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UPQC-Based Power Quality Improvement in Grid-linked PV, Battery & Wind Systems

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Abstract. This paper portrays an examination into the enhancement of power quality in grid-connected photovoltaic (PV), battery, and wind systems using Unified Power Quality Conditioner (UPQC). The incorporation of non-conventional energy resources such as PV, wind, and battery storage into the grid introduces challenges related to power fluctuations, voltage sags, harmonics, and power factor variations. To address these confronts, the UPQC approach is employed to improve power quality parameters and ensure grid stability. In this study, Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) techniques are utilized for both PV and wind energy systems to optimize power extraction from these sources. Additionally, Adaptive Neuro-Fuzzy Inference System (ANFIS) control is applied to the shunt and series inverters to regulate voltage levels, mitigate harmonics, and improve overall system efficiency. The ANFIS-based control strategy enhances the performance of the inverters by dynamically adjusting their parameters based on system operating conditions. Simulation results demonstrate the effectiveness of the proposed UPQC-based approach in mitigating power quality issues, reducing voltage fluctuations, improving power factor, and enhancing system stability during varying load conditions. The integration of P&O MPPT for PV and wind systems along with ANFIS control for inverters significantly contributes to the overall power quality enhancement in grid-linked non-conventional energy structures.

1 Introduction

The incorporation of non-conventional power resources such as photovoltaic (PV), battery storage, and wind generation into the grid has gained significant attention due to their environmental benefits and potential to reduce dependency on conventional fossil fuels. However, the variability and intermittency of these renewable sources pose challenges to grid stability and power quality. Power fluctuations, voltage sags, harmonics, and power factor variations are among the issues that can impact the reliability and performance of grid-connected systems.

A study on power quality enrichment in a grid-linked PV, wind & battery system using UPQC with atom search optimisation was conducted by [1]. The main findings of the study include improved power quality, reduced harmonics, and enhanced voltage regulation in the system. It does not consider the impact of varying weather conditions on the performance of the PV/wind/battery system, which could affect the overall power quality enhancement.[2] investigated the performance of a grid-linked distributed production structure incorporating a hybrid wind & Solar farm using UPQC. The study focused on analysing the system's stability, efficiency, and power quality improvement. It does not address the economic feasibility of implementing a hybrid wind-PV farm with UPQC, which could be a crucial factor for real-world applications. A performance analysis of a UPQC for microgrid structures with integrated solar PV array and storage was conducted by [3]. The study aimed to optimize the system's power quality, efficiency, and reliability. It does not consider the impact of varying load conditions on the performance of the PV and battery combined UPQC, which could affect the overall system performance.[4] investigated power quality improvement in a solar photovoltaic/wind energy integrated system using UPQC. The study focused on reducing harmonics, improving voltage regulation, and enhancing power quality in the system.[5] analysed the performance of a fuzzy-based controller for wind and battery-fed UPQC in microgrid systems. The study focused on improving power quality, stability, and efficiency in the system. It does not consider the impact of communication delays or signal processing limitations on the performance of the fuzzy-based controller for wind and battery-fed UPQC, which could affect the overall system performance.

The goal of the research by [6] is to employ UPQC to improve the quality of energy in PV energy structures that are linked to the grid. The grid-linked PV power system's harmonics, voltage swells, and sags are among the power quality problems that the UPQC helps

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to reduce. The limitations of this study may include the specific focus on power quality enhancement in solar power systems with grid connection using UPQC. The study may not address other aspects of power quality enhancement in different types of renewable energy systems. To improve power quality in 3 phase solar PV, battery systems, and wind integrated UPQC systems, an improved fractional-order Proportional-Integral controller was presented by [7].

