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Original Article

Power Quality Analysis of Fuzzy Logic Controller Based Distributed Generation System with UPQC

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Abstract - *This paper explores the integration of renewable energy sources into current power systems as a means to enhance energy efficiency, reduce emissions of greenhouse gases, and tackle the issue of climate change. A variety of renewable energy sources, including wind, solar panels, and solid oxide fuel cells, are integrated into the proposed hybrid system. The following challenges (Maximum power production) must be overcome, and effective control algorithms must be devised when renewable energy sources generate electricity. This paper presents a comprehensive power quality analysis of a Fuzzy Logic Controller (FLC) based Distributed Generation (DG) system integrated with a Unified Power Quality Conditioner (UPQC). The proposed system aims to enhance power quality by mitigating issues such as voltage sags, swells, and harmonics, which are common in distributed generation environments. A detailed MATLAB/SIMULINK model is developed to promote the integration of hybrid renewable energy sources to enhance the performance of the Fuzzy Logic Controller (FLC) and the Unified Power Quality Conditioner (UPQC) under diverse operational conditions. Significant improvements in power quality are demonstrated by the results obtained quality, evidenced by reduced Total Harmonic Distortion (THD) and stabilized voltage levels. This study highlights the effectiveness of integrating FLC with UPQC in DG systems, providing a robust solution for maintaining power quality in modern power networks. The system results are validated using the IEEE 1547 and IEEE 519 standards to demonstrate the System's effectiveness.*

Keywords - *PV, Wind, SOFC, Grid, Fuzzy.*

1. Introduction

Power system management and operation have become more unpredictable due to the advent of Renewable Energy Sources (RES). The integration of Distributed Generation (DG) systems into modern power grids has significant attention due to their potential to enhance energy efficiency, reliability, and sustainability. However, the increasing penetration of DG systems also brings forth several challenges, particularly in maintaining power quality. Power quality challenges, including voltage sags, swells, harmonics, and flicker, can severely affect the performance of electrical systems, sensitive equipment and the overall stability of the power system. To guarantee that the linked loads and the electrical grid can operate reliably, it is critical to address these concerns.

Unified Power Quality Conditioners (UPQCs) have emerged as effective solutions for mitigating power quality disturbances in DG systems. To address power quality difficulties caused by voltage and current, these devices integrate the features of active power filters in series and shunt configurations. However, the performance of UPQCs heavily depends on the control strategy employed. While effective, traditional control methods often struggle to adapt to the dynamic and nonlinear nature of power quality disturbances in DG systems. Recent advancements in artificial intelligence and control theory have introduced Fuzzy Logic Controllers (FLCs) as a promising alternative to conventional control techniques. FLCs are particularly well-suited for dealing with uncertainties and nonlinearities in complex systems, making them an attractive option for controlling UPQCs in DG systems.

Despite the potential benefits, there is a noticeable research gap in the comprehensive analysis of power quality in DG systems using FLC-based UPQCs. Most existing studies have focused either on the design of fuzzy logic controllers or on the performance of UPQCs in isolation, with limited exploration of their combined application in a DG context. Due to its weather sensitivity, RES requires more resources. In such instances, Energy Storage Systems (ESS) are necessary to help RES penetration. Hybrid energy systems use many energy sources, including both renewable and fossil fuels, to maximize power output and efficiency. The hybridization of sources is crucial for decarbonizing power systems via renewable energy. More and more renewable energy sources are finding their way into the power grid, but their intermittent and unpredictable output makes battery integration more important.

The rapid expansion of Photovoltaic (PV) and wind power has significantly impacted the electrical grid. Activation of energy storage technology may facilitate the storage of additional renewable energy within the power system. However, Energy Storage Systems (ESS) alone cannot fulfill all application requirements; therefore, multiple ESS can be combined to form a composite ESS. The implementation of power-sharing control is vital when integrating these ESS. Consequently, this report consolidates control mechanisms proposed in the literature. It is critical to create ideal micro-level conditions for the production and use of hybrid renewable energy systems in light of the present effort to increase the share of Renewable Energy (RE) in the world's energy mix. This is especially important considering the rising cost of energy, which impacts socioeconomic factors. Research focusing on AC motor-based water pumping systems has blossomed because of its numerous benefits. The critical assessment is composed of the motor type, power electronics interface, and control algorithms [3].

Batteries, solar- and wind-energy conversion hardware, power electronics, control algorithms, and controllers are all put through their paces in a hybrid microgrid test [4]. Energy management systems balance renewable energy power generation with load demand. Parallel energy sources ensure consistent power supply and optimal accumulative element charging [5]. To do this, a solar energy factor-based simulation system [6].

Energy storage ensures secure energy transmission and recovery. A multi-objective cost function optimizes profit and reduces battery value loss [7]. Peak shaving and a social grid link may both be offered by a CSP plant and TES system. This paper outlines a hybrid power system for SWHs that uses two PHS-TES energy storages, an operator approach that is optimally coordinated, and multi-objective scaling [8]. This study determines the best capacity, energy dispatching, and techno-economic benefits of a freestanding microgrid in remote Tamil Nadu, India.

The study presents a method for optimally sizing various energy sources in an isolated hybrid microgrid, which includes renewable energy sources, such as solar and wind, alongside conventional sources. The authors also introduce a novel optimization algorithm inspired by turbulent flow in water. This algorithm is used to determine the optimal configuration and sizing of the energy sources, demonstrating improved efficiency and effectiveness compared to traditional optimization methods [9]. The paper contributes significantly to the field of microgrid optimization by introducing a novel algorithm and demonstrating its effectiveness in a case study. However, the limitations highlighted suggest areas for further research to enhance the applicability and robustness of the findings. Voltage regulation in microgrids with RES integration is given [10], and the study presents the modelling of PV for economic viability [11]. Combining RES with a small nuclear reactor was the aim of this project to create an off-grid Hybrid Energy System (HES) that is robust, flexible, affordable, sustainable, and environmentally friendly [12]. This approach aligns with the findings of [13]. It provides a comprehensive review of solar, wind, and hybrid wind-PV water pumping systems, emphasizing the potential of hybrid systems to enhance energy access in remote areas.

Furthermore, [14] explored the optimal planning of nuclear-renewable micro-hybrid energy systems using Particle Swarm Optimization, showcasing the versatility of optimization techniques in energy system design. The convergence of these studies underscores a growing recognition of hybrid systems as viable solutions for energy challenges, particularly in isolated regions where traditional grid connections are impractical. By leveraging advanced optimization algorithms, researchers are paving the way for more resilient and efficient energy systems that can adapt to varying demands and resource availability.

The ongoing exploration of hybrid microgrid configurations not only contributes to energy security but also supports the transition towards sustainable energy practices globally. The study examines the frequency, unit ramp, low-frequency oscillation, and cascade failure as the primary reasons for renewable energy power variation [15]. Additionally discussed are the types of energy storage, mitigation topologies, and grid-connected renewable energy fluctuation rate standards. Energy sources and cost factors are considered in a hybrid RE-based Power System (REPS) techno-economic feasibility study [16]. This author provides a thorough reference for academics, engineers, and policymakers in this area by reviewing energy source combinations, modelling, power converter topologies, scaling, and optimization methods used in present HRES [17].

