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Power Quality Enhancement in Distributed PV-Wind Systems Using Neuro-Fuzzy Based Unified Power Quality Conditioner

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Abstractt: This project proposes an ANFIS-based Unified Power Quality Conditioner (UPQC) for a grid-connected hybrid system integrating solar PV and wind energy sources to address power quality issues such as harmonics, voltage imbalance, and current disturbances at the point of common coupling (PCC). Replacing the ANN controller in the series inverter with an Adaptive Neuro-Fuzzy Inference System (ANFIS) improves DC-link voltage regulation and grid current quality by generating reference DC current (Idc) with faster dynamic response and higher accuracy. Simulation results under varying conditions show that the ANFIS-based UPQC achieves lower total harmonic distortion (THD) and better transient performance than conventional ANN-based systems, offering a reliable and cost-effective solution for distributed generation power quality enhancement.
Keywords: Renewable Energy Integration, Power Quality, Distributed Generation (DG) Systems, Adaptive Neuro-Fuzzy Inference System (ANFIS), Unified Power Quality Conditioner (UPQC).

I. INTRODUCTION

This project focuses on enhancing the performance of renewable energy-based distributed generation systems by addressing power quality challenges caused by the intermittent nature of solar and wind sources. A Unified Power Quality Conditioner (UPQC) is employed to mitigate issues such as harmonics, voltage imbalance, and current disturbances. To improve the dynamic response and accuracy of control, an Adaptive Neuro-Fuzzy Inference System (ANFIS) is integrated into the UPQC's series inverter controller. This ANFIS-tuned UPQC ensures better DC-link voltage stability and reduced total harmonic distortion, making it a robust and efficient solution for maintaining power quality in hybrid renewable energy systems.

II. LITERATURE SURVEY

Several studies have explored power quality improvement in distributed generation (DG) systems using various control techniques. Traditional UPQC systems with PI or ANN-based controllers have shown effectiveness in mitigating voltage sags, harmonic distortion, and reactive power issues. However, these methods often suffer from slower dynamic response and limited adaptability under varying load and source conditions. Recent research highlights the potential of intelligent control techniques like Adaptive Neuro-Fuzzy Inference Systems (ANFIS), which combine the learning capability of neural networks with the reasoning of fuzzy logic. ANFIS-based controllers have demonstrated improved accuracy, faster response, and better handling of nonlinearities in power systems. Integrating ANFIS into UPQC control strategies offers a promising approach for enhancing power quality in renewable-based DG systems.

III. MATERIALS AND METHODOLOGY

A. System Overview

The proposed system integrates solar photovoltaic (PV) and wind energy sources into a grid-connected distributed generation (DG) network. A Unified Power Quality Conditioner (UPQC) is employed to improve power quality at the Point of Common Coupling (PCC). The UPQC consists of two main components: a series inverter and a shunt (parallel) inverter. In the base model, Artificial Neural Network (ANN)-based controllers manage both inverters.

In the proposed enhancement, the ANN in the series inverter is replaced with an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller to generate the reference DC current (Idc) more accurately and rapidly.

The ANFIS controller uses training data derived from various operating conditions to adaptively tune its parameters, providing better regulation of the DC-link voltage and improved compensation of voltage-related disturbances. The shunt inverter continues to handle current harmonics and reactive power compensation. MATLAB/Simulink is used for system modeling and simulation. The performance of the system is evaluated under different scenarios including load variation, source disconnection, and transient events. Key performance metrics include Total Harmonic Distortion (THD), voltage regulation, and dynamic response time. This methodology ensures enhanced power quality and system stability in renewable energy-based distributed generation networks.

B. System Design

The proposed system is designed to integrate solar PV and wind energy sources into a grid-connected Distributed Generation (DG) network, enhanced with a Unified Power Quality Conditioner (UPQC) to mitigate power quality issues. The system consists of several major subsystems, each performing a specific role to ensure stable and high-quality power delivery.

1) Renewable Energy Generation Unit

- Solar PV System: Designed using standard PV panel models in Simulink, with input irradiance and temperature parameters.
- Wind Energy System: Implemented using a Permanent Magnet Synchronous Generator (PMSG) or DFIG-based wind turbine model.
- MPPT Algorithm: Employed (e.g., P&O or ANN-based) for both PV and wind systems to extract maximum power under varying conditions.
- DC-DC Converters: Used to boost or stabilize the voltage from renewable sources before feeding into the DC-link.

2) DC-Link Design

- A common DC-link connects both series and shunt inverters of the UPQC.
- Designed using a capacitor bank with optimized capacitance value to ensure stable voltage and energy buffering during dynamic conditions.

3) Unified Power Quality Conditioner (UPQC)

- Series Inverter:
  - Injects compensating voltage in series with the grid.
  - Designed using a PWM-controlled Voltage Source Inverter (VSI).
  - Controlled by an ANFIS-based Controller to improve dynamic response and reduce voltage distortions.
- Shunt Inverter:
  - Injects compensating current in parallel with the load.
  - Handles current harmonics, reactive power, and load balancing.
  - Controlled by an ANN-based or hysteresis current control strategy.

4) Control Strategy Design

- Phase-Locked Loop (PLL): Synchronizes with grid voltage for accurate reference signal generation.
- ANFIS Controller (Series Side):
  - Trained using input-output datasets under various disturbances.
  - Outputs the reference DC current (Idc) and maintains DC-link voltage regulation.
- ANN Controller (Shunt Side):
  - Used for generating reference current signals for harmonic compensation.