The controller aims to enhance power quality by regulating voltage and current harmonics. The limitations of this study may include the focus on a specific type of controller (FOPI) for power quality enhancement in integrated renewable energy systems. The study may not consider other types of controllers or factors that could impact power quality A hybrid metaheuristic aided collateral fractional-order regulator is presented in the work by [8] to enhance quality of power in wind, BESS, and 3 phase solar PV combined UPQC systems. The controller's goal is to minimize voltage and current harmonics to maximize the efficiency of the UPQC system. The particular emphasis on a hybrid metaheuristic aided collateral fractional-order regulator for improving power quality in combined non-conventional energy systems may not be included. The research may not include other control methods or any difficulties in putting the suggested controller into practice. In their discussion, [9] highlighted the better efficiency of a UPQC and Battery Storage System powered by solar systems with the use of an AI control.

The controller is designed to optimize the operation of the UPQC and BESS for improved quality of the power [10]. The limitations of this study may include the specific focus on the use of an artificial intelligent controller for power quality enhancement in UPQC and BESS systems supplied by photovoltaic systems. The study may not consider other control strategies or potential limitations of the proposed controller. A hybrid control strategy based on ANFIS and Firefly Algorithm for enhancing power quality in UPQC systems in smart grids was presented by [11]. The proposed strategy aims to optimize the performance of the UPQC for mitigating power problems. The demerits of this study may include the specific focus on a hybrid ANFIS-FA-relied controller for enhancing the quality of the energy in UPQC systems in smart grids [12]. The study may not address other control strategies or potential challenges in implementing the proposed strategy. The UPQC shows promise as a means of addressing these issues and advancing quality of the energy produced in grid-linked PV, battery, and wind systems [13-15]. A sophisticated electrical device called UPQC may enhance power quality attributes including power factor correction, harmonic reduction, and voltage control. This research examines the use of UPQC to improve power quality in grid-linked wind, battery, and photovoltaic structures [16-17].

The study focuses on utilizing P&O MPPT approaches for optimizing power from PV and wind sources. Furthermore, ANFIS control is employed for the shunt and series inverters to regulate voltage levels, mitigate harmonics, and enhance overall system efficiency. By integrating UPQC, P&O MPPT, and ANFIS control, this research aims to demonstrate the effectiveness of these technologies in mitigating power quality issues and ensuring grid stability in renewable energy-based grid-connected systems.

2 System Decryption

The hybrid renewable energy system integrates a wind turbine for capturing wind energy through turbine blades converting kinetic energy into rotational energy, a photovoltaic array generating DC electricity from sunlight, and a battery storage system storing surplus energy from both sources to provide power during low generation periods. The system can connect to the electrical grid for power exchange. In the wind and solar power generation process, a rectifier converts wind turbine rotational energy into DC electricity, while the PV array's DC output is boosted in voltage for reduced transmission losses. The Maximum Power Point Tracking (MPPT) optimizes power output, and both sources' boosted DC electricity feeds into a common DC bus. The battery storage system employs bidirectional and shunt converters to store and release energy as needed. A control system is essential, likely including UPQC Control for enhancing power quality from the wind turbine and PV array and ANFIS Control, utilizing Adaptive Neuro-Fuzzy Inference System for overall system optimization. Figure 1 shows the overall representation of the UPQC Control.

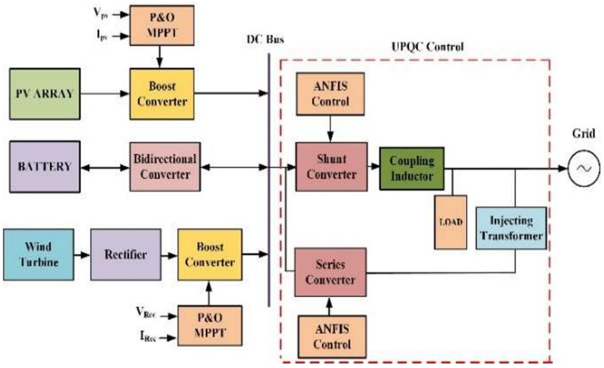

Fig.1. Overall Block diagram of UPQC Control

2.1 PV Model with MPPT Control

The mathematical representation of a photovoltaic cell is exhibited in Figure 2, where the cell's photocurrent is denoted by the current source Iph. The resistances in the cell are intrinsic shunt (Rsh) and series (Rs). Rsh has a very high value whereas Rs has a very low value. Consequently, to simplify the study, these resistances are often ignored. PV cells are arranged into larger components known as PV modules for practical uses. PV arrays are the building blocks of PV generation systems, and they are created by connecting these modules in either a series or parallel arrangement.