A dynamic ramp limit reduces energy curtailment during operation and boosts power grid energy sales [18]. A crucial energy management method for off-grid cellular networks with hybrid power sources like solar PV arrays and Diesel Generators (DG) improves Energy Efficiency (EE) and reduces fuel usage [19]. This research examines dependability, carbon footprint, and EE to maximize PV technology, which has resulted in substantial transformations in the operation and management of power grids. Distributed Generation (DG) has several benefits, such as better energy efficiency and lower transmission losses; however, it may be difficult to keep power quality consistent. Maintaining grid stability and dependability requires efficient management of power quality challenges, such as voltage variations and harmonic distortion, caused by renewable energy sources' intermittent nature. This study endeavors to address the existing research deficiency by performing a comprehensive analysis of power quality within a Distributed Generation (DG) system that employs a Unified Power Quality Conditioner (UPQC) governed by a Fuzzy Logic Controller (FLC). The effectiveness of the FLC in augmenting the operational performance of the UPQC across diverse operating conditions and power quality disturbances will be examined. This analysis aspires to yield significant insights regarding the applicability of FLC-based UPQCs in enhancing power quality within contemporary DG systems, thereby contributing to the advancement of more robust and efficient electrical grids. The following is the outline of the paper: Section II presents the fuzzy algorithm-based wind MPPT system and its results. Section III covers the fuzzy algorithm-based PV MPPT system and its results. Section IV describes the SOFC system equipped with a fuzzy logic controller. Section V analyzes the results obtained by a battery management system using fuzzy logic controllers. Finally, Section VI discusses the proposed grid integration of the hybrid PV/Wind/SOFC system with an energy storage system.

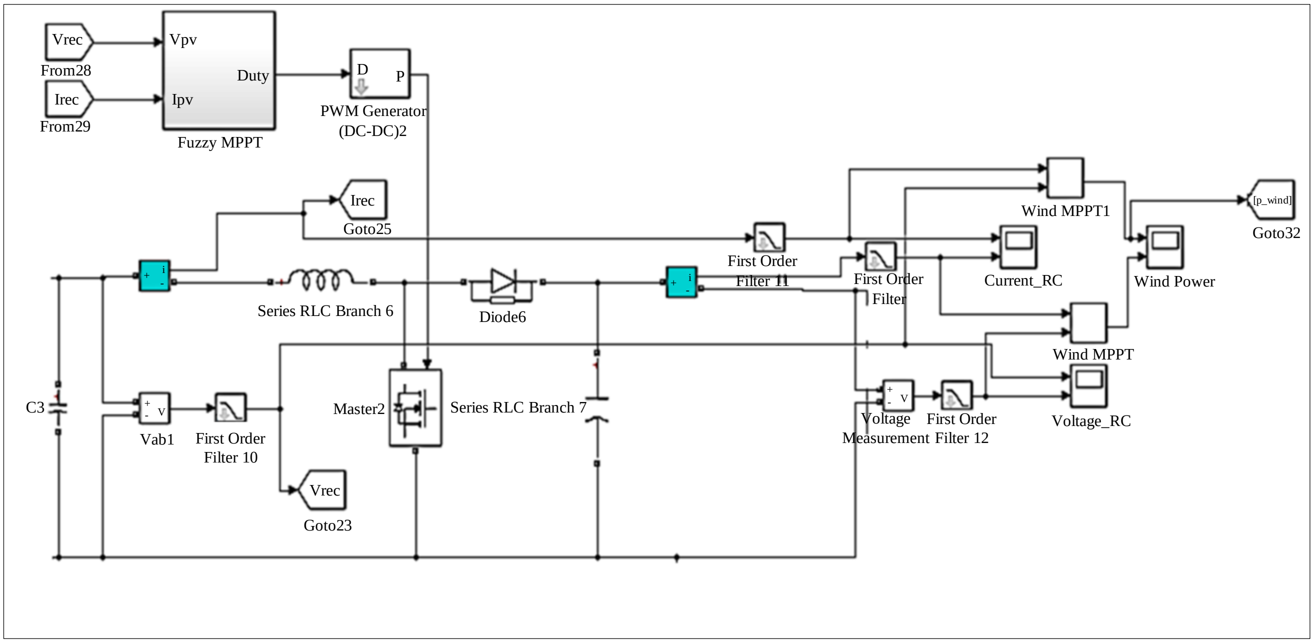


Fig. 1 Fuzzy-based MPPT algorithm for wind energy system simulation model

2. Fuzzy-Based Wind MPPT System

Using fuzzy logic, a wind energy conversion system may control the maximum power point tracking. The creation of the controller is shown in Figure 1.

The suggested WES is constructed using Matlab, and its performance is assessed in a variety of meteorological conditions. Fuzzy control produces the membership function of a triangle, which may be something like the duty cycle.

Both Input 1 and Input 2 have a membership function that can take on the values Low, Medium, or High, and the output also has a membership function that can take on these values. On the PMSG MPPT, the suggested fuzzy logic controller was put into practice and simulated under a range of various operating conditions, including wind speeds of 5, 7, 9, 11, and 12 meters per second. The following statistics are examined to assess the System's performance after the simulation.

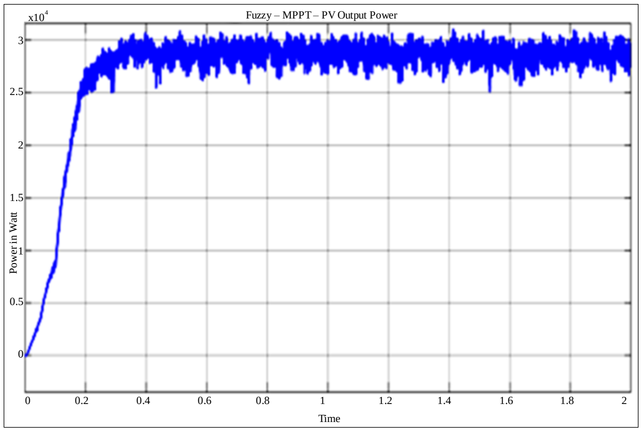


Fig. 2 Fuzzy-based wind MPPT power waveform

Figure 2 shows the results of an investigation on the link between the wind speed and the 30 kW WES's output power. Figure 3 shows the RMS voltage and current of the wind power system.

