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A Fuzzy Logic Controller Based Distributed Generation System With An Integrated Unified Power Quality Conditioner.

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Abstract
This research Work introduces a novel control framework for distributed generation (DG) systems using fuzzy logic controllers integrated with a Unified Power Quality Conditioner (UPQC). The system addresses key challenges posed by the high penetration of intermittent renewable sources, such as solar PV and wind, alongside nonlinear loads that degrade power quality and system stability. Unlike conventional PID-based UPQCs, the proposed solution employs adaptive fuzzy logic controllers for two critical subsystems: battery energy management and power quality conditioning. The battery system dynamically regulates charge/discharge operations in response to real-time generation-load mismatches, while the UPQC compensates for voltage sags and harmonic distortions. Simulated in MATLAB/Simulink, the hybrid grid-connected DG system—comprising solar PV, wind turbines, battery storage, and utility grid—demonstrated significant improvements. The system maintained a stable DC bus voltage at 820 V and regulated battery output within ±2 MW. Harmonic distortion was reduced from 20.31% to 0.07%, achieving full compliance with IEEE 519-2022 standards. This dual fuzzy logic approach enhances adaptability, resilience, and operational efficiency, providing a robust solution for smart grid applications that face increasing integration of renewable energy.

Keywords: *Fuzzy Logic Control, Distributed Generation, Power Quality, UPQC, Renewable Energy, Energy Management, Harmonic Reduction, Smart Grid, Adaptive Systems, MATLAB Simulation.*

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I. Introduction

Distributed Generation (DG) systems are vital to modern power networks, offering localised energy production and supporting the integration of renewable energy. However, their deployment introduces power quality challenges such as voltage fluctuations and harmonic distortions. To address these, advanced control methods are required. Fuzzy Logic Controllers (FLCs) provide a robust solution due to their adaptability to nonlinear and uncertain conditions typical of renewable sources. Unlike traditional controllers, FLCs use rule-based logic, enhancing system reliability and performance. The Unified Power Quality Conditioner (UPQC), when integrated with fuzzy logic control, offers a comprehensive solution for mitigating power quality issues. This paper explores the design and implementation of a fuzzy logic-based DG system with UPQC integration, aiming to improve power quality, system stability, and support seamless renewable energy integration.

II. Related Works

Several studies have explored advanced control strategies and power conditioning systems aimed at enhancing the stability and power quality of distributed generation systems (DGS) integrated with renewable energy sources. Mwasilu and Ojo (2024) proposed an R-MIMO controller to mitigate high-frequency switching harmonics and improve voltage-sourced converter (VSC) performance in grid-connected DGS. This controller effectively decouples the control of real and reactive power. However, the approach faces challenges in system complexity and practical implementation. Shavani Chapala et al. (2023): Explored a modular Unified Power Quality Conditioner (UPQC) for harmonic mitigation, significantly improving power quality by addressing voltage sags and current distortions. Despite its effectiveness, the high cost and complexity of UPQC systems pose challenges, particularly for smaller systems. Tuan and Wang (2018); Zhao and Xu (2019) demonstrated the effectiveness of Fuzzy Logic Controllers (FLC) and Model Predictive Control (MPC) in managing fluctuating renewable energy inputs in hybrid DGS. FLC is adaptable and robust, but requires further optimisations for real-time applications. While MPC is highly effective for multi-variable optimization, it is limited by computational requirements and dependence on accurate system models. Zhou and Yu (2020) investigated hybrid control strategies that combine FLC with PID or MPC, thereby improving system stability and performance. However, these strategies remain complex to design and tune, especially for large-scale systems. Huang and Tang (2017): Applied Genetic Algorithms (GA) and Particle Swarm Optimizations (PSO) for optimizing the integration of renewable energy and energy storage in DGS. Despite their power, GA and PSO face challenges with computational complexity and sensitivity to initial conditions for practical application in large-scale systems. Although fuzzy logic controllers (FLCs) are effective in managing the nonlinearities and uncertainties of renewable energy systems, most existing studies are limited to simulations focused on battery optimization and power mismatch correction. This research aims to integrate FLCs with Unified Power Quality Conditioners (UPQC) to enhance system stability, simplify control, improve power balance, and boost cost-efficiency. The findings will lay the groundwork for future real-time hardware implementations, supporting the scalability and reliability of renewable energy systems**.**

III. System Methodology

System Design

High-level system architecture was first designed to define the main components required for the work, the following materials and tools were used in the modelling, simulation, and analysis of the proposed distributed generation (DG) system: MATLAB/Simulink: Used for modelling and simulating the DG system, fuzzy logic controller (FLC), and Unified Power Quality Conditioner (UPQC). HOMER Pro: Used for techno-economic analysis, cost evaluation, and greenhouse gas (GHG) emissions comparison. DG System Components: The system consists of solar photovoltaic (PV) panels, wind turbines, battery energy storage, and the utility grid, all modelled within MATLAB/Simulink.