$$I_{ph} = [I_{sc} + K_i(T - 298)] * I_r/1000 \qquad (1)$$

In this case, I_{sc} stands for the short-circuit current in amperes (A), while I_{ph} stands for the photo-current in amperes (A). Ki is the cells short-circuit current at 1000 W/m2 and 25°C. The variables T and Ir represent the operating temperature and sun irradiation, respectively, in kelvins (K) and watts per square meter (W/m2). Irs stands for the reverse saturation current of the module.

$$I_{rs} = I_{sc}/[\exp\left(\frac{qV_{oc}}{N_s knT}\right) - 1] \qquad (2)$$

In this case, 1.6 × 10^−19 coulombs (C) is the electron charge (q). Volts (V) are used to represent the open circuit voltage (Voc). The number of cells linked in series is denoted by Ns. 'n' stands for the idealist factor. The value of Boltzmann's constant (k) is 1.3805 × 10^−23 joules per kelvin (J/K).

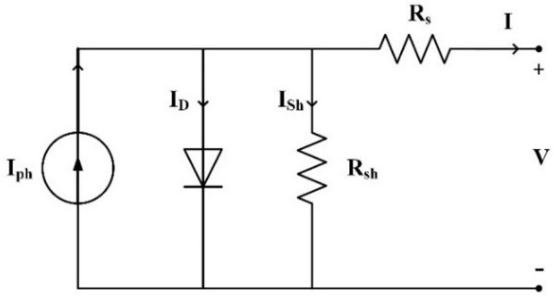

Fig.2. Mathematical model of PV cell

2.2 Step by Step Procedure of P&O MPPT

Here is a step-by-step procédure P&O Maximum Power Point Tracking

- Initialize variables: Set the initial voltage value Initial to a known value (e.g., the open-circuit voltage of the PV panel). Set the perturbation step size ΔV to a lesser value.
- Measure the PV panel's current and voltage IPV and VPV.
- Calculate the output power of the PV array using the formula:
  PPV = IPV ×VPV
- Perturb the PV panel's voltage:
  Increase the voltage by ΔV : Vnew = VPV + ΔV.
- Measure the new current and voltage Inew and Vnew.
- Calculate the new power output Pnew = Inew ×Vnew.
- Assess the new power output Pnew with the former power output PPV:
- If Pnew > PPV, continue increasing the voltage and go to step 4.
  If Pnew < PPV, decrease the voltage by ΔV and go to step 8.
- Perturb the voltage in the opposite direction:
  -Decrease the voltage by ΔV : Vnew = VPV - ΔV.
- Measure the new current and voltage Inew and Vnew.
- Calculate the new power output Pnew = Inew× Vnew.
- Relate the new output power Pnew with the former power output PPV: If Pnew > PPV, decrease the voltage by ΔV and go to step 8. If Pnew < PPV, the maximum power point (MPP) has been reached.
- The voltage at which Pnew < P is the estimated maximum power point (MPP).
- Output the MPP voltage VMPP and current IMPP for optimal power extraction from the PV panel. The PV manipulation with P&O MPPT is represented in Figure 3.