5) Load and Grid Modelling

- Non-linear Loads: Simulated using diode bridge rectifiers or variable loads to evaluate harmonic distortion.
- Grid Model: A 3-phase source connected through a transformer at the Point of Common Coupling (PCC).

6) Simulation Environment

- Platform: MATLAB/Simulink with SimPowerSystems Toolbox.
- Monitors: Scopes and Measurement blocks for voltage, current, power factor, and Total Harmonic Distortion (THD).
- Performance Evaluation: Conducted under different test cases:
  - Load variation
  - Source disconnection
  - Voltage sag/swells
  - Harmonic injection

IV. PROPOSED SYSTEM

The proposed system introduces an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based Unified Power Quality Conditioner (UPQC**)** for a grid-connected hybrid renewable energy system that integrates both solar PV and wind energy sources. The system is designed to address power quality issues such as harmonic distortion, voltage imbalance, and current disturbances at the Point of Common Coupling (PCC).

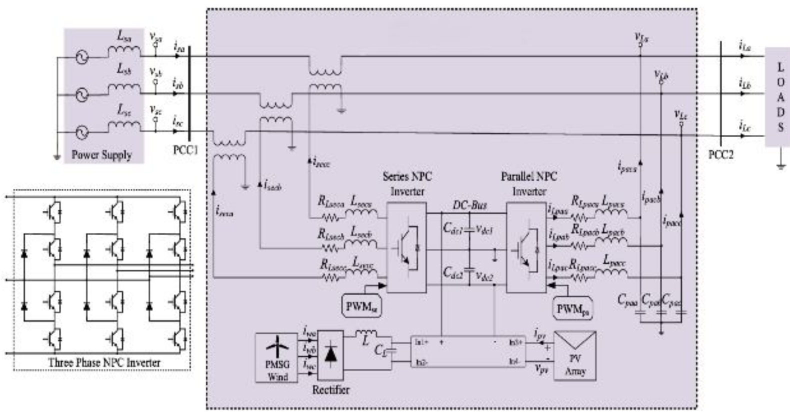

Fig 1: Circuit diagram of the UPQC-ANN-RE system

In this setup, the series inverter of the UPQC is controlled using an ANFIS controller, replacing the conventional ANN controller, to generate more accurate reference signals and enhance the DC-link voltage regulation. The shunt inverter uses an ANN-based control for harmonic compensation and reactive power support.

The proposed hybrid system is simulated in MATLAB/Simulink and tested under various dynamic conditions like load variations and grid faults. The results show significant improvement in power quality, reduced Total Harmonic Distortion (THD), and better system stability compared to traditional control approaches.

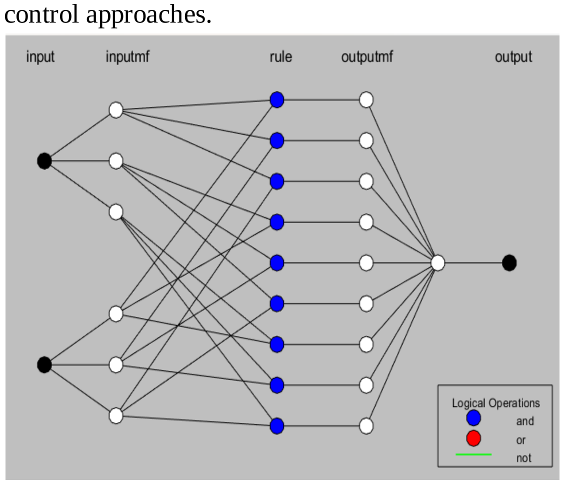

Fig 2: Structure of ANFIS

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V. SIMULATION AND RESULTS

The proposed ANFIS-based UPQC system was simulated using MATLAB/Simulink to evaluate its performance under various operating conditions, including non-linear load conditions, source disconnection, voltage sag/swell, and load variation scenarios.

1) OPC 1: UPQC-ANFIS-RE only performs active/real power-line conditioning with Ppv-wind =0W

In this case, both the PV and wind energy sources are disconnected. The entire load is supplied by the grid. The UPQC ensures that the grid current remains sinusoidal and compensates for any harmonics or unbalance introduced by the non-linear load. The series and shunt inverters work together to maintain power quality. ANFIS provides improved DC-link regulation and lower THD compared to ANN.