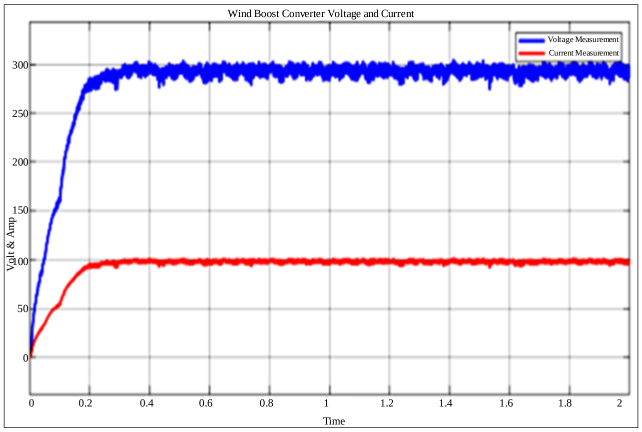
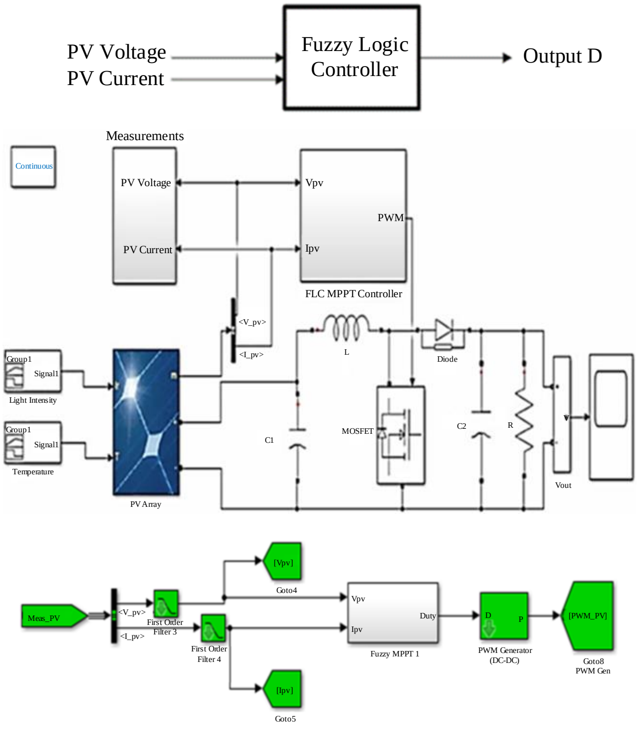


Fig. 3 Fuzzy-based wind MPPT voltage and current waveform

3. Fuzzy-Based PV MPPT System

There has been a dramatic increase in the cost of traditional fossil fuels, and there is a limited capacity for reserve capacity. In addition, there are growing environmental concerns. Therefore, interest in renewable energy as a substitute energy source has increased.



Fuzzy MPPT Algorithm

Fig. 4 Fuzzy-based MPPT technique for PV system simulation model

Methods for following the greatest powerpoint using a fuzzy logic controller are provided. Even when the irradiance varies, the algorithm quickly locates the MPP and follows it; it does not behave unexpectedly throughout this process. The proposed power waveform for the fuzzy-based PV MPPT can be found in Figure 5. The controller that is being proposed has two inputs: the PV voltage, which is shown in Figure 4.

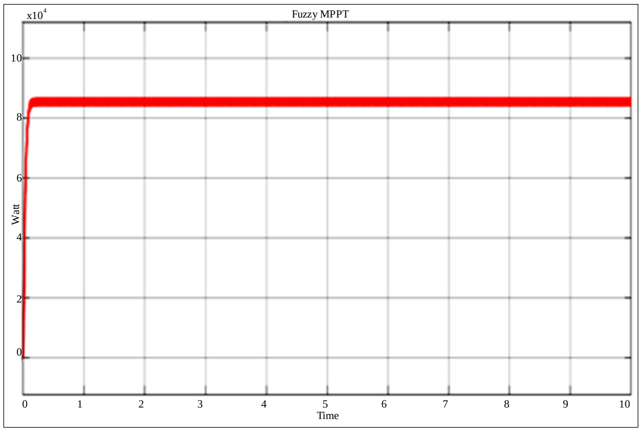


Fig. 5 PV power waveform fuzzy-based MPPT algorithm

4. Fuzzy-Based SOFC System

An anode, also known as the positive electrode, and a cathode are the two electrodes that are typically present in a cell. An electrolyte (positive electrode) separates them. The anode is supplied with fuel, the site of electrochemical oxidation, and the oxidant is introduced to the cathode, the site of electrochemical reduction, to generate an electric current. Most of the work done within a cell ends up as water. As hydrogen passes from the cathode to the anode, it undergoes a chemical transformation at the catalyst, becoming hydrogen ions and electrons along the way. Matlab/Simulink is used to generate a simulation model of the SOFC once the dynamic SOFC stack has been used as the basis.

The parameters were created by the model, which also verified their correctness. The SOFC model employs the partial pressure expressions for water, oxygen, and hydrogen in conjunction with Nernst's voltage, activation loss, mass transportation loss, and ohmic loss. The model also accounts for losses brought on by ohmic resistance and mass transit. The MATLAB/SIMULINK environment was used to simulate the fuzzy-based MPPT controller model, as illustrated in Figure 6. The proposed controller takes in two parameters: SOFC voltage and PV current. It has the membership function of two fuzzy inputs, SOFC voltage and current, respectively, and the duty cycle is the result of the fuzzy controller. Figures 7 and 8 display the output power, voltage and current, respectively.

5. Fuzzy-Based Battery Management System

A battery management system for the PV system's upcoming microgrid integration was developed with the assistance of the fuzzy logic controller. Figure 9 shows the result of running a MATLAB/SIMULINK simulation of the bidirectional converter.