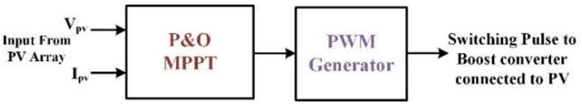

Fig.3. PV Control with P&O MPPT

2.3 Battery with Bidirectional regulator control

When a battery is linked to a DC bus through a bidirectional regulator, it facilitates energy storage (charge) from the DC bus during surplus power situations and energy release (discharge) back into the DC bus when needed. The bidirectional converter, operating in charging mode, regulates voltage and current to safely charge the battery with excess power from renewable sources like solar panels or wind turbines. In discharging mode, it draws energy from the battery to convert it into DC electricity compatible with the DC bus, meeting load demands or supplying power to the grid when generation is insufficient. A BMS observes and directs the charging & discharging procedures, ensuring safe operation and providing status information. This setup, combined with an energy management system, optimizes renewable energy utilization, load balancing, and grid support services for enhanced system flexibility, reliability, and efficiency. Figure 4 shows the Control of battery Connected to Bidirectional controller.

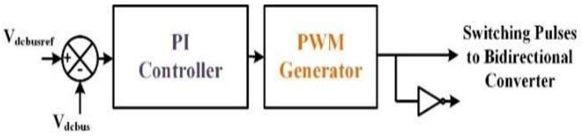

Fig.4. Control of battery Connected to Bidirectional controller Wind MPPT Control

The wind turbine's output power was determined by the wind velocity at a certain base height. The control logic for the wind turbine's power output involves several key components. Firstly, the turbine blades capture wind energy and convert it into rotational energy, which is then converted from AC to DC electricity by the rectifier. The MPPT algorithm, likely implemented as Perturb and Observe (P&O), continuously adjusts the blade pitch angle to maximize power output. This adjustment is facilitated by the PWM generator, which controls the pitch angle based on the MPPT algorithm's guidance. The reference voltage (VRec) and reference current (IRec) for the rectifier ensure that it operates within specified limits, providing the desired DC voltage and current output. This control system optimizes the wind turbine's performance by dynamically adjusting blade pitch to track the maximum power point, enhancing overall energy conversion efficiency.

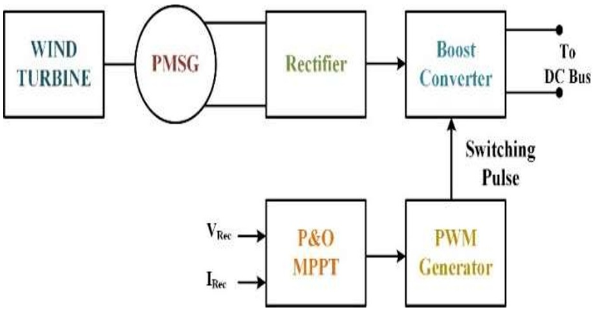

Fig.5. Wind Turbine MPPT Control

3 UPQC for Power quality Improvement

A flexible electricity electronic device known as a Unified Power Quality Conditioner (UPQC) has the capability to address multiple electricity quality issues such as voltage sags, swells, harmonics, and power factor correction. Comprising series and shunt active electricity filters connected back-to-back, the UPQC offers both voltage and current compensation capabilities. Through the injection of appropriate compensating voltages and currents, the grid voltage and current waveforms can be adjusted by the UPQC, thereby enhancing power quality.

Configuration and Control Strategies of UPQC: Various configurations and control strategies for UPQC have been proposed by researchers to enhance its performance in grid-connected renewable power systems. These strategies include hysteresis control, proportional-integral (PI) control, fuzzy logic control, and model predictive control (MPC). Comparative studies have been conducted to evaluate the effectiveness of these control strategies in terms of performance, dynamic response, and computational complexity.

Challenges and Solutions in Integration: The integration of UPQC with photovoltaic (PV), battery, and wind systems presents technical challenges such as synchronization, power sharing, and control coordination. Several studies have addressed these challenges by proposing synchronization methods, droop control techniques, and communication protocols to ensure seamless integration and operation of UPQC with renewable energy systems.