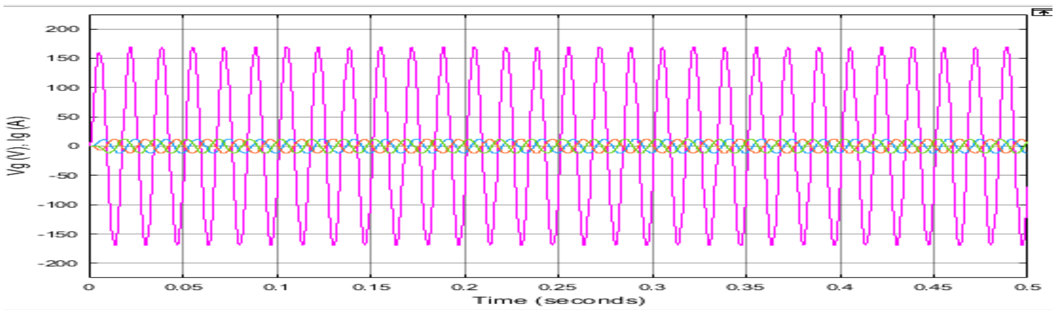

Fig 3 Grid Voltage and Grid Current of ANFIS

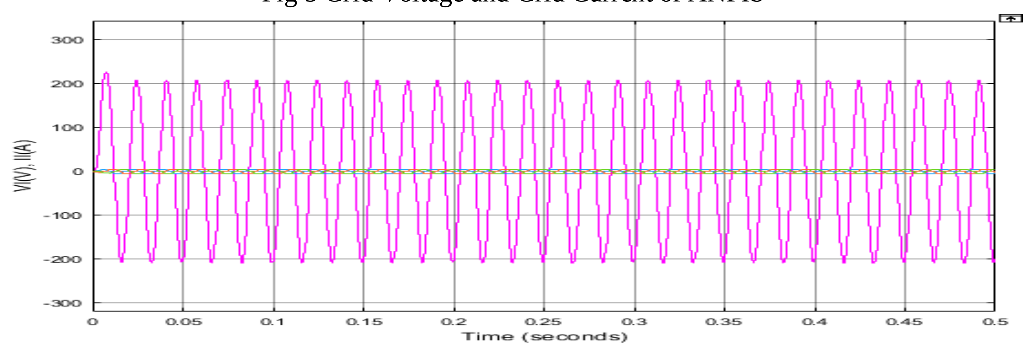

Fig 4 Load Voltage and Load Current of ANFIS

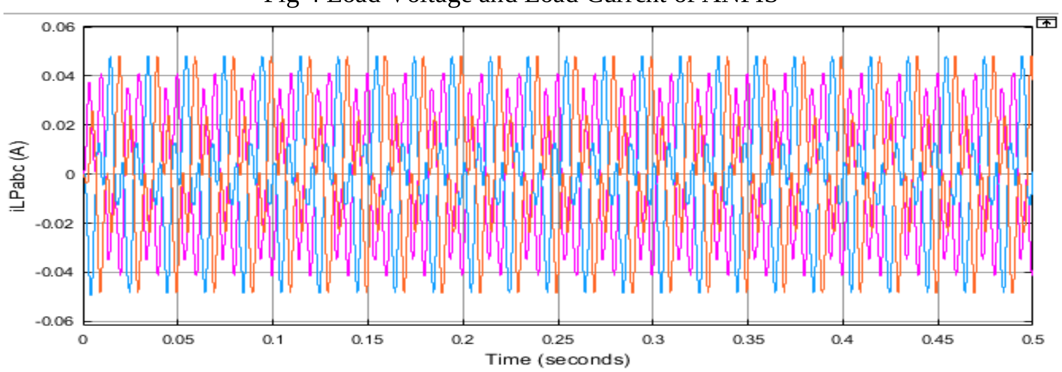

Fig 5 Current at Parallel Inverter of ANFIS

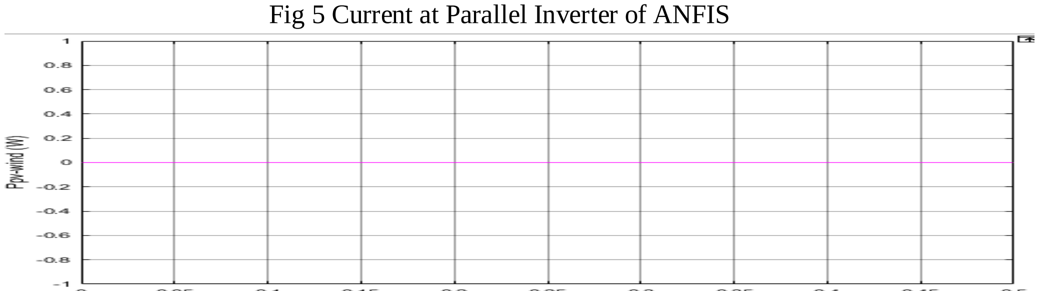

Fig 6 Power of PV array and Wind turbine of ANFIS

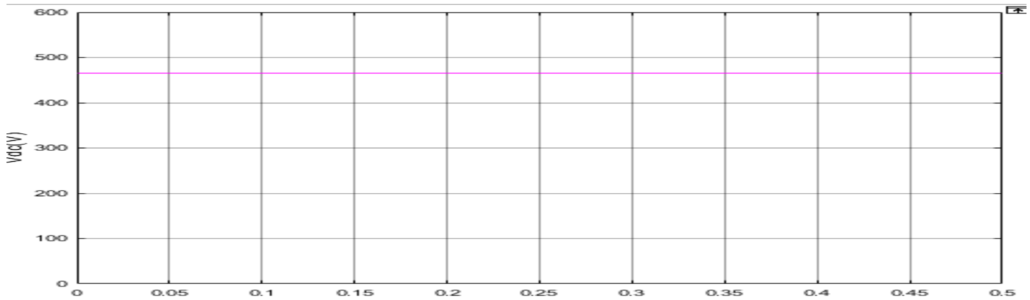

Fig 7 DC Link Voltage of ANFIS

The waveform plots demonstrate the voltage and current profiles when the grid is the sole power source. With ANFIS control, the output shows smoother voltage levels and reduced harmonic content. All THD values are considerably improved compared to ANN, indicating better compensation and cleaner power delivery.

2) OPC 2: UPQC-ANFIS-RE performs simply active power insertion in the utility grid with PL = 0 W and Ppv-wind = 3500 W
Here, the load is disconnected while the PV-wind hybrid source continues to operate. The generated power is unused, and the system enters a low-power mode. This case evaluates how the UPQC maintains DC-link voltage stability without load disturbances. ANFIS shows better dynamic voltage regulation and avoids overshoot or instability that is slightly noticeable in the ANN-based control.