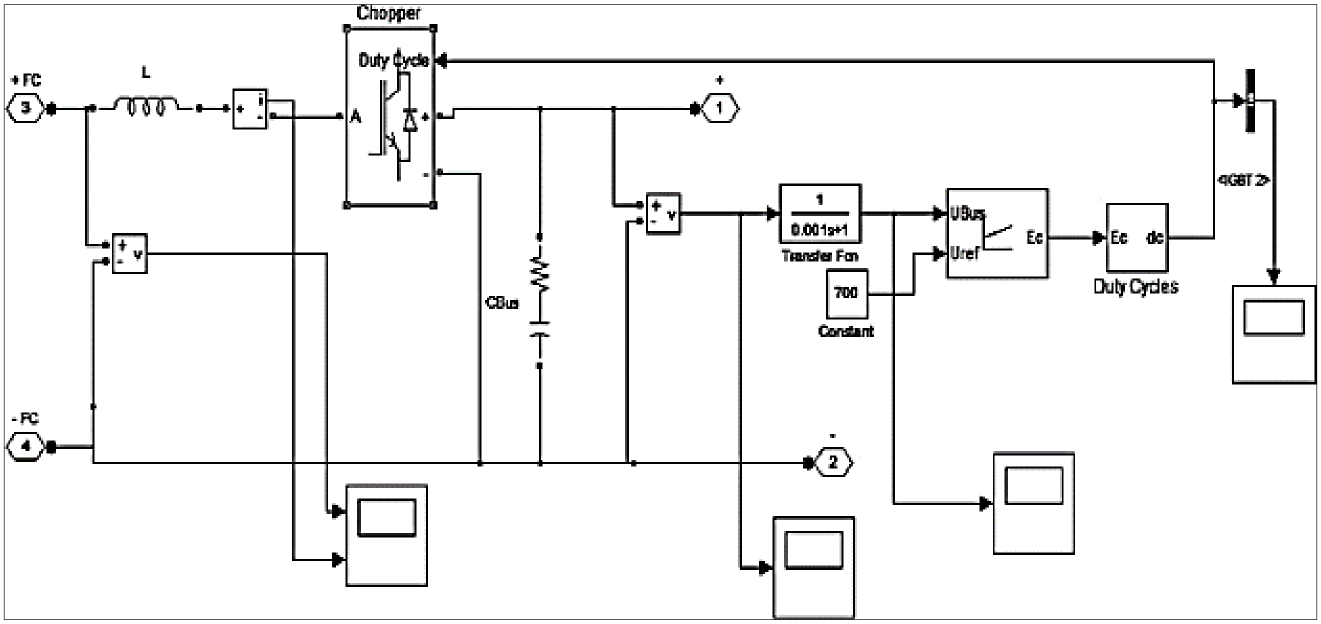


Fig. 6 Fuzzy-based SOFC MATLAB/SIMULINK model

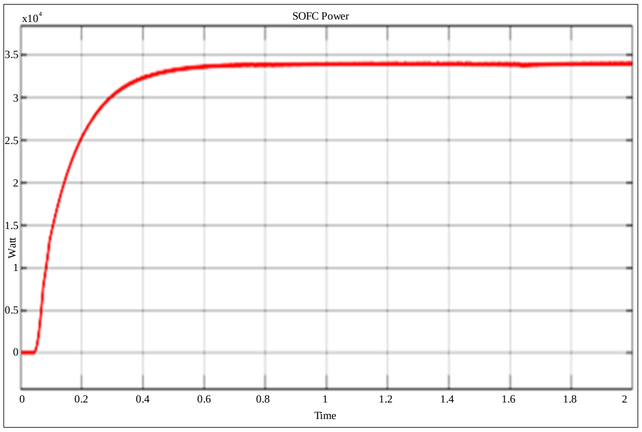


Fig. 7 Fuzzy-based SOFC power system output power waveform

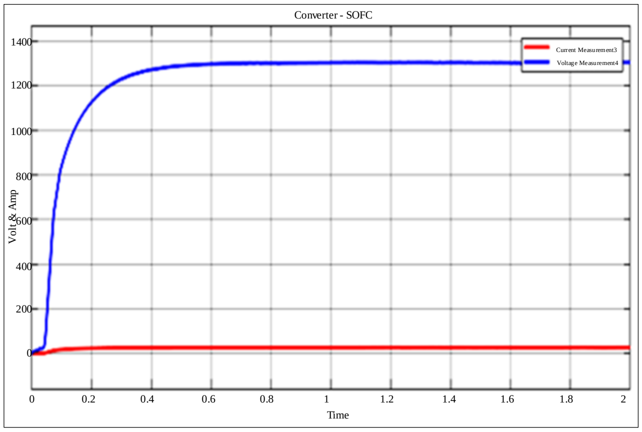


Fig. 8 Fuzzy-based SOFC power system output voltage and current

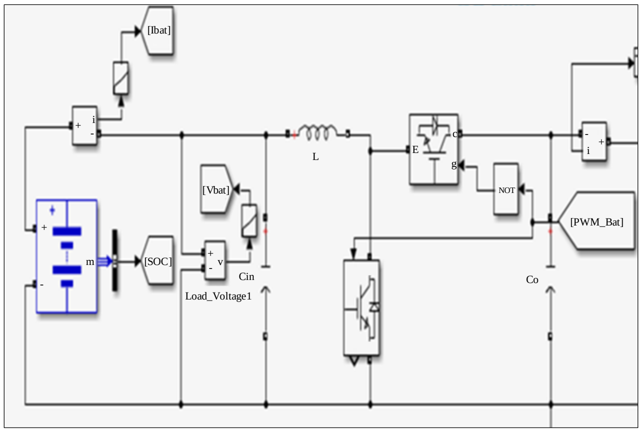


Fig. 9 Fuzzy-based battery management simulation model

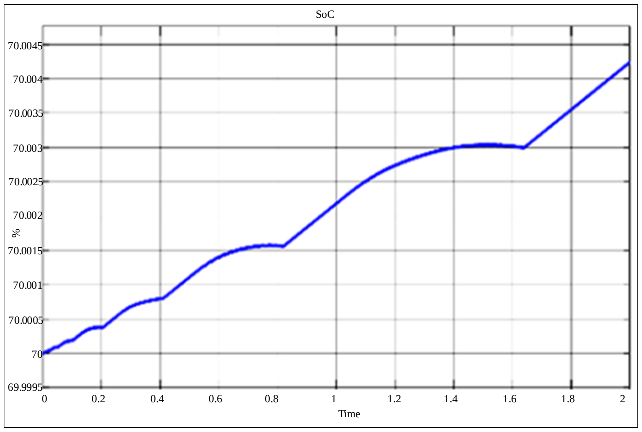


Fig. 10 Fuzzy-based battery SOC waveform

The bidirectional converter comes with a 300 Ah battery. Inductance is one millihenry, and capacitance is one thousand microfarads for the bidirectional converter. A fuzzy logic controller-based Battery Management System (BMS) is used. The error value constitutes the fuzzy input membership function of the BMS. This value is (PV power – Load power). It has the BMS's fuzzy output membership function, which displays the bidirectional converter's duty cycle, and the fuzzy-based Battery SOC, which is shown in Figure 10.

6. Motivation for Integration of FLC with UPQC in Distributed Generation Systems

6.1. Increasing Penetration of Distributed Generation (DG)

Power grid operations and management have undergone radical changes due to the increasing use of distributed generation, particularly the incorporation of distributed production from renewable energy sources like solar and wind. Although distributed generation presents various advantages, such as diminished transmission losses and improved energy efficiency, it concurrently introduces challenges related to the maintenance of power quality. The sporadic characteristics of renewable energy sources may lead to voltage fluctuations, harmonic distortion, and other issues pertaining to power quality. These challenges necessitate effective management to guarantee the reliability and stability of the grid.

6.2. Challenges in Maintaining Power Quality

As the power grid becomes more decentralized, with a higher number of distributed energy resources connected to it, maintaining power quality becomes increasingly complex. Voltage sags, swells, flickers, and harmonic distortion are common issues that can affect both consumers and utilities. Traditional control methods often struggle to adapt to these new conditions, necessitating more advanced solutions that can handle the dynamic and nonlinear characteristics of modern power systems.

6.3. Need for Advanced Control Techniques

Conventional control strategies may not provide the required flexibility and responsiveness in managing power quality in DG systems. There is a growing need for intelligent control techniques that can adapt to changing conditions in real-time. Fuzzy logic controllers, with their ability to handle uncertainties and non-linearities, offer a promising solution for these challenges. Integrating such advanced controllers with existing power quality enhancement devices like the Unified Power Quality Conditioner (UPQC) can lead to more effective management of power quality issues in DG systems.

6.4. Gap in Existing Research

While considerable research has been conducted on both UPQC and fuzzy logic controllers, there is a noticeable gap in studies that combine these two approaches specifically for power quality improvement in distributed generation systems. This paper aims to fill this gap by exploring the potential of a fuzzy logic controller integrated with UPQC to address the unique power quality challenges posed by DG systems.

6.5. Ensuring Reliable and Efficient Power Supply

Ensuring a reliable and efficient power supply is critical as the power grid evolves to accommodate more distributed generation. Power quality issues can lead to equipment damage, increased operational costs, and customer dissatisfaction. By developing and analyzing a more robust control strategy, this research seeks to contribute to the overall reliability and efficiency of power systems, benefiting both utilities and consumers.