A. Control System: A Fuzzy Logic Controller (FLC) integrated in the Distributed Generation (DG) system was used to optimise power flow, voltage regulation, and frequency stability by handling uncertainties and nonlinearities in renewable energy sources
B. Power Conditioning Devices: A Unified Power Quality Conditioner (UPQC) integrated in the Distributed Generation (DG) system was used to enhance power quality by mitigating voltage sags, swells, harmonics, and reactive power imbalances, ensuring a stable and reliable power supply.

Model of a Scalable Grid-Connected Distributed Generation (DG) System

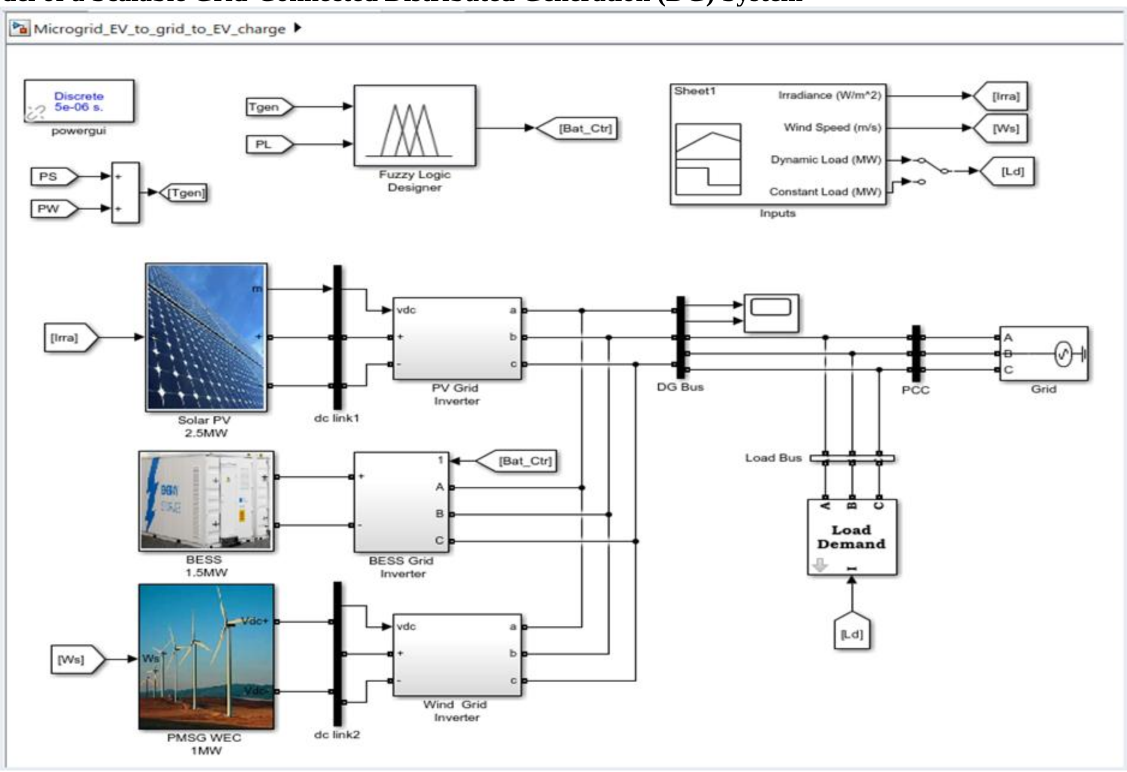

Fig.1.0 Simulink Block of Distributed Generation System without an Integrated Unified Power Quality Conditioner.

Fig.1.0 Above shows the Simulink diagram indicating a distributed generation (DG) system consisting of two primary renewable energy sources such as solar PV array of 2.5 MW and a permanent magnet synchronous generator (PMSG) wind turbine of 1 MW a battery energy storage system (BESS) of 2MW, a load demand of 2.5MW peak, and a utility grid connection. The renewable energy sources are fed into the distribution bus. The battery storage system plays a vital role in absorbing excess energy during peak generation and supplying energy when the renewables underperform or the load increases, thereby ensuring optimal utilization of resources and stability of supply. The fuzzy logic controller (FLC) effectively optimizes the battery storage performance under varying operating conditions and handles decision-making processes, such as when to charge or discharge the battery.