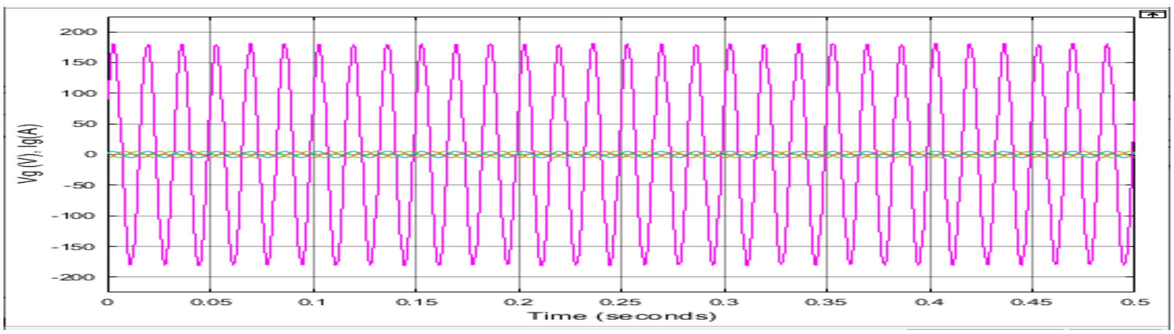

Fig 8 Grid Voltage and Grid Current of ANFIS

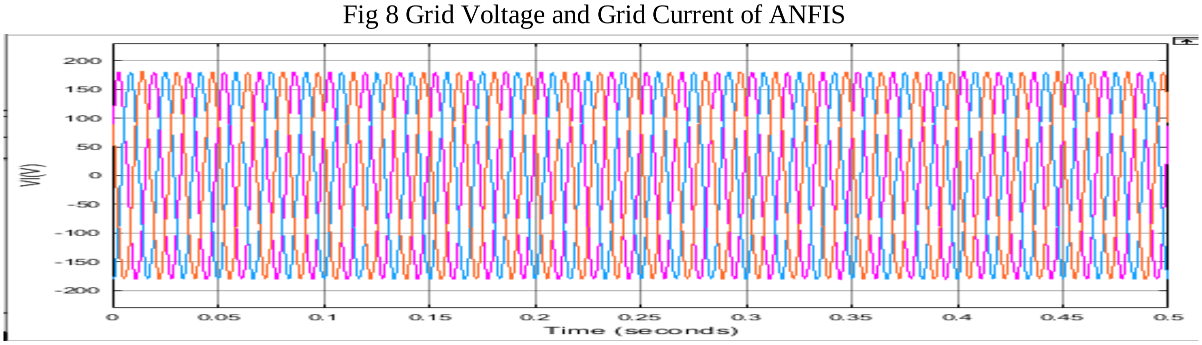

Fig 9 Load Voltage and Load Current of ANFIS

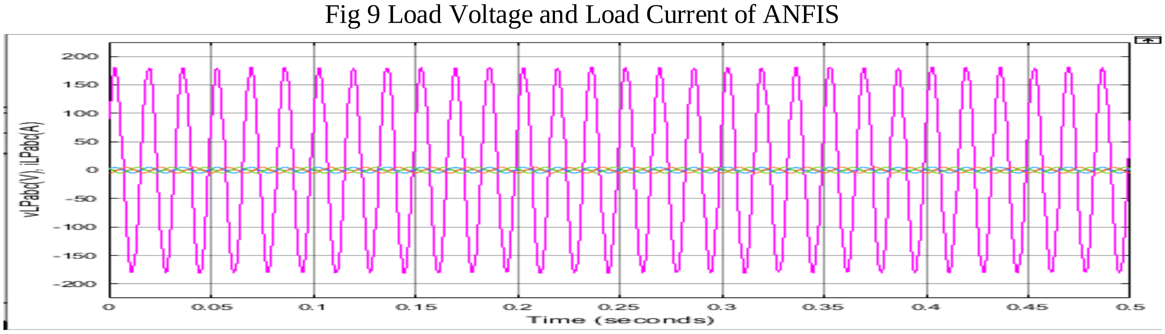

Fig 10 Parallel Voltage and Current of ANFIS

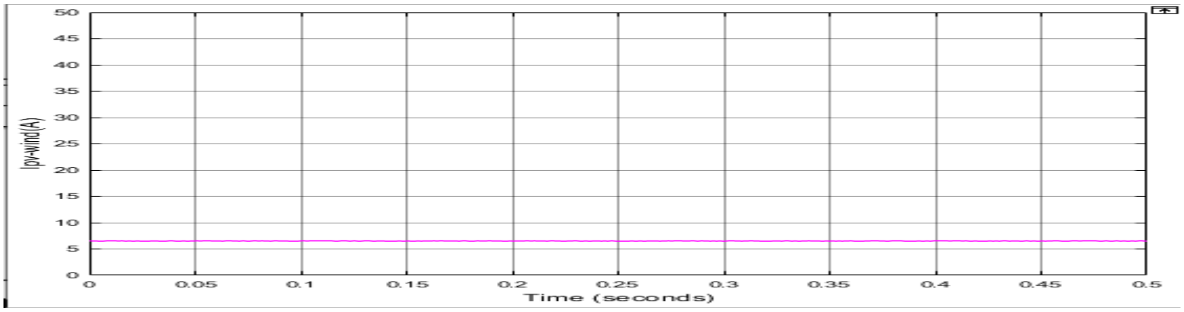

Fig 11 PV array and Wind turbine current of ANFIS

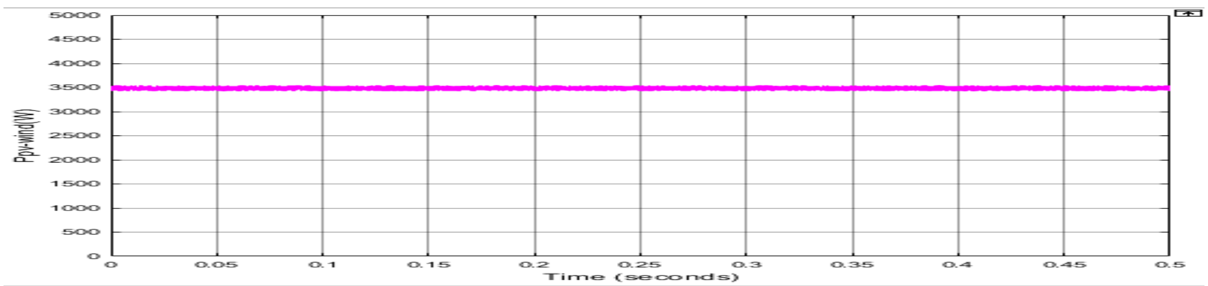

Fig 12 PV array and Wind turbine Power of ANFIS

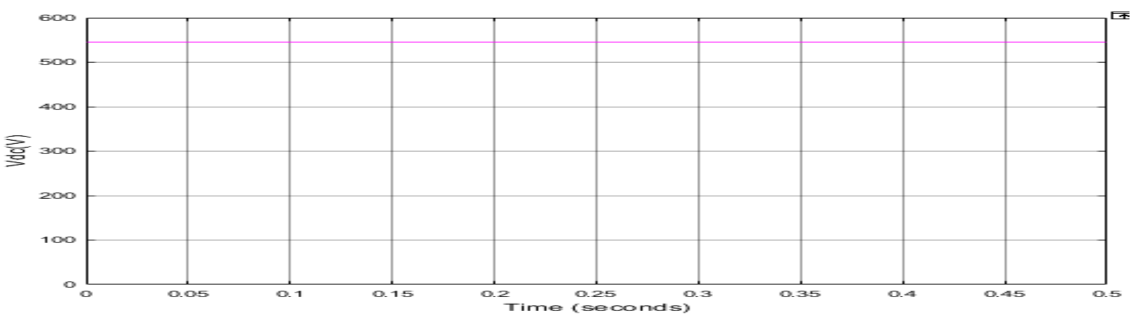

Fig 13 DC Link Voltage of ANFIS

These graphs reflect the system operation under light-load conditions where only PV and wind sources inject power into the grid. The ANFIS controller maintains voltage stability and effectively minimizes harmonic injection. The improved THD performance highlights its ability to operate efficiently even without load.

3) OPC 3: UPQC-ANFIS-RE performs active power insertion along with active filtering with Ppv wind < PL

This condition simulates a scenario where the hybrid renewable generation is insufficient to supply the full load. The grid supports the additional demand. The UPQC ensures that grid current distortion due to load and source imbalance is minimized. ANFIS helps generate a more accurate reference current for the series inverter, reducing grid current THD and improving transient response during load changes.