Evaluation of Performance and Simulation Studies: Numerous simulation studies and experimental validations have been carried out to assess the performance of UPQC-based power quality improvement in grid-connected renewable energy systems. These studies analyse key performance indicators such as voltage regulation, harmonic distortion reduction, power factor correction, and dynamic response under various operating conditions and grid disturbances.

Analysis of Economic Viability and Feasibility: In addition to technical aspects, researchers have explored the economic feasibility and cost-effectiveness of deploying UPQC in grid-connected renewable energy systems. Economic evaluation models, including life cycle cost analysis, net present value analysis, and payback period estimation, have been developed to evaluate the financial benefits and potential return on investment associated with the deployment of UPQC.A UPQC, sometimes referred to as a shunt-series connection, offers the greatest defence against low-quality sources for sensitive loads. A UPQC has been shown to be effective in resolving all power quality concerns, including voltage sag, swell, outage, and excessive correction of power factor. The basic layout of the UPQC is shown in Figure 6.

Reactive power, negative-sequence current, harmonic distortion, and flickering or uneven supply voltage are the main problems that a UPQC is intended to address. Stated differently, the UPQC may be put in an industrial power system or at the distribution point to improve the quality of the electricity right away.

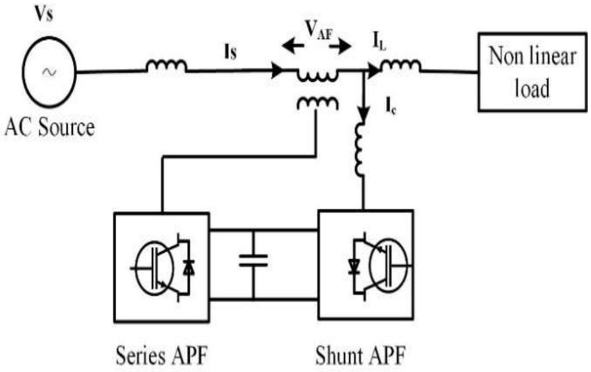

Fig.6. Basic configuration of UPQC

Therefore, one of the most effective solutions to the issue of voltage flicker/unbalance in large capacity loads is expected to be the UPQC. A UPQC for Varying and sensitive loads has the following features:

- It reduces harmonics from the input current, increasing the quality of utility power for loads.
- UPQC ensures that the given current and Voltage are always in phase, consequently further correction in power factor are not required.
- The load end voltage will remain at its graded merit even if the supply voltage lowers due to the presence of UPQC.

3.1 ANFIS Controller for Shunt & Series Converters

ANFIS, which stands for Adaptive Neuro-Fuzzy Inference System, is an intelligent control system that combines the adaptability of neural networks with the explanatory power of fuzzy logic. This combination makes ANFIS control suitable for various applications, including power electronics systems like UPQCs. It is a device used to enhance power quality in electrical systems by mitigating conflicts such as sags, Frequency changes etc. When ANFIS control is implemented in the shunt and series converters of a UPQC, its primary objective is to optimize the working of these regulators relied on the system's operational conditions and the specific power quality improvement goals. The ANFIS control system achieves this optimization by dynamically adjusting control parameters in response to varying load conditions, grid disturbances, and other environmental factors. For the shunt converter of the UPQC, ANFIS control ensures efficient regulation of voltage levels, helping to stabilize the grid and mitigate voltage fluctuations. Meanwhile, in the series converter, ANFIS control focuses on harmonic elimination and voltage compensation, contributing to better power factor and less THD in the system. Overall, ANFIS control plays a vital part in improving the execution of both shunt and series converters in a UPQC, leading to better power quality, increased system efficiency, and improved grid stability. Its adaptability and intelligent decision-making capabilities make ANFIS a valuable tool in modern power electronics applications aimed at optimizing power delivery and mitigating power quality issues.