6.6. Comparison with Existing Systems

Previous studies have extensively explored the use of fuzzy logic controllers to enhance power quality in distribution systems, and they have been applied in various power system control scenarios. However, the combination of fuzzy logic controllers with UPQC specifically for Distributed Generation (DG) systems has been minimally addressed. This paper introduces a novel integration of a fuzzy logic controller with UPQC within DG systems, aiming to address both voltage and current-related power quality issues more effectively. This combination is relatively unexplored, especially in the context of dynamically varying load conditions and renewable energy integration.

Many studies have focused on using traditional control methods with UPQC to improve power quality, but these approaches may not always handle the complexities of DG systems, particularly in non-linear and dynamic environments. By employing a fuzzy logic controller, your research provides a more adaptive and intelligent approach to managing power quality. The fuzzy logic controller's ability to handle uncertainties and nonlinearities in the system offers a significant improvement over conventional control strategies, leading to better performance in relieving power quality issues, such as voltage droops, growth, and music.

While there are studies that analyze the performance of UPQC in various settings, they often focus on specific scenarios or lack a detailed examination of the system's behavior under different operating conditions. This system offers a more comprehensive power quality analysis by simulating and evaluating the performance of the fuzzy logic controller-based UPQC system under a wide range of operating conditions, including varying load profiles and the presence of renewable energy sources. This thorough analysis provides deeper insights into the system’s effectiveness and reliability, which is less frequently covered in existing literature.

The power quality challenges posed by modern DG systems, particularly with the increasing penetration of renewable energy, are a growing concern. However, many existing studies have not fully addressed these challenges with advanced control techniques. This work specifically targets these challenges by leveraging the flexibility and robustness of fuzzy logic control in conjunction with UPQC, offering a more tailored solution for DG systems. This approach is particularly novel in how it addresses the unique demands of power quality management in a renewable-rich distributed generation environment.

Traditional control methods may offer acceptable performance in maintaining power quality, but they can fall short in terms of response time, adaptability, and overall system efficiency. This system improved performance metrics, such as faster response times, better voltage regulation, and reduced harmonic distortion, compared to existing methods. These improvements are critical for the reliable operation of DG systems, particularly in scenarios where quick adaptation to changing conditions is necessary.

This research presents a significant advancement over existing studies by integrating a fuzzy logic controller with UPQC in distributed generation systems, offering a more adaptive, intelligent, and comprehensive solution for power quality management. The novelty lies in the enhanced performance, broader applicability, and deeper analysis provided by your approach, addressing gaps that have not been fully explored in prior research.

7. Hybrid Renewable Energy System with UPQC

In this section, a MATLAB/SIMULINK environment was used to create the modelling of hybrid PV / wind / SOFC, and battery varied loads. The results of this development are provided in Figure 11. The model has been run through a series of simulations under a wide variety of operational settings, including load and climate.

The voltage source converter controller regulates how hybrid renewable energy technologies are integrated into the grid. The main sub-controllers in this controller are the voltage regulator, the current regulator, and the phase look loop. The phase lock loop will make it easier to lock the frequency within the synchronous renewable energy system and at the point of standard coupling (PCC). The regulation of PCC voltage, as well as the voltage of renewable energy, will be supported by the voltage regulator.

Figure 12 illustrate the operational framework of UPQC as well as the fundamental capabilities of a UPQC controller. Figure 13 demonstrates the UPQC simulation model. Both figures can be found in the same document. The voltage compensation (vC) and current infusion (iC) reference signals needed for compensation are derived by fast calculations of the source voltage (vS), DC-transport voltage (VDC), and heap current. These cues originate from compensatory intentions (iL).

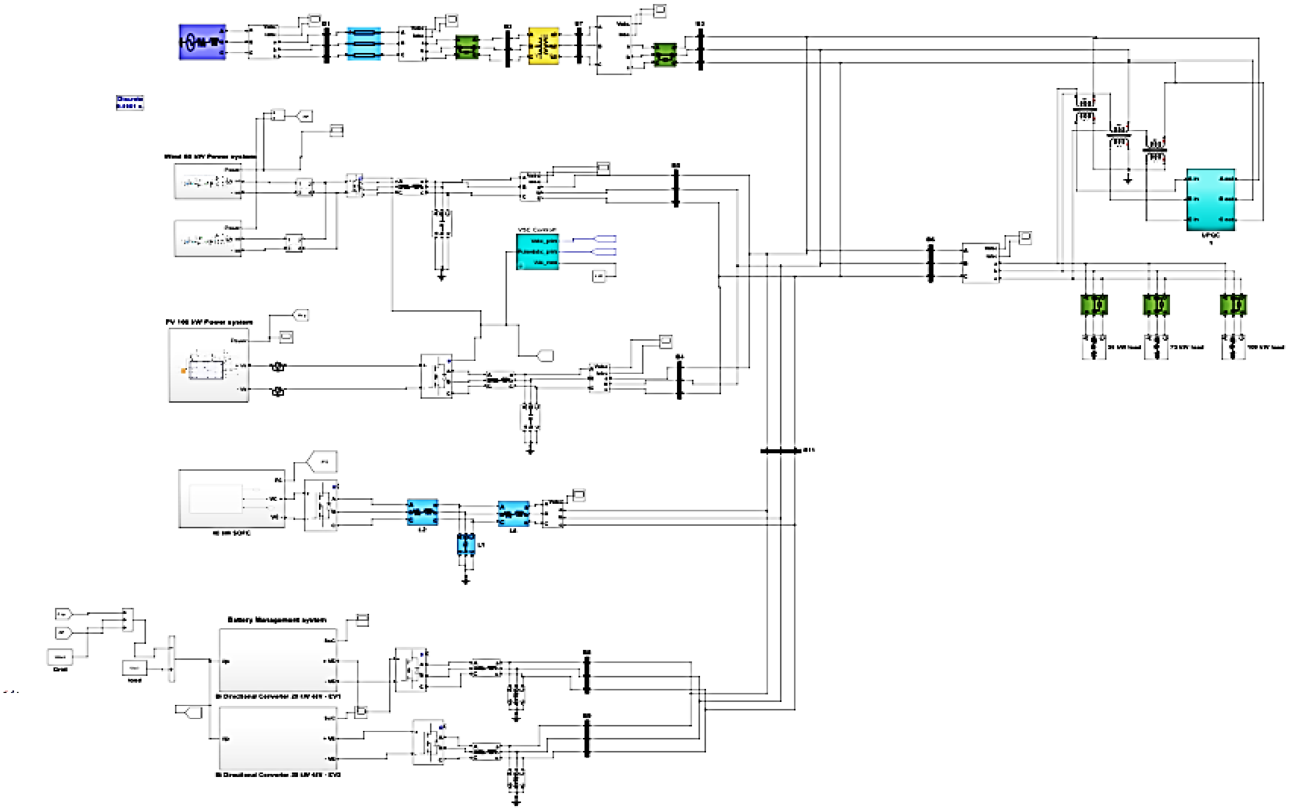


Fig. 11 MATLAB simulation model of grid integration of hybrid PV/ Wind /SOFC and battery system

