fuzzy representation of different magnitudes of voltage and frequency deviations, while the fuzzy-rule structure establishes the corresponding BESS power response. The adaptive learning capability of the ANFIS network allows the parameters of the fuzzy membership functions and rules to be adjusted during training, thereby improving the controller's ability to represent the nonlinear relationship between voltage/frequency deviations and BESS power requirements. During operation, voltage and frequency deviation is measured from its reference and processed into a BESS active-power reference. The resulting command enables the BESS to absorb or supply active power according to the operating condition, thereby complementing the variable solar PV generation and supporting the active-power balance of the islanded microgrid. The configuration shown in Figure 10, thus, establishes the computational basis for adaptive coordination of PV generation and battery storage, with the overall objective of improving voltage and frequency regulation and enhancing the dynamic stability of the Tende-Ama Community islanded microgrid.

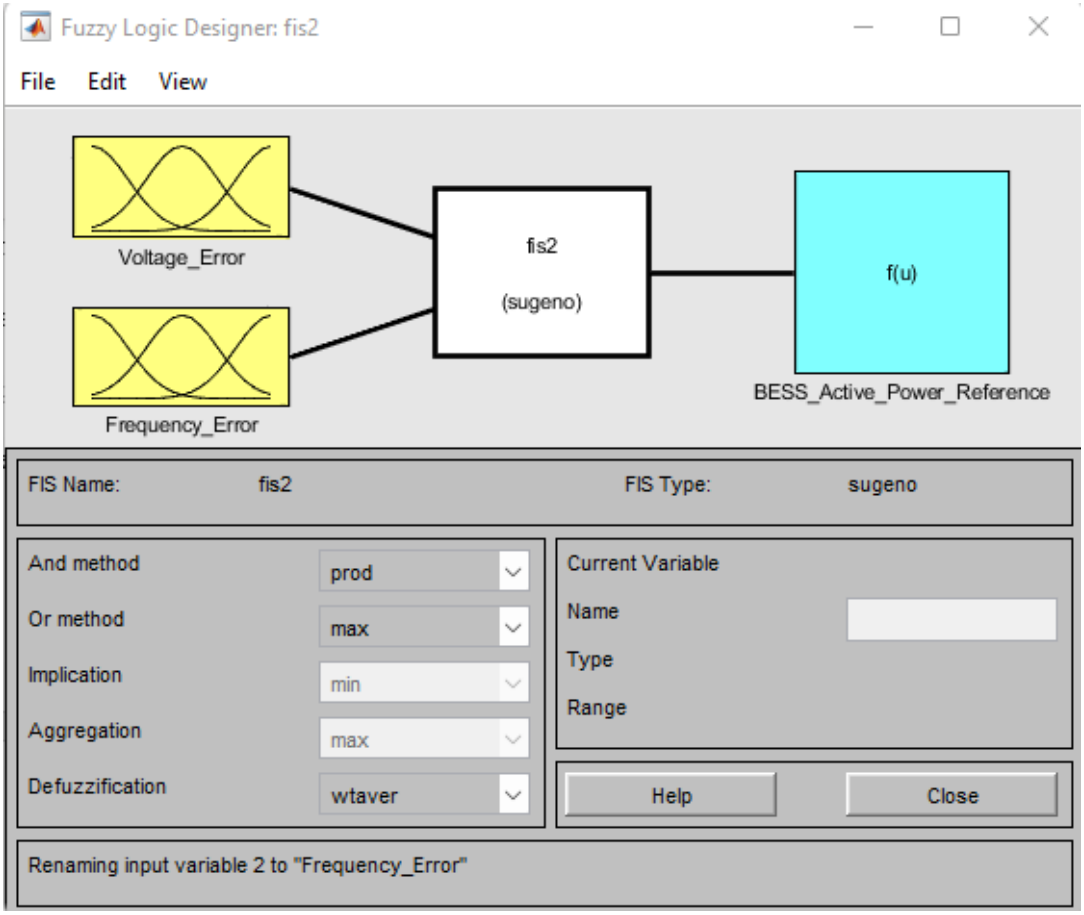


Figure 10. Fuzzy logic designer representation of the developed ANFIS controller.