3.2 Shunt Converter Control

The control logic for the shunt converter part of a UPQC structure, a tool for addressing power quality problems in electrical distribution networks, is shown in Figure 7. The control logic consists of several interconnected blocks that process various inputs produce switching pulses for the shunt converter. The main blocks include ANFIS Control, P-q Control, abc to alpha-beta transformation, Low Pass Filter, Inverse P-q Control, and Hysteresis Controller. The overall aim is to regulate the DC bus voltage and compensate for power quality issues by appropriately controlling the shunt converter based on the processed inputs and control signals.

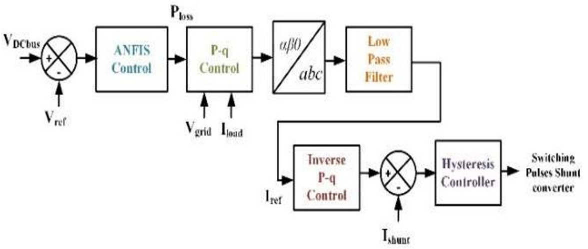

Fig.7. Shunt Converter Control logic

3.3 Series Converter Control

Figure 8 depicts the control logic for the series converter portion of a UPQC system. The control logic takes two inputs: the voltage at load (Vload) and the source voltage (Vabc). The load voltage goes through an abc to dq0 transformation block. The source voltage also goes through a similar abc to dq0 transformation. Both transformed signals are then processed by summing blocks, which are used for voltage comparisons. The resulting signals are fed into an ANFIS Control block that generates the appropriate control signals. These control signals then go through a dq0 to abc transformation and into a PWM Generator, which produces the switching pulses for the series converter of the UPQC system based on the processed inputs and control logic.

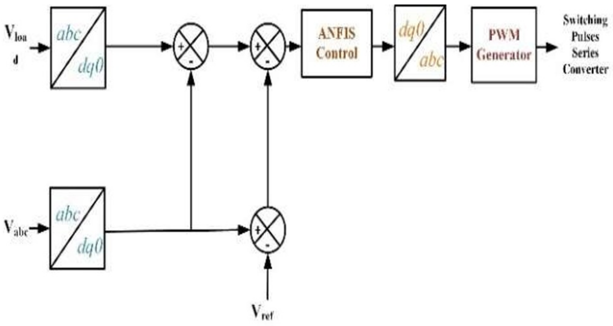

Fig.8. Series Converter Control logic

4 Simulation Results & Discussions

The simulation of the suggested method is conducted utilizing MATLAB/Simulink to increase power quality in a system incorporating PV, wind, and battery sources. The PV array operates under a constant irradiance of 1000 W/m2 throughout the simulation. Power quality issues are intentionally introduced at different time instances to evaluate the system's response and performance under varying conditions. The input powers from the PV array, wind source, and battery are represented and analysed in Figure 9, providing a visual depiction of how these sources contribute to the overall power generation and system operation. This simulation approach allows for a comprehensive assessment of the system's ability to address power quality challenges and optimize energy utilization from renewable sources while ensuring grid stability and reliability.

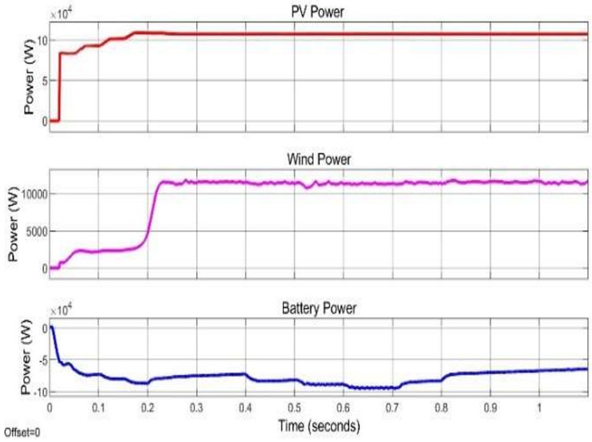

Fig.9. Power of PV, Wind & Battery

The Voltage & Current of the battery is represented in Figure 10. It clearly shows that the battery is charging and the PV & Wind supply power to the DC bus.