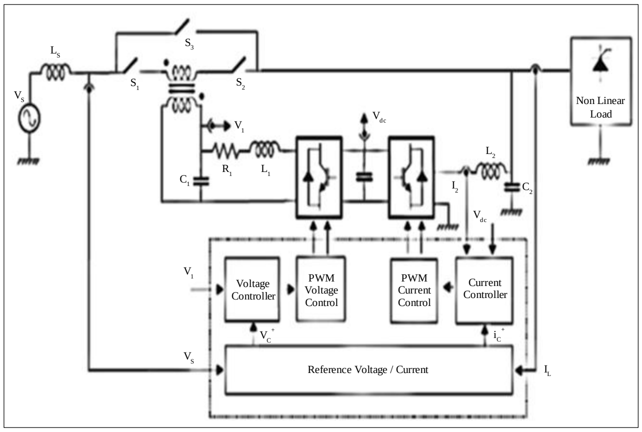


Fig. 12 UPQC controller functional structure

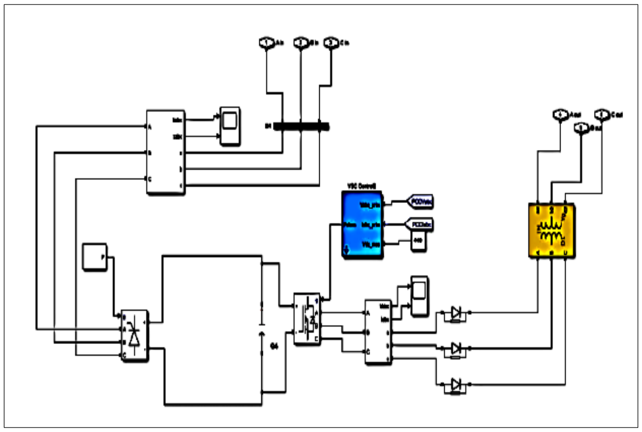


Fig. 13 MATLAB simulation model of UPQC system

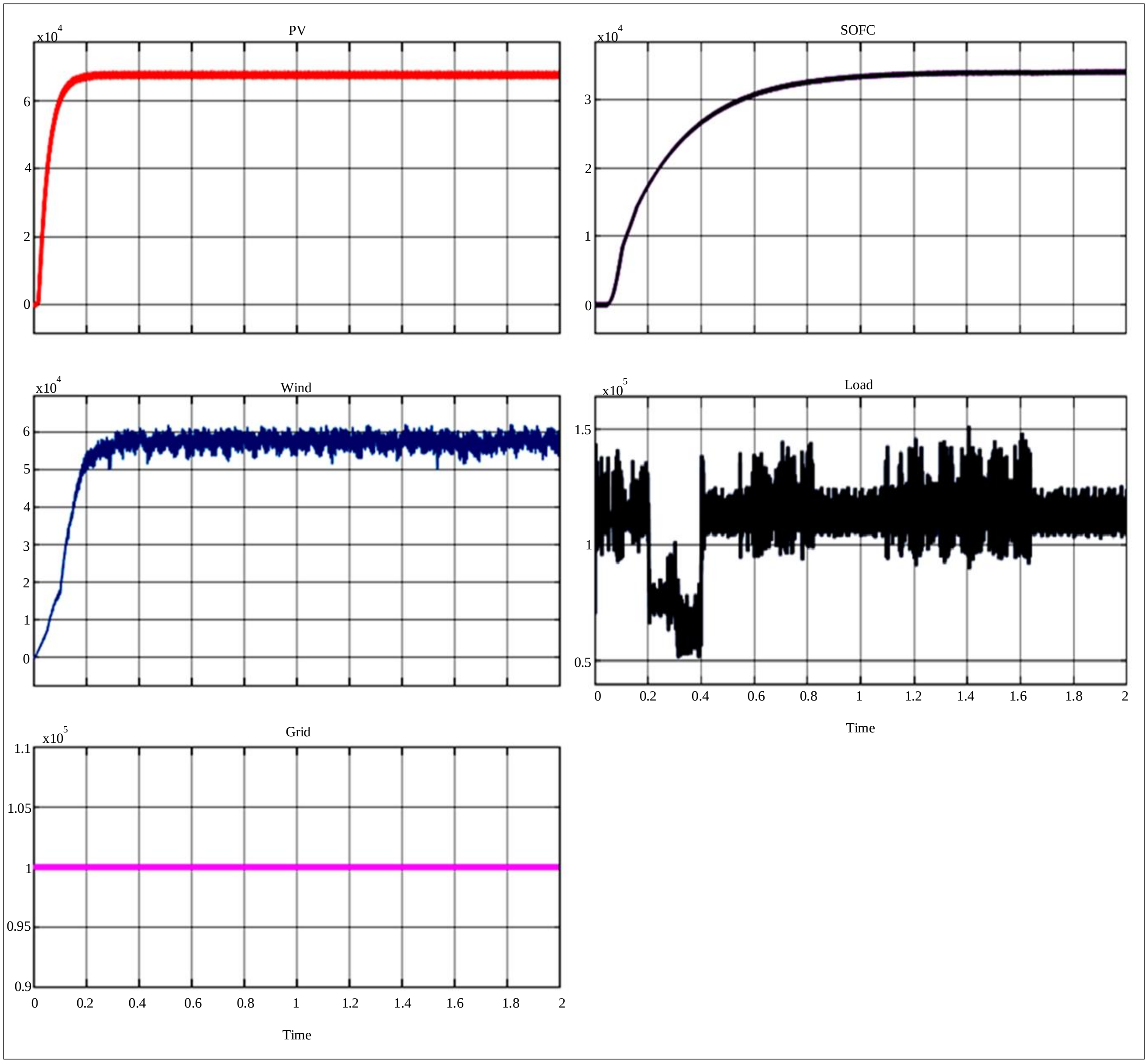


Fig. 14 Power generation: PV, wind , grid, SOFC, and load

After comparing these signals to the anticipated criticism signals v1 and i2, the decoupled voltage and current controllers get these reference signals. This makes sure the pay signals stack up favorably against the reference ones. By applying beat width modulators to the regulator's results, it is possible to get the door indicators for the power converters.

Once it has been identified, the link between the PLL synchronizing the compensation standard and the voltage motion must be disconnected to retain the prior stage. It is possible to attach a tedious controller to lessen the effect of all voltage harmonics when the compensatory goal is to reduce the heap voltage harmonic.

Since the voltage controller is responsible for generating the reference signal in this scenario, the signal does not allow for specific consonant pay, either in terms of symphonic order or consonant grandeur. Controlling the voltage source converters that are associated with a network has been approached from a variety of different angles.