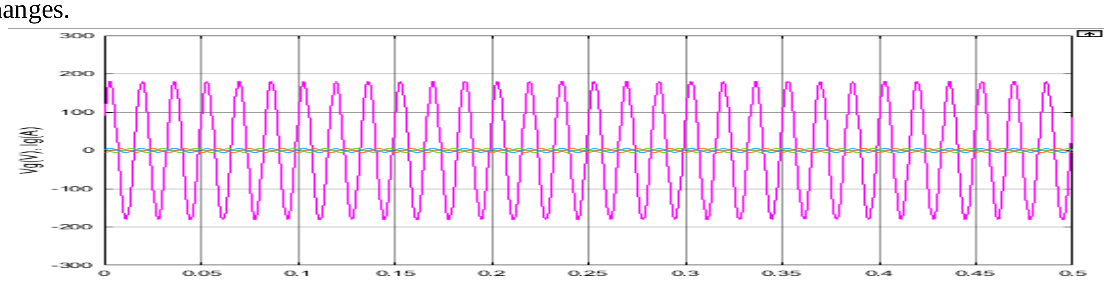

Fig 14 Grid Voltage and Grid Current of ANFIS

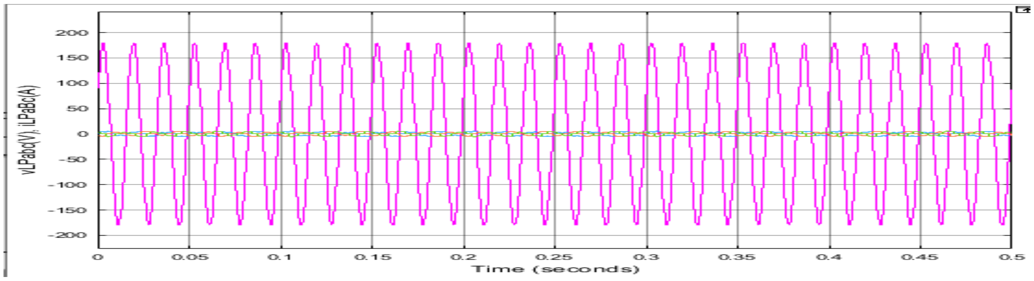

Fig 15 Load Voltage and Load Current of ANFIS

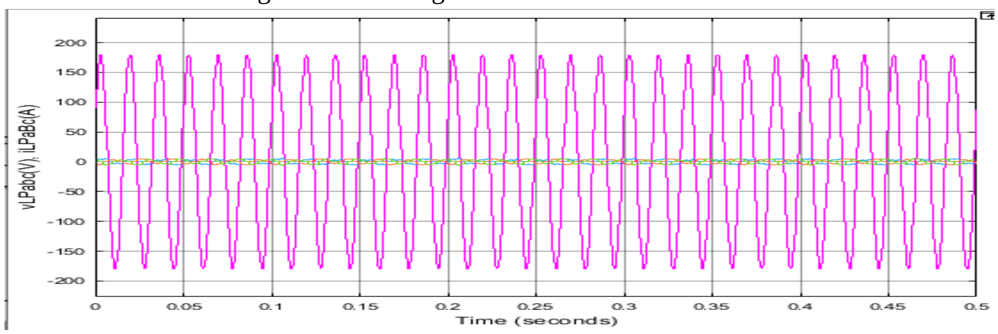

Fig 16 Parallel Voltage and Current of ANFIS

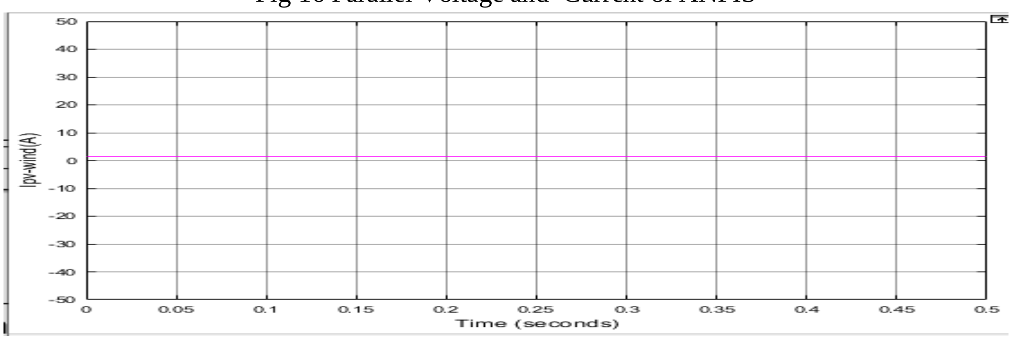

Fig 17 PV array and Wind turbine current of ANFIS

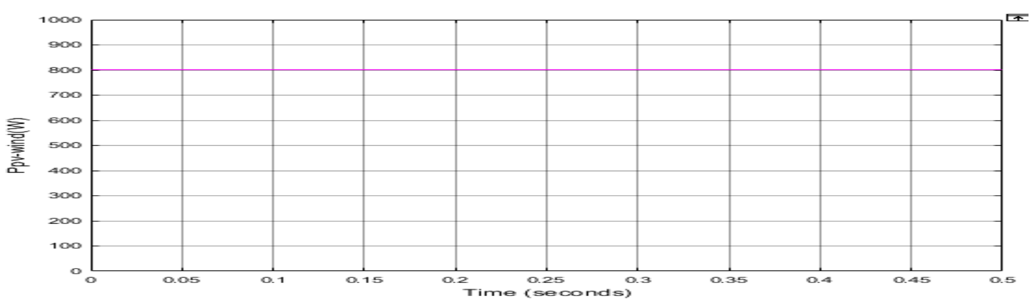

Fig 18 PV array and Wind turbine Power of ANFIS

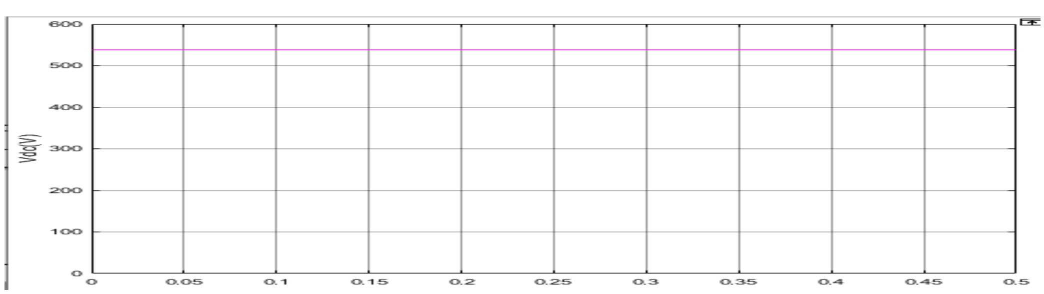

Fig 19 DC Link Voltage of ANFIS

This set of waveforms illustrates how the system behaves when the load draws more power than the PV and wind can provide. The grid supplements the deficit, and the ANFIS controller ensures a more sinusoidal current flow and reduced harmonic levels in both grid and load currents, with better dynamic tracking than ANN.

4) OPC 4: UPQC-ANFIS-RE performs active power insertion along with active filtering with Ppv-wind > PL

In this case, the renewable source produces more power than the load demand. The excess power may be fed back to the grid. The UPQC regulates voltage and prevents reverse power flow disturbances. The ANFIS-based control maintains better current waveform quality and ensures the DC-link voltage remains steady even with source-load mismatch.