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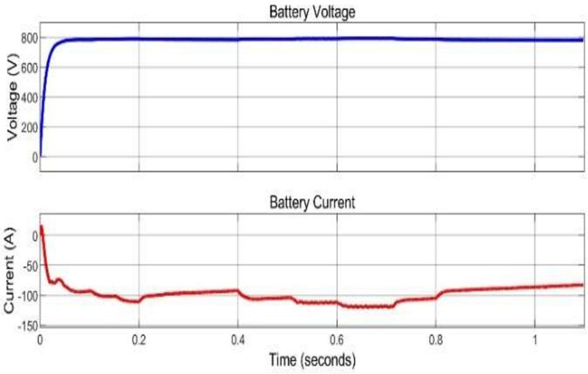

Fig.10. Voltage & Current of the Battery

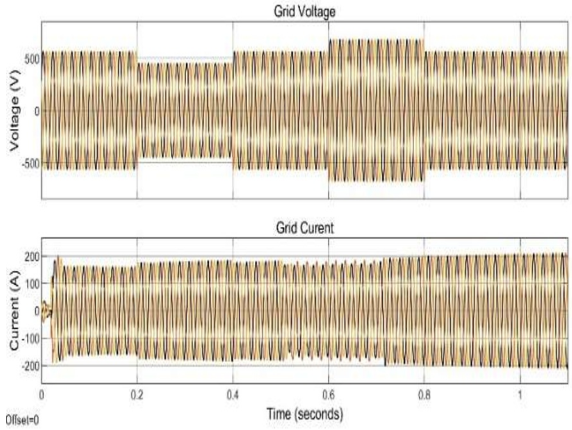

Fig. 11. Voltage & Current of the Grid

Figure 11 displays the grid's voltage and current. Here the deviation in the above parameters shows the power quality issues. From 0.2 to 0.4s clearly indicates the occurrence of voltage sag. The presence of the swell is exhibited from 0.6 to 0.8 s. The load's voltage and current are shown in Figure 12. Figure 13 shows the THD of the grid current. In this case, the THD is 1.82 percent.

Figure 14 in the simulation outcomes clearly illustrates the behaviour of grid & load voltage, and the voltage injected by the UPQC in response to power quality issues. When disturbances occur in the grid voltage due to power quality hitches, such as voltage fluctuations or harmonics, the UPQC intervenes by injecting the necessary voltage using the series transformer connected to the grid. This injection of voltage by the UPQC, controlled by the ANFIS control strategy, ensures that the voltage at the load stays persistent despite fluctuations in the grid voltage.