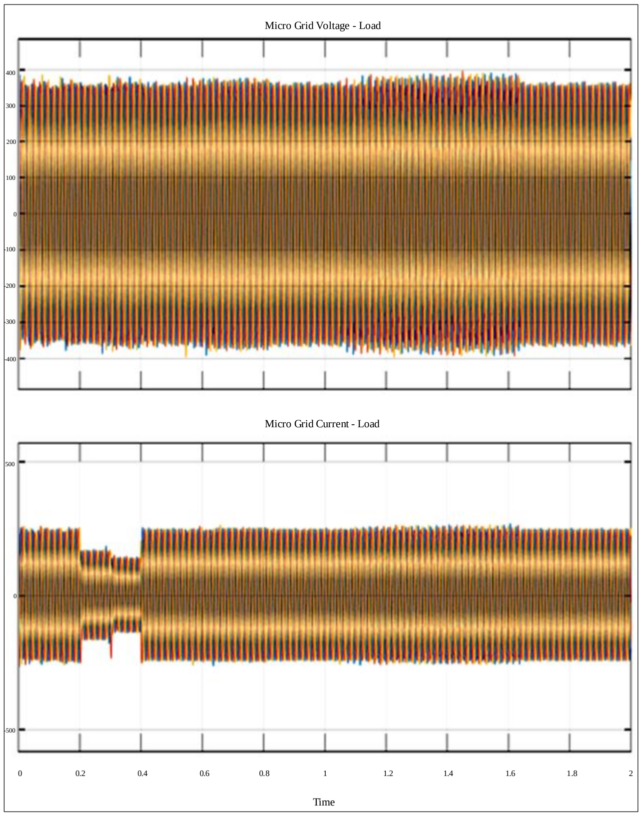


Fig. 15 Microgrid's load voltage and current system

The suggested study work centered on enhancing the quality of the power and assuring that the power would always be reliable. Along with the demand waveform and power production, Figure 14 displays several renewable energy sources, such as photovoltaic, wind, and solid oxide fuel cell grids. The microgrid load's voltage and current waveform in various load states are shown in Figure 15. A closer look at Figure 15 is provided in Figure 16.

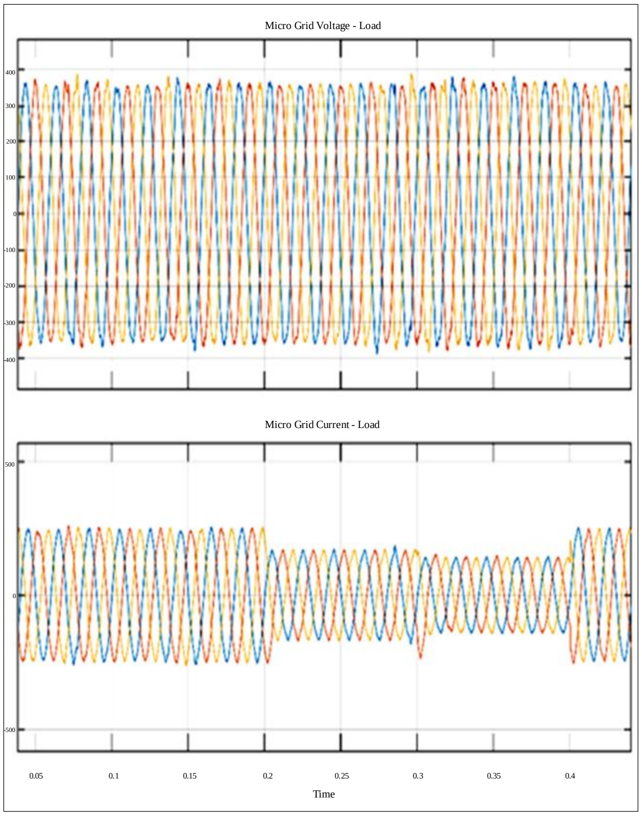


Fig. 16 Microgrid's load voltage and current System

The main goal of this investigation is to find out how much Total Harmonic Distortion (THD) is present on both the load side and the microgrid. The load voltage has a THD value of 3.78 percent in the scenario shown in Figure 17, which shows the initial synchronization of hybrid renewable energy sources. In the situation shown in Figure 18, the load current has a THD value of 3.32 percent in the initial condition of synchronizing hybrid renewable energy sources.

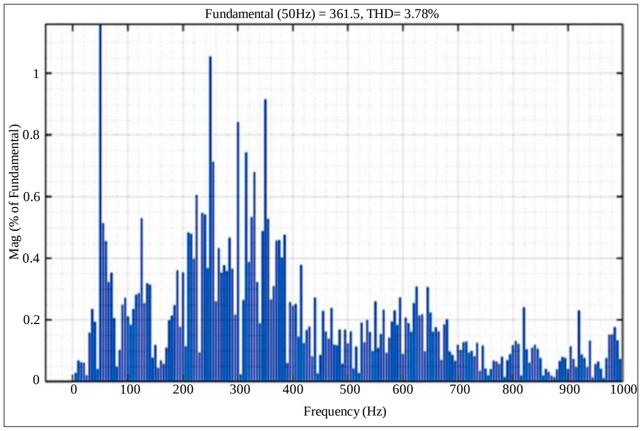


Fig. 17 Load voltage THD

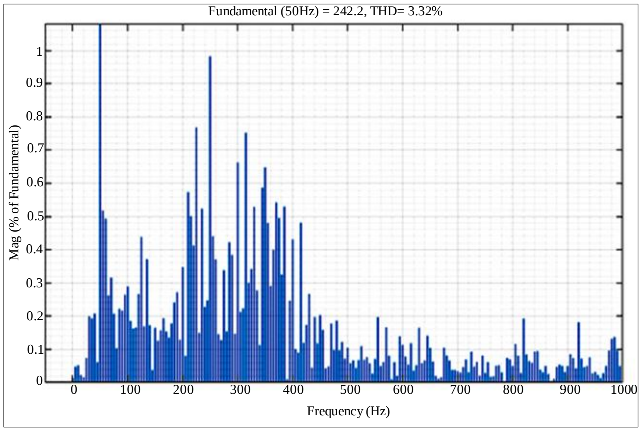


Fig. 18 Load current THD at 0 sec (10 cycles)

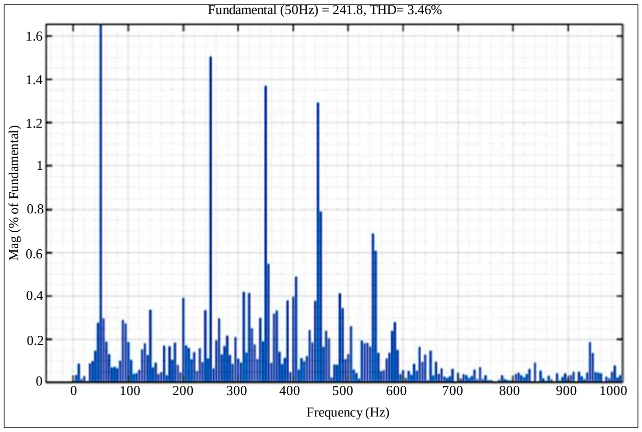


Fig. 19 Load current THD at 1 sec (10 cycles)

The current value of THD was tested once more under a variety of loading situations, and the results are displayed in Figure 19 as 3.46 percent (intermediate period). Figure 20 depicts the microgrid's (PCC) voltage and current waveforms under a variety of load circumstances. Under the initial condition of synchronizing hybrid renewable energy sources, as illustrated in Figure 21, the THD value of the microgrid voltage is 3.77 percent. In the first scenario of synchronizing hybrid renewable energy sources, Figure 22 revealed a load current Total Harmonic Distortion (THD) value of 13.18 percent. Figure 23 shows that the present value of THD was examined once again at 8.26 percent under various loading scenarios. The THD values for load voltage, load current, grid voltage, and grid current are presented in Table 1. PI controllers, while widely used, often struggle with non-linear systems and varying load conditions, potentially resulting in higher THD compared to FLC. The FLC achieves a THD of 3.32%, which is significantly lower than the expected THD with a PI controller. This indicates that the FLC provides better harmonic suppression in the load current, leading to improved power quality. With a THD of 3.78% under FLC control, the load voltage quality is also better than what would typically be achieved with a PI controller, which might have a THD of 5-6%.