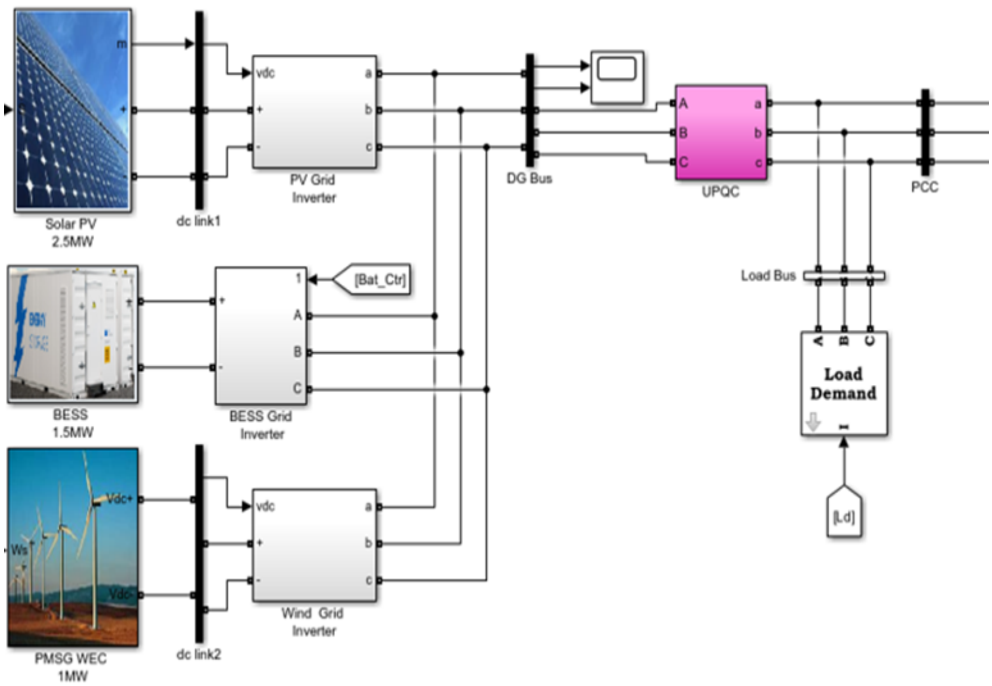

Fig.2 Block Diagram of Distributed Generation System with an Integrated Unified Power Quality Conditioner.

Fig.2 shows the Simulink model of a Distributed Generation System integrated with a Unified Power Quality Conditioner (UPQC), which combines both series and shunt inverters to improve voltage stability, suppress harmonics, and ensure high power quality throughout the system. The Fuzzy Logic Controller (FLC) monitors parameters such as voltage and harmonic distortion and enhances the performance of the Unified Power Quality Conditioner (UPQC) by intelligently managing both the series and shunt inverters. It adjusts the series inverter control to mitigate voltage sags, ensuring that the load receives a stable and consistent voltage even during disturbances. At the same time, it manages the shunt inverter to reduce Total Harmonic Distortion (THD), effectively filtering out unwanted harmonics and maintaining clean power quality. Through this coordinated control, the FLC enables the UPQC to respond adaptively to dynamic grid and load conditions, thereby ensuring improved system stability, protection of sensitive equipment, and overall power reliability.

IV. Solar Power Generation

The power output from the solar panels depends on solar irradiance, panel area, and efficiency. The power generated by the solar system at any time is given by

$$P_{PV}(t) = A * G(t) * \eta PV \quad \text{in (KW)} \qquad (1.1)$$

Where: $P_{PV}(t)$: power generated by the photovoltaic system at time, (t).
A: area of the solar panels (m2)
$G(t)$: Solar irradiance at time t (W/m2)
ηPV : efficiency of the photovoltaic system (%)

V. Wind Power Generation

Wind power generation depends on wind speed, the turbine's swept area, and the air density. The power generated by the wind turbine is given by

$$P_w(t) = \frac{1}{2} * \rho * A_t * V^3(t) * \eta_w \ \text{(MW)}. \qquad (1.2)$$

Where:

$P_w(t)$: power generated by the wind turbine at time (MW).
ρ : air density (kg/m3)
A_t : swept area of the wind turbine blades (m²)
v (t): wind speed at time (m/s)
η_w : efficiency of the wind turbine (%).

VI. Battery Storage

Battery energy storage is essential for stabilizing intermittent renewable generation from solar and wind. The battery's state of charge (SoC) changes based on the charging and discharging processes. The change in battery energy

$$SoC(t) = SoC(t-1) + \frac{\eta_{charge} * P_{charge}(t) - \frac{P_{discharge}(t)}{\eta_{discharge}}}{E_{bat}} \ \text{in (Watt)} \qquad (1.3)$$

Where;

SoC(t): state of charge at time (t) in (S)
$P_{charge}(t)$: power used to charge the battery (W)
$P_{discharge}(t)$: power discharged from the battery (W)
η_{charge} and $\eta_{discharge}$: efficiencies for charging and discharging the battery (%)
E_{bat}: battery capacity (Ah).