6.6 BESS response under varying solar-generation conditions

This section evaluates the dynamic response of the BESS under varying solar-generation conditions. The assessment focuses on the charging and discharging behaviour, state-of-charge variation, and active-power exchange of the battery in maintaining the power balance of the islanded microgrid. Thus, Figure 11 presents the state of charge (SoC), battery voltage, battery current, and battery

power of the BESS under varying solar-generation conditions. The results show the coordinated control of the bidirectional power exchange between the solar PV system, BESS and the islanded microgrid, which is implemented using the ANFIS. The battery current and power are negative and peak at around -350 A and -220 kW, respectively, from 0 - 5s, which indicates battery charging. When the PV generation is more than the load demand, the excess electricity is utilized by the BESS. This means the SoC has risen from 30.00% to 30.03%, which indicates that energy has been stored during times of excess generation.

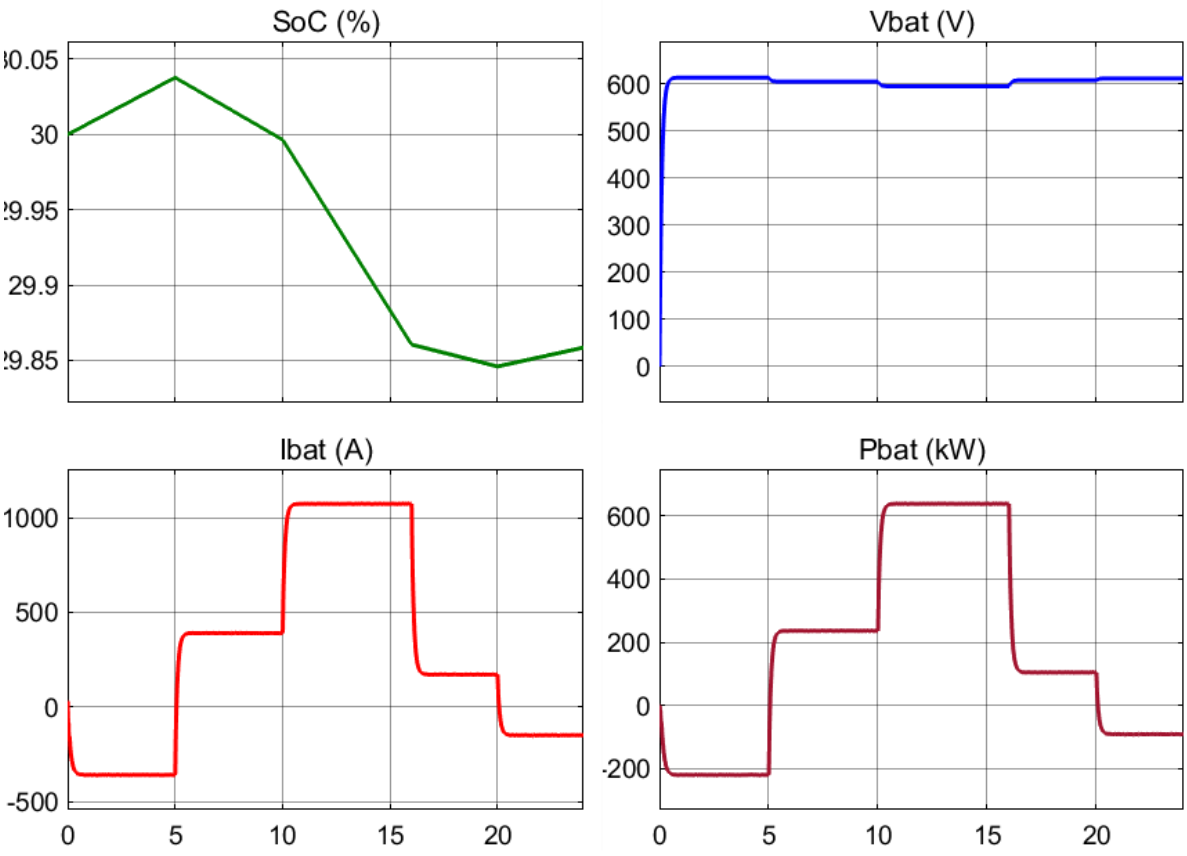


Figure 11. BESS response under varying solar-generation conditions: state of charge, battery voltage, current and power.