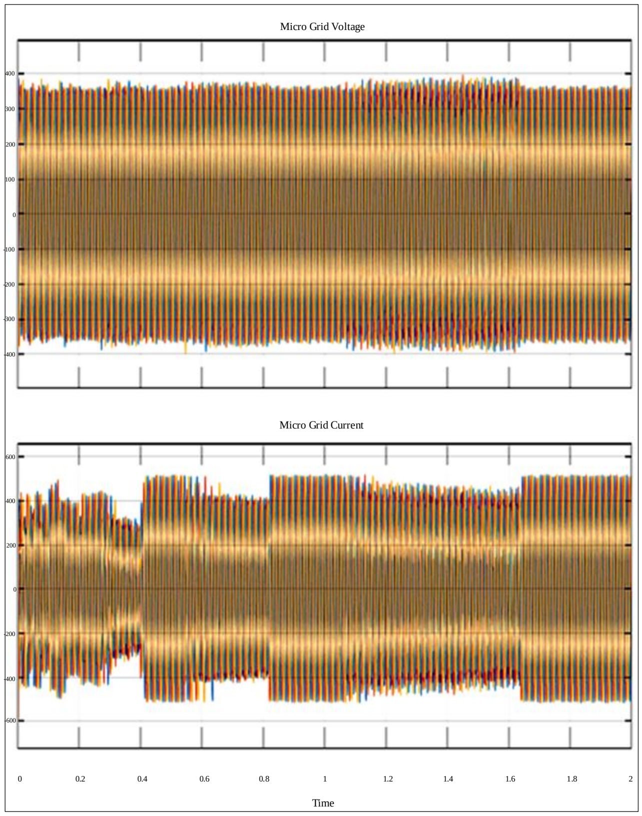


Fig. 20 Microgrid voltage and current waveform

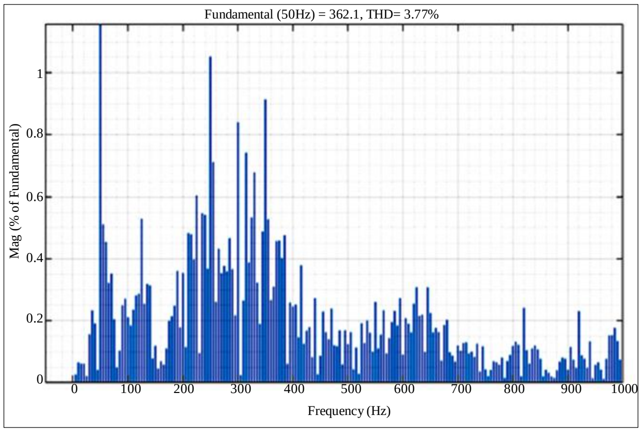


Fig. 21 Microgrid grid voltage THD

This suggests that FLC is more effective in maintaining a clean voltage waveform at the load. The grid current THD with FLC is 8.26%, which, while higher than the THD for load parameters, is still lower than what a PI controller would likely achieve (10-12%). This reflects the FLC's superior ability to handle the complexities of grid interaction and reduce harmonic distortion.

The grid voltage THD of 3.77% with FLC control is notably better than the expected PI controller THD. This indicates that the FLC can better maintain grid voltage quality, which is crucial for overall system stability and power quality. This comparison clearly shows that FLC offers significant advantages over PI controllers, especially in scenarios where minimizing harmonic distortion is critical.

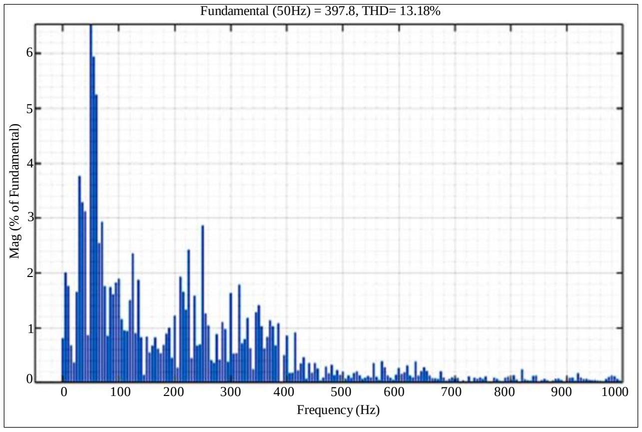


Fig. 22 Microgrid current THD

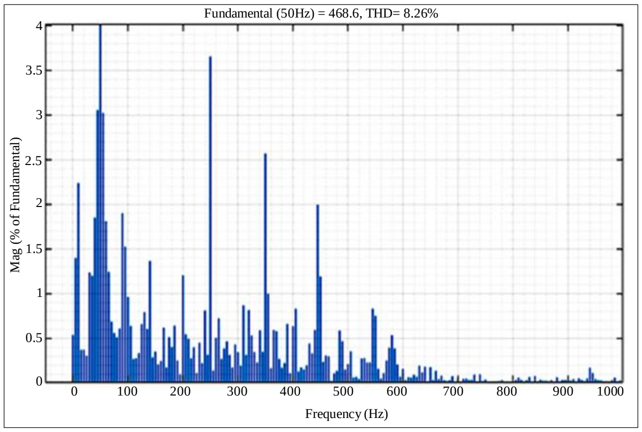


Fig. 23 Microgrid current THD (intermediate conditions)

Table 1. Voltage and current THD

Parameter	Load Current	Load Voltage	Grid Current	Grid Voltage
% THD with PI Controller	3.55	4.01	9.25	3.98
% THD with FLC	3.32	3.78	8.26	3.77

8. Conclusion

This paper focused on the development of a hybrid electricity generation system and the enhancement of its quality through the application of a fuzzy logic controller. The proposed system incorporates solid oxide fuel cells, wind, and solar photovoltaic energy. Simulations conducted in a MATLAB environment revealed that the fuzzy logic technique optimized electricity generation under various conditions, demonstrating its effectiveness through these simulations.

The fuzzy logic algorithm also developed and controlled the battery management system, leading to improved power management, as shown in the results provided in this study. An advanced FACTS device, the UPQC, was employed to enhance power quality and manage both real and reactive power. This device was integrated with the described hybrid renewable energy source.

In conclusion, the proposed hybrid system was connected to the electrical grid, and its total harmonic distortion was analysed under various loading and operating conditions. The effectiveness of the suggested hybrid power generation system was tested against IEEE 1547 and IEEE 519 standards, and the simulation results were evaluated based on these standards.

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