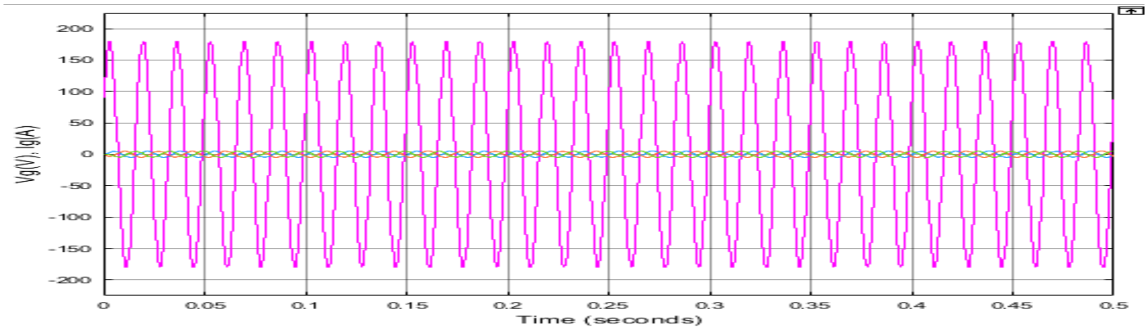

Fig 20 Grid Voltage and Grid Current of ANFIS

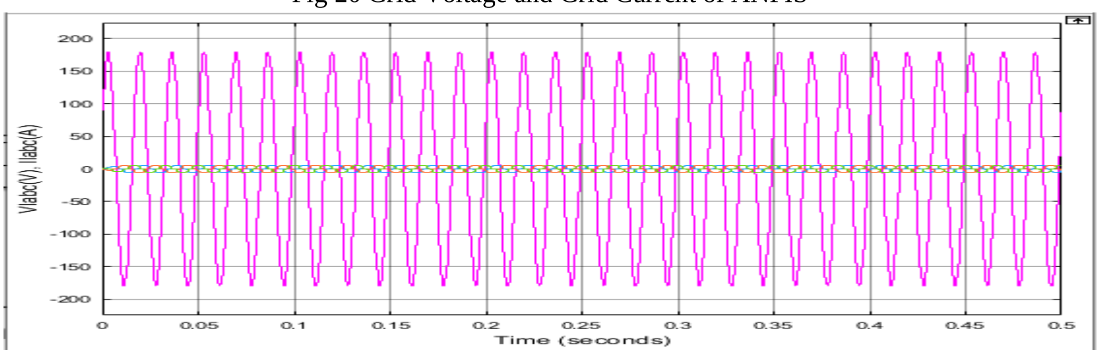

Fig 21 Load Voltage and Load Current of ANFIS

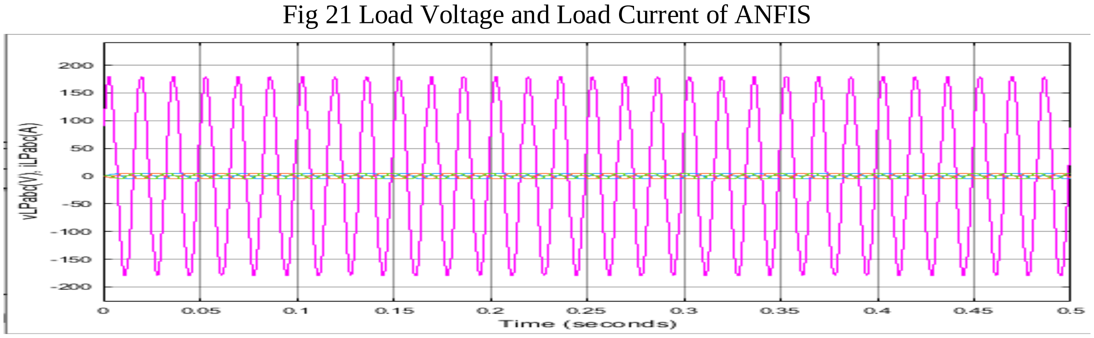

Fig 22 Parallel Voltage and Current of ANFIS

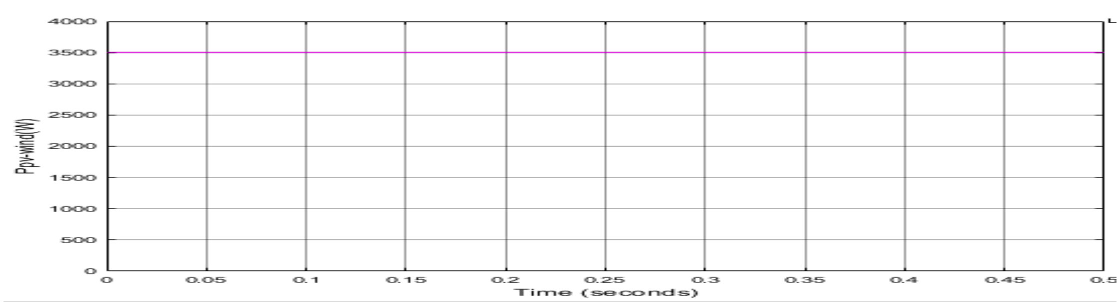

Fig 23 PV array and Wind turbine Power of ANFIS

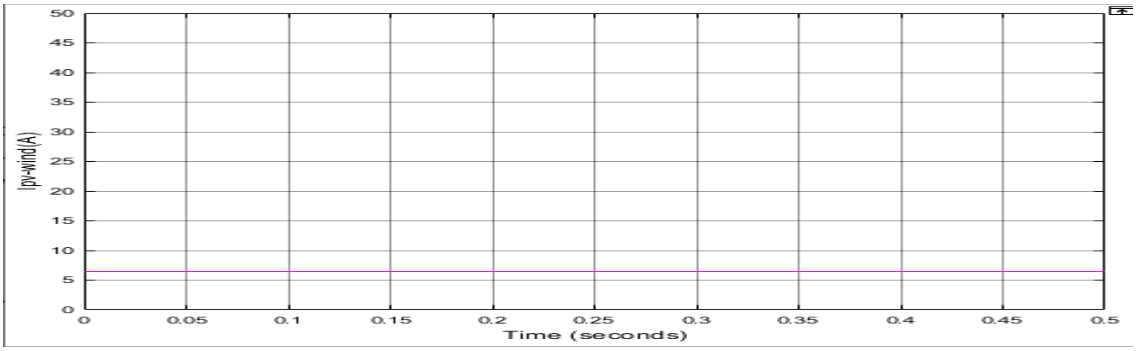

Fig 24 PV array and Wind turbine current of ANFIS

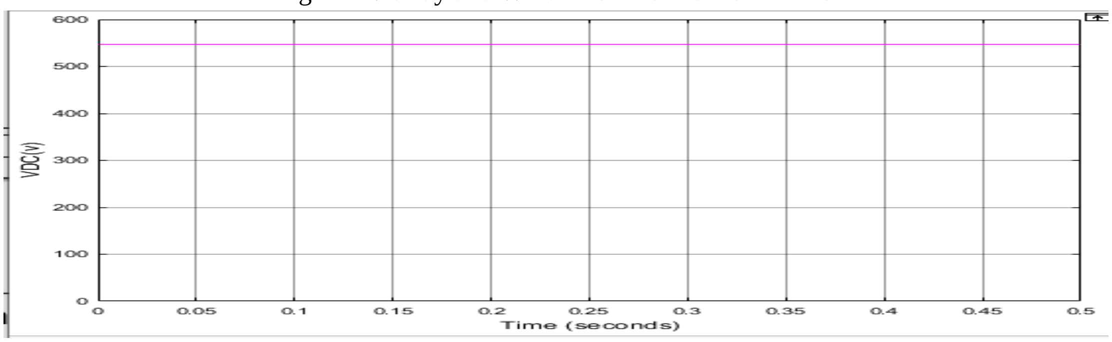

Fig 25 DC Link Voltage of ANFIS

When there is surplus power from renewables, the system feeds excess energy back to the grid. The plots show that ANFIS achieves more accurate harmonic compensation and better waveform quality in this condition. Lower THD levels confirm improved power flow and stability.

5) *OPC 5: Sudden change in solar irradiance and wind speed: UPQC-ANN-RE performs active power insertion along with active filtering with Ppv wind >PL*

This test observes the UPQC's performance when the renewable sources are suddenly turned off. ANFIS reacts faster than ANN, quickly adjusting the reference current and stabilizing the grid current with reduced overshoot.

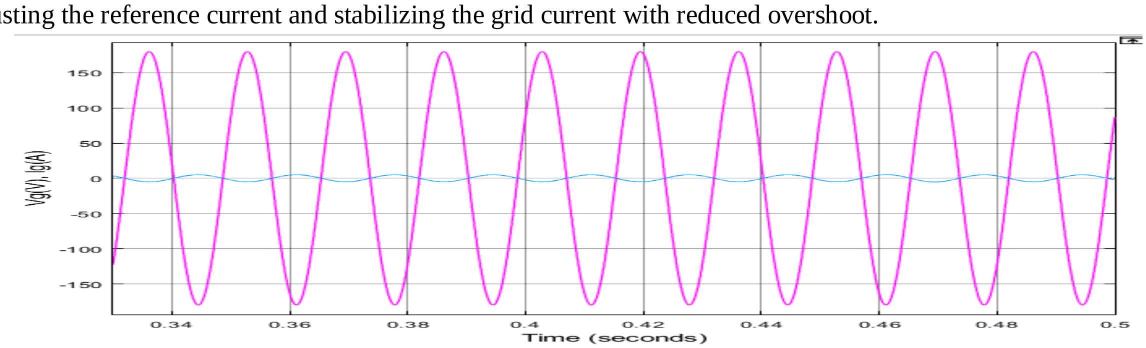

Fig 26 Grid Voltage and Grid Current of ANFIS

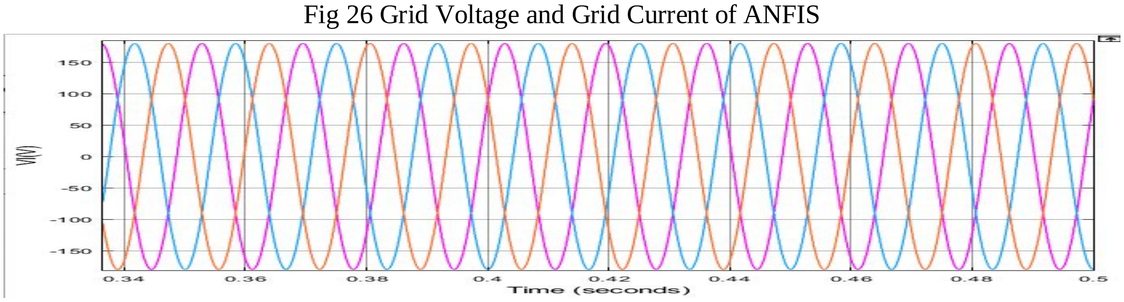

Fig 27 Load Voltage and Load Current of ANFIS