Additionally, the BESS cycles between charging and discharging states between 5 - 10s, providing charging currents of ~+380 A and charging powers of ~+230 kW. This shift represents a decrease in solar energy available to meet the load demand and more reliance on stored energy. The ANFIS controller senses the resulting power imbalance and adjusts BESS discharge accordingly to keep the operating conditions of the islanded microgrid as desired. The BESS discharge is rapidly ramped up from 10 – 16s, reaching a value of ~+1.05 kA and ~+640 kW, which corresponds to a considerable jump in the power deficit. The SoC value corresponds to the decrease, which shows that the microgrid is receiving stored energy from the battery. For a coordinated controller, this response indicates that it can provide a fast response on active power support when PV power production is not enough. In addition, the battery discharge drops to about +150 A and +100 kW between 16 and 20s, thus showing that the lack of power has diminished. The BESS thus delivers a lesser power support, whereas the SoC achieves the lowest recorded value of around 29.85%. The drop in discharge represents an adaptive response of the controller to varying generation and load. The current and power in the battery again turn negative from 20 - 24 s until they reach values of around

-150A and -80 kW. This means that the transition will be from discharging to charging when the PV generation is surplus.

6.7 Overall performance of the ANFIS-controlled PV–battery–UPQC system

Table 4 and Figure 12 presents the bus voltage profiles of the Tende-Ama community distribution system without and with the installation of the voltage-compensation driven ANFIS-controlled UPQC under heavy loading conditions. The results show that, the installation of UPQC improved the voltage magnitude at all buses, with the most significant improvements occurring at the previously identified weak buses. The assessment and application present the effectiveness of the intelligent control strategy in restoring the voltage profile of the distribution system that mitigate voltage deviations. Recall that, before UPQC installation, Bus 5, Bus 10, Bus 13, Bus 14, and Bus 18 were recorded whose voltage magnitudes are 93.25%, 92.77%, 93.50%, 91.59%, and 90.72%, respectively and they were below the 95% lower operating limit.

Table 4. Bus voltage profile without and with UPQC.

Load Bus		Nominal	Operating (%)	
ID	**Bus Type**	**(kV)**	**Without UPQC**	**With UPQC**
Bus1	PQ	11	98.07	98.073
Bus2	PQ	11	98.80	98.800
Bus3	PQ	11	98.07	98.073
Bus4	PQ	11	98.07	98.309
Bus5	PQ	11	93.25	99.327
Bus6	PQ	11	98.07	99.218
Bus7	PQ	11	98.31	99.218
Bus8	PQ	11	98.31	99.464
Bus9	PQ	11	98.07	99.218
Bus10	PQ	11	92.77	99.091
Bus11	PQ	11	98.80	99.091
Bus12	PQ	11	98.31	99.464
Bus13	PQ	11	93.50	99.945
Bus14	PQ	11	91.59	99.500
Bus15	PQ	11	97.64	99.545
Bus16	PQ	11	98.98	99.891
Bus17	PQ	11	98.03	99.845
Bus18	PQ	11	90.72	99.536

Data from this research.

Following UPQC installation, their voltage magnitudes increased to 99.327%, 99.091%, 99.945%, 99.500%, and 99.536%, respectively. The remaining buses also experienced improvement or maintained their voltage levels within the acceptable range.