VII. Utility Grid

Grid interaction for a distributed generation (DG) system can be modelled by considering both the power exported to the grid and the power imported from the grid. If renewable generation is low and the battery cannot meet the load demand, then the power deficiency is purchased. The imported power from the grid is given by

$$P_{grid}^{imp} = \min\left(\mathbf{P_d(t) - P_{pv}(t) - P_w(t) - P_b^{out}(t)}\right) \text{in (KW)} \qquad (1.4)$$

Similarly, if the total generation from renewable sources and batteries exceeds the load demand, the surplus power is exported. The exported power to the grid is given by

$$P_{grid}^{exp} = \max\left(\mathbf{P_{pv}(t) + P_w(t) + P_b^{out}(t) - P_d(t)}\right) \ \text{in (KW)} \qquad (1.5)$$

Where:

$P_d(t)$: total power demand at time in (kw)
$P_{pv}(t)$: power from Solar PV Generation at time in (kw)
$P_w(t)$: power from wind Generation at time in (kw)
$P_b^{out}(t)$: power Supplied by the Battery at time in (kw)

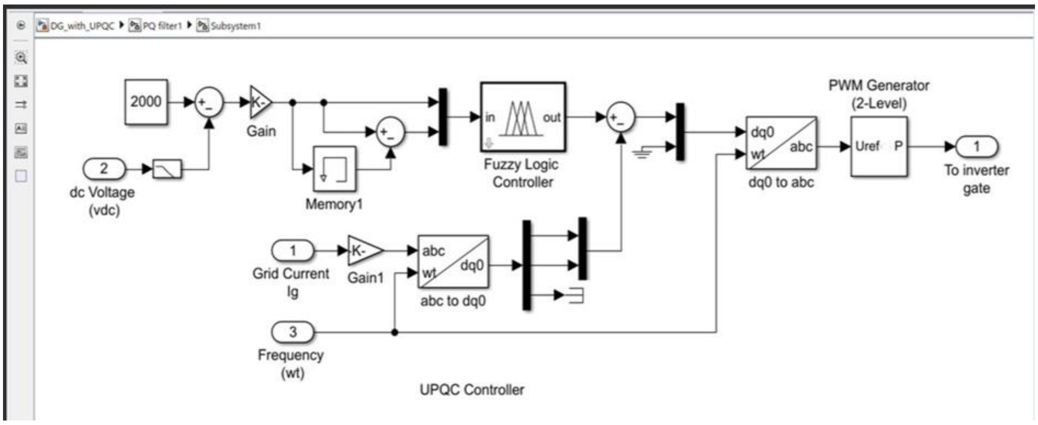

Fig.3 MATLAB/Simulation Block of UPQC Configuration with component details.

The Unified Power Quality Conditioner (UPQC) controller shown in the diagram is an advanced power electronic control system designed to improve power quality by addressing voltage sags/swells, current harmonics, and load imbalances in distribution networks. It features a dual-loop control structure comprising a DC-link voltage regulation loop and a grid current control loop. The input signals to the controller include: (1) the measured DC-link voltage (vdc), (2) a reference DC voltage (typically 2000 V), (3) the grid current (Ig) in three-phase (abc) format, and (4) the system frequency or angular position (wt..). The DC-link voltage loop computes the voltage error by comparing the actual vdc with the reference, and this error is processed through a fuzzy logic controller, which dynamically generates a compensating control signal with enhanced adaptability and nonlinearity handling. In parallel, the three-phase grid currents are transformed to the synchronously rotating reference frame, where control actions are performed to minimize current distortions. The compensated control signal is then transformed back to the abc frame, and the output of the controller, which is the modulated three-phase voltage reference (Uref), is passed to a two-level PWM generator, which then produces the final gate signals for the inverter switches. This coordinated control ensures real-time compensation by the series and shunt converters of the UPQC, resulting in enhanced voltage regulation, harmonic suppression, and improved dynamic response of the power system under both steady-state and transient operating conditions, making it highly suitable for integration into modern smart grid environments.