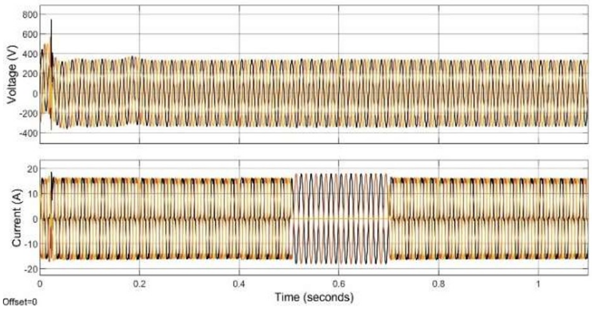

Fig. 12. Voltage & Current of the Load

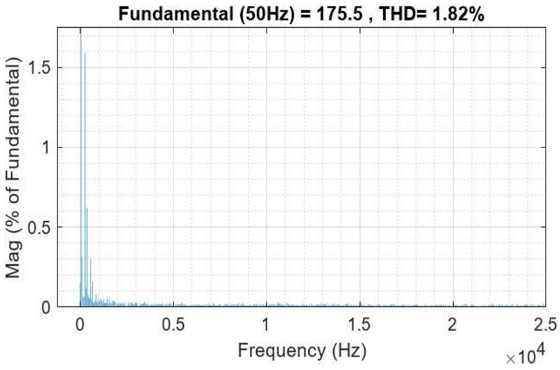

Fig.13. THD of Grid Current using ANFIS Control

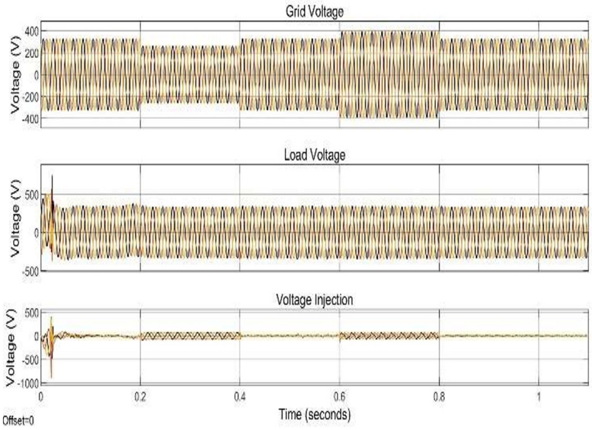

Fig.14. Grid & Load Voltage and injected Voltage

As a result, the power quality is significantly enhanced, as evidenced by the maintained stability of the load voltage even during grid disturbances. The UPQC's ability to swiftly respond to grid voltage variations and provide precise voltage injection demonstrates its effectiveness in mitigating power quality issues and ensuring a dependable and stable power source to the load. The integration of ANFIS control further optimizes the UPQC's performance, making it a valuable tool for enhancing power quality in grid-connected systems.

The table.1 provides a comparative analysis of three control methods, PI control, Fuzzy control, and ANFIS control based on key parameters: THD of the grid current, load voltage during sag, and load voltage during swell. ANFIS control demonstrates superior performance with the lowest THD of 1.82 %, indicating better harmonic suppression compared to PI (4.5%) and Fuzzy (4.1%) control methods.

Table 1. Comparative analysis of THD for PI, Fuzzy & ANFIS Control

Parameter	PI	FUZZY	ANFIS
THD of the Grid Current in (%)	4.55	4.13	1.82
Load Voltage During Sag(V)	225	228	230
Load Voltage During Swell(V)	238	235	230

Additionally, ANFIS control maintains a slightly higher load voltage during sag (230V) and a lower load voltage during swell (230V) compared to PI (225V sag, 238V swell) and Fuzzy (228V sag, 235V swell) control methods. These results suggest that ANFIS control offers better voltage compensation, regulation, and protection against voltage fluctuations during sag and swell events, highlighting its effectiveness in enhancing power quality and system stability.

5 Conclusion

The investigation into enhancing power quality in grid-connected PV, battery, and wind systems using UPQC technology has provided valuable insights into control strategies and their impact on system performance. Comparing ANFIS control, PI control, and fuzzy control has highlighted ANFIS as the preferred choice due to its ability to reduce Total Harmonic Distortion (THD) and improve voltage compensation. ANFIS control, a hybrid intelligent system merging fuzzy logic and neural network techniques, excels in regulating voltage levels, reducing harmonics, and enhancing system efficiency. By adapting inverter parameters based on operating conditions, ANFIS control ensures optimal power quality and stability in renewable energy systems connected to the grid. In contrast, traditional PI and fuzzy control methods have limitations in addressing power quality challenges effectively, potentially leading to higher THD levels and reduced grid stability. Integrating P&O MPPT techniques for PV and wind systems further boosts the effectiveness of ANFIS control, optimizing power extraction and enhancing overall system efficiency. Simulation results confirm the superiority of ANFIS control in mitigating power quality issues, reducing voltage fluctuations, improving power factor, and enhancing system stability under varying loads. These results emphasize the significance of advanced intelligent control strategies like ANFIS in achieving superior power quality enhancement and ensuring grid stability in modern grid-connected renewable energy systems.

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