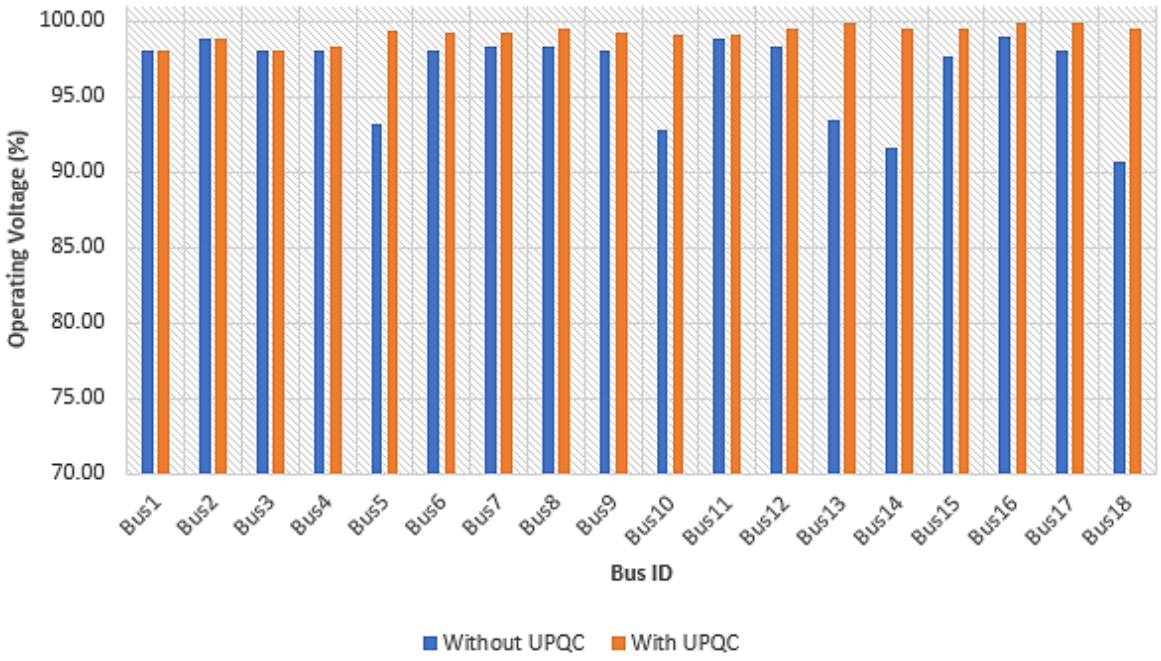


Figure 12. Bus voltage profile of the improved Tende-Ama distribution system without and with UPQC.

Overall, the post-compensation results of Figure 12 show that all 18 load buses operated between 98.073% and 99.945%. Thus, all buses have been restored to within the specified 0.95–1.05 pu voltage range. These results demonstrate that the ANFIS-controlled UPQC can effectively compensates for voltage deviations and restores load bus voltages without and with UPQC.

7 Conclusion

This study which was to examine the neuro-fuzzy inference system-based controller, the assessment via (NASA POWER, 2026) database online revealed the Global Horizontal Irradiance (GHI) data from the period January 2024 to August 2026, inclusive of solar PV energy yield, capacity factor, and performance ratio. We noted, an average daily GHI of 4.13 kWh/m^2/day, capacity factors ranging from 60.19% to 62.79% and a consistent performance ratio of 88.89% across the assessed periods at the study location. The results so obtained confirmed the availability of solar resources for solar PV electricity generation at the Tende-Ama community for the proposed solar-powered islanded microgrid. The dynamic voltage compensation of the UPQC under transient conditions revealed distorted compensation between the source voltage (at 0.2 - 0.5s ; 0.8 – 1s improved) and injected voltage recorded distortion (at 0 – 0.2s, improved at 0.2 – 0.5s) later distorted (at 0.5 – 0.8s) and improved again from (0.8 -1s). Each time the source voltage goes distorted, the injected voltage from the UPQC improve the source voltage to normalcy as required.

The developed model of the Photovoltaic-Battery with UPQC system into the Tende-Ama distribution network via MATLAB/Simulink software simulation while ascertaining the enhanced power quality and system power stability, and this assessment was successfully achieved. Simulation results demonstrated that the UPQC effectively mitigated harmonic disturbance, reducing total harmonic disturbance from 20.62% to 1.15% thereby bringing the harmonic distortion within the applicable IEEE 519-2022 limit, while also compensation for voltage sag and swell conditions, thereby enhancing power quality and dynamic stability in the islanded microgrid.

7.1 Recommendation

Based on this study, ANFIS-based coordinated Photovoltaic-Battery Energy Storage System (PV-BESS) control strategy for voltage and frequency regulation in the islanded microgrid as seen in the Fuzzy Logic representation of the developed ANFIS controller. The developed Sugeno-type ANFIS controller used voltage error and frequency error as inputs and BESS active-power reference as the control output that effectively coordinated battery charging and discharging operations in response to voltage and frequency deviations, enabling adaptive power management and maintaining system stability under varying solar generation and load conditions.

The state of charge (SoC), that increases slightly from 30.00% to 30.03%, confirming energy storage during the period of excess generation; battery voltage (throughout the simulation, the battery voltage remains) close to 600 V despite significant variations in charging and discharging of power, indicating stable battery-side operation. Battery current, and battery power of the BESS under varying solar-generation conditions presents the same waveform though different in magnitude. The system provided 720kW. The results demonstrated that, the ANFIS-based coordinated control scheme managed the bidirectional power exchange between the solar PV system, BESS, and islanded microgrid.

This integrated ANFIS-controlled Solar PV-Battery-UPQC system proved effective in enhancing voltage regulation, improving power quality and ensuring stable operation of the islanded microgrid. Overall, the study demonstrated that the integration of a Solar PV-Battery Energy Storage System (BESS), Unified Power Quality Conditioner, and ANFIS-based coordinated control strategy provides and effective solution for improving voltage stability, power quality and operational reliability of the Tende-Ama community for proposed islanded microgrid operation. The proposed approach offers a viable framework for sustainable electrification for remote and underserved communities which is in line with the Sustainable Development Goals number 7 (Affordable and Clean energy).

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