VIII. Results Obtained

Result of Impact of High DG Penetration without Power Quality Conditioning

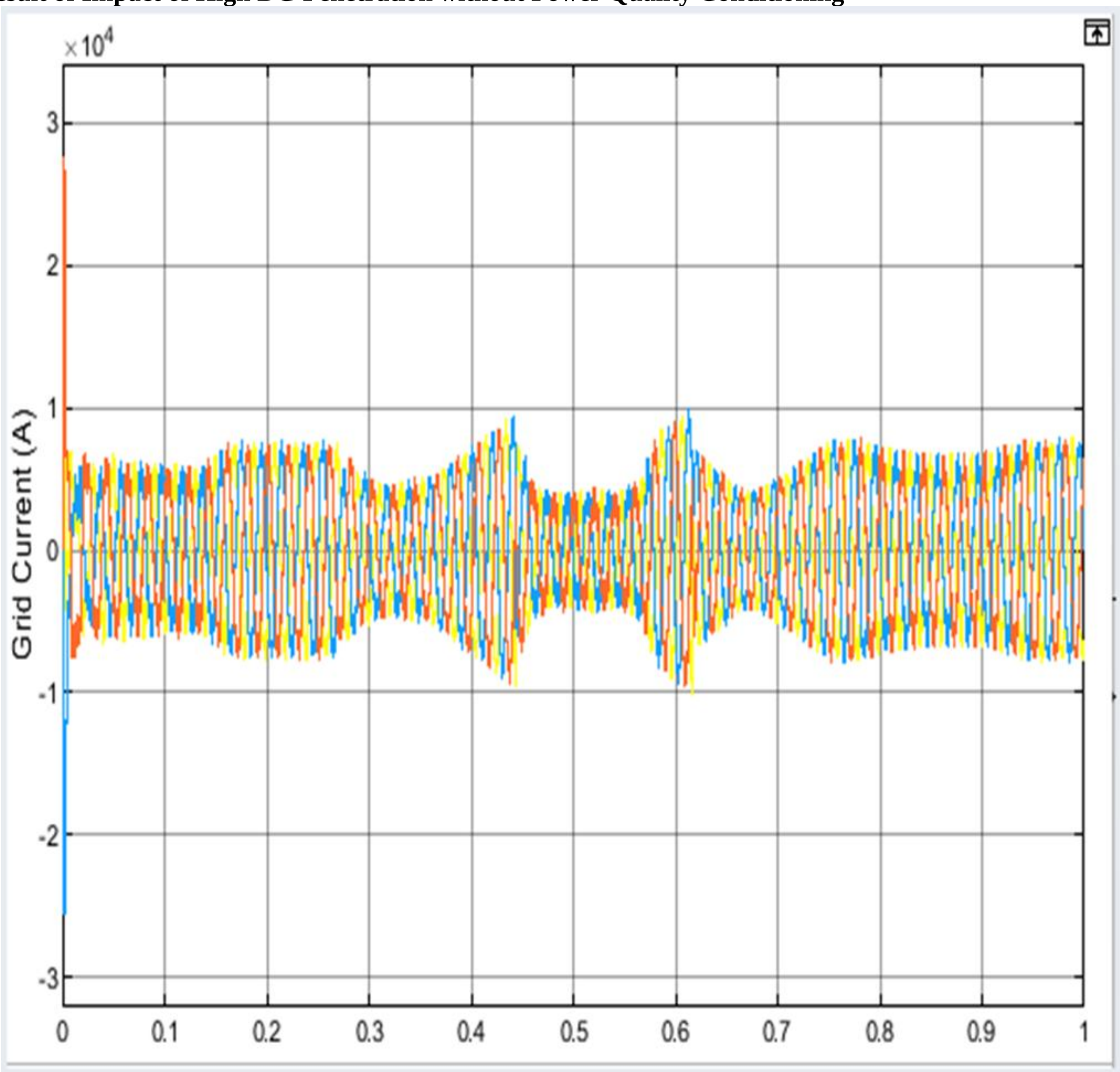

Fig. 4 Grid Current Waveform without UPQC.

Figure 4 above shows the waveform of grid current, which shows a clear deviation from an ideal sinusoidal wave due to harmonic distortion. These distortions are indicative of the presence of harmonic components, frequency elements that are integer multiples of the fundamental grid frequency, including power mismatch in a system with high penetration of distributed generation (DG) and renewable energy sources. The inherent variability and intermittency of renewable energy, such as wind and solar, cause fluctuations in power generation, leading to mismatches between the supply and demand of electricity. These power imbalances strain the operation of grid inverters, which may not function optimally under such conditions. Consequently, additional harmonic components are injected into the grid, further distorting the current waveform. This contributes to an increase in Total Harmonic Distortion (THD), which adversely affects the stability of the grid.

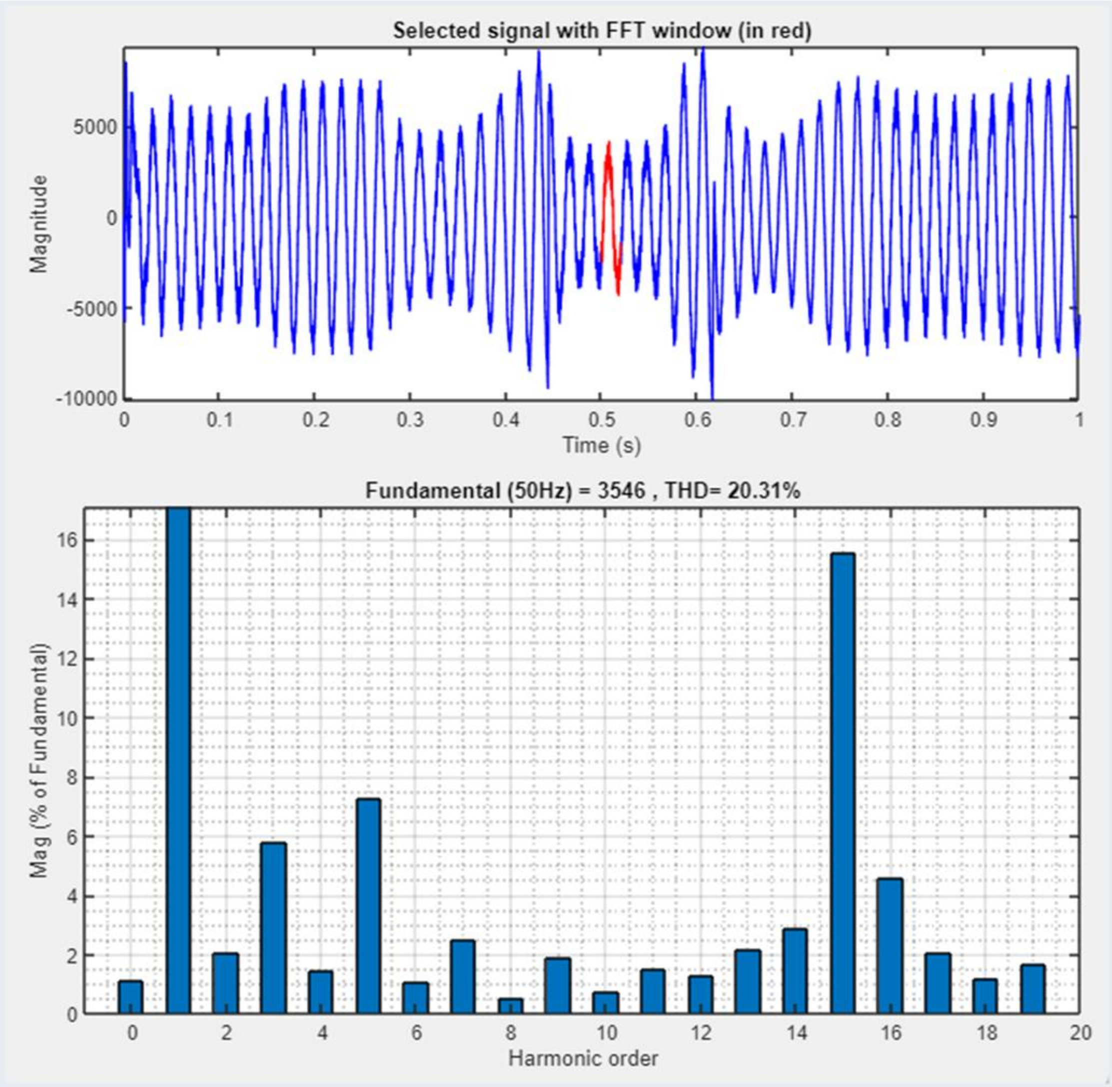

Fig. 5 Fast Fourier Transform (FFT) Analysis of Grid Current without UPQC.

Figure 5 above shows the fast Fourier transform (FFT) analysis of grid current to determine the order of harmonic frequency injected at the point of common coupling before the integration of the Unified Power Quality Conditioner (UPQC). To determine the harmonic content of the unconditioned current, Fast Fourier Transform (FFT) analysis was conducted. The results revealed a high total harmonic distortion (THD) of 20.31%, which indicates significant waveform distortion occasioned by nonlinear loads and power imbalance from high renewable energy penetration. This value violates the predefined limit condition of 8% for medium voltage systems according to the IEEE 519-2022 standard. Secondly, the distorted current waveform highlights the absence of harmonic mitigation and underscores the system's vulnerability to poor power quality. This high THD value serves as a baseline for evaluating the effectiveness of the UPQC in subsequent compensation, emphasizing the need for advanced power quality enhancement techniques in a distributed generation system.

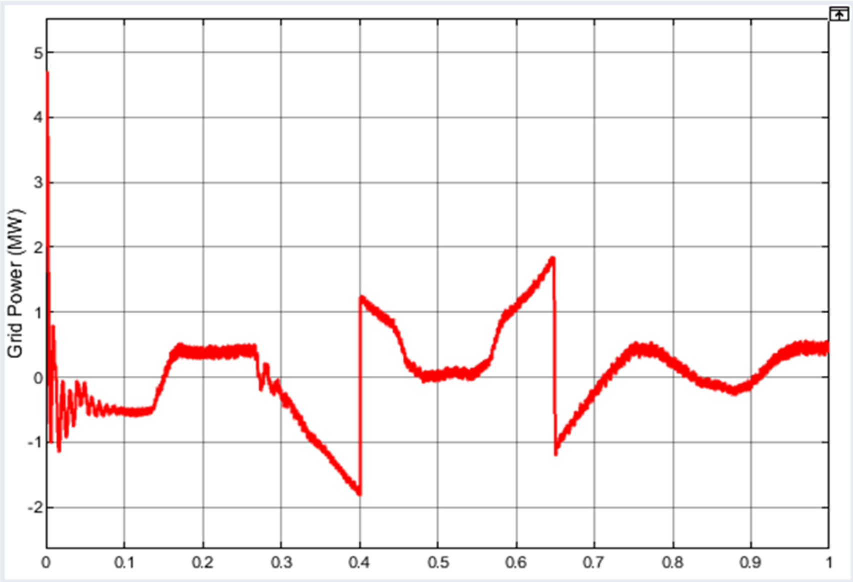

Fig. 6 Grid Active Power without UPQC.

Figure 6 above shows the grid active power profile in the absence of a unified power quality conditioner (UPQC) for a hybrid distributed generation (DG) system consisting of a photovoltaic (PV) array, wind turbine, and battery storage. A cursory look at the waveform clearly shows significant fluctuations and instability in active power. These fluctuations are attributed to the inherent intermittency of renewable energy sources, and in the absence of an effective power conditioning mechanism. Throughout the plot, several abrupt transitions and deviations are observed, with grid power oscillating between positive and negative values, indicating periods of both surplus generation and power deficits. These sudden variations signify mismatches between generated and demanded power, which can place stress on grid infrastructure, reduce inverter efficiency, and degrade the quality of power delivered to the load. The pronounced dips and peaks, particularly at time intervals around 0.4 s and 0.7 s, show how the lack of a coordinated control strategy permits uncontrolled power swings. Additionally, the small ripples and high-frequency components present throughout the waveform suggest the presence of harmonics and noise, further exacerbating power quality issues. Without the UPQC, the system lacks a dynamic compensation mechanism to buffer renewable fluctuations, leading to erratic power injection into the grid.

Result of Evaluating the Effectiveness of UPQC in Mitigating Power Quality Issues under High DG Penetration

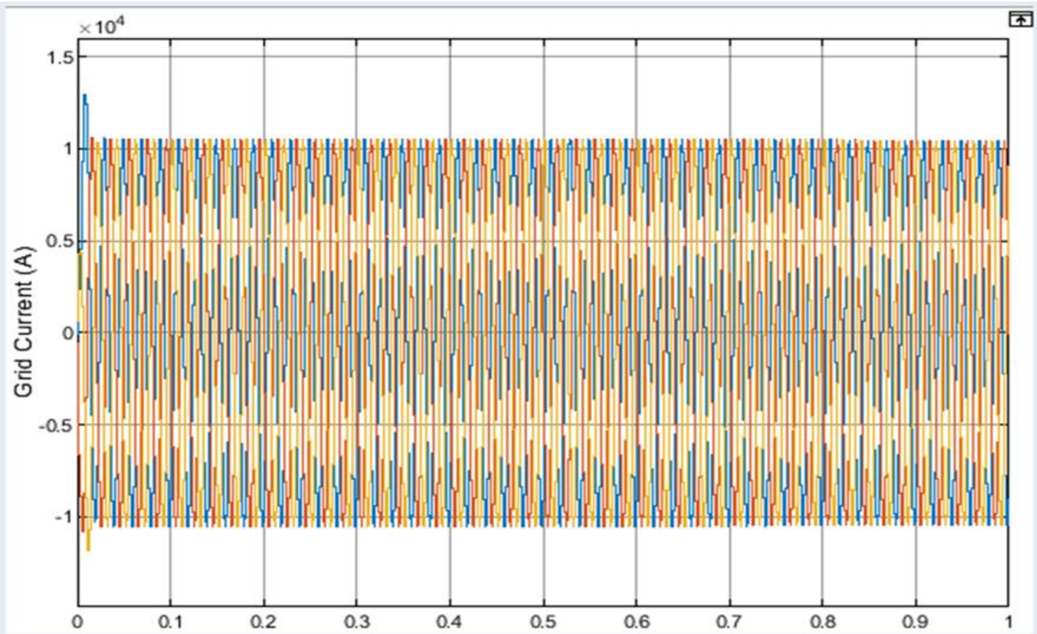

Fig.7 Grid Current Waveform with UPQC.

Fig.7 Above shows the grid current waveform after the integration of the unified power quality conditioner (UPQC) into the network. The waveform indicates a substantial improvement in signal quality close to a pure sinusoidal wave. This marked improvement shows the ability of UPQC to effectively mitigate harmonic distortions and manage power mismatch caused by high distributed generation (DG) penetration as previously observed in Figure 4.10 due to the intermittent nature of renewable energy sources, such as solar and wind which often introduce fluctuations in power output that lead to supply-demand imbalances and nonlinear inverter operation, both of which contribute to harmonic injection. However, the UPQC addresses these challenges through its coordinated control of series and shunt converters, enabling filtering of harmonic components and stabilization of grid current, thereby significantly improving the operating conditions of the grid-connected inverters, which minimizes the extent of harmonic propagation within the network with a notable reduction in total harmonic distortion (THD).

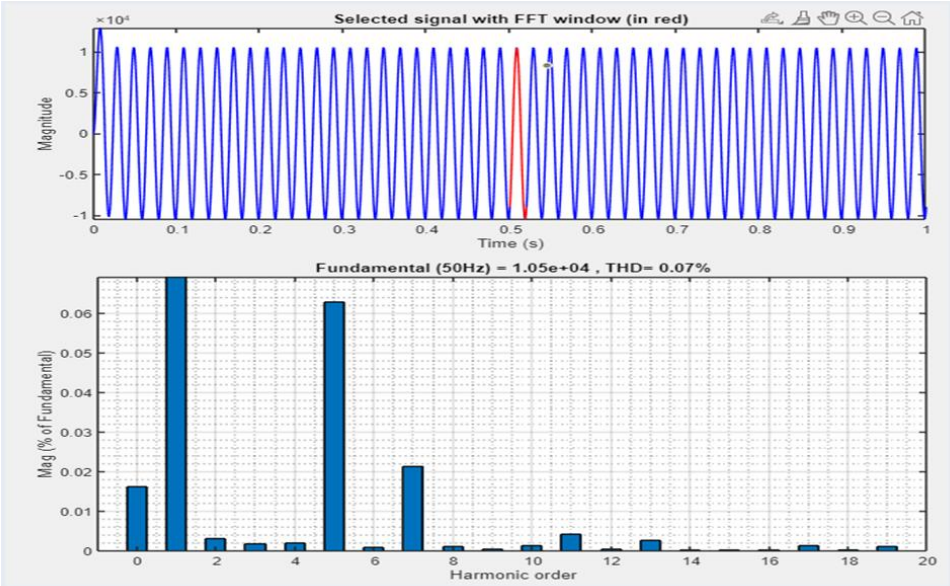

Fig. 8 Fast Fourier Transform (FFT) Analysis of Grid Current with UPQC.

As shown in Figure 8 above, after the integration of the UPQC, the grid current waveform exhibits significant improvement in sinusoidal quality compared to the pre-compensation state depicted in Figure 4.8. The Fast Fourier Transform (FFT) analysis confirms a substantial reduction in total harmonic distortion (THD) from 20.3% before compensation to 0.07% after UPQC operation. This drastic improvement demonstrates the effectiveness of the UPQC's series and shunt converters in mitigating harmonics caused by nonlinear loads and power mismatch in a system with high-DG penetration. The UPQC not only filters out current harmonics but also stabilizes voltage disturbances and power mismatch, thereby enhancing overall power quality and ensuring reliable operation of the grid under high renewable energy penetration.

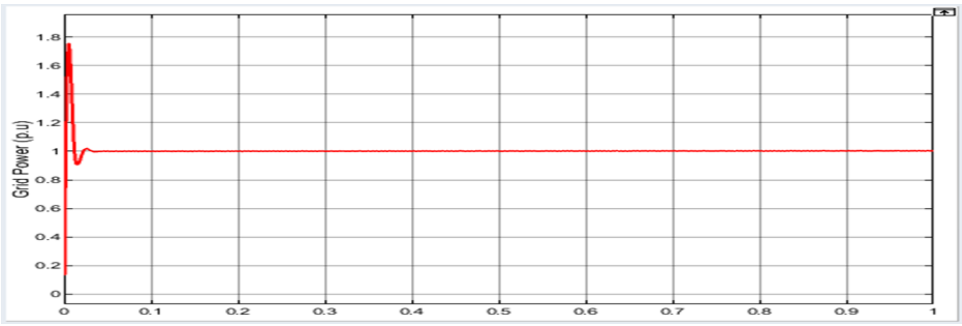

Fig.9 Grid Active Power with UPQC.

Figure 9. The above shows the active power profile of the grid following the integration of the unified power quality conditioner (UPQC) in a high-penetration distributed generation (DG) system comprising photovoltaic (PV) arrays, wind turbines, and battery storage. Before compensation, as shown in Figure 4.9, the active power fluctuation as observed was due to the intermittent nature of the renewable sources, leading to periodic mismatches between generation and load demand. However, with the UPQC in operation, the active

power output becomes significantly more stable. As shown in Figure 4.12, after an initial transient oscillation, the active power quickly stabilizes and maintains a consistent value of 1 MW (p.u.), indicating a well-balanced and regulated power flow. This stabilization is achieved through the UPQC's shunt converter, which dynamically manages real power exchange at the point of common coupling (PCC), compensating for short-term mismatches introduced by renewable variability and intermittency. The UPQC plays a central role in ensuring the output delivered to the grid remains steady. The result is a smoother and more reliable power profile, minimizing the adverse effects of DG intermittency and improving overall grid performance.

IX. Conclusion

This study demonstrates that a hybrid renewable energy system—combining solar, wind, and battery storage—can reliably meet energy demands when managed with adaptive fuzzy logic controllers. The integration of a Unified Power Quality Conditioner (UPQC) significantly improves power quality, reducing harmonic distortion and stabilizing grid operations. Key contributions include a dual-layer fuzzy control framework for energy and power quality management, a scalable simulation model for diverse grid environments, and empirical validation of UPQC's effectiveness in reducing THD. The research advances intelligent, real-time energy management and supports the development of stable, efficient, and clean distributed generation systems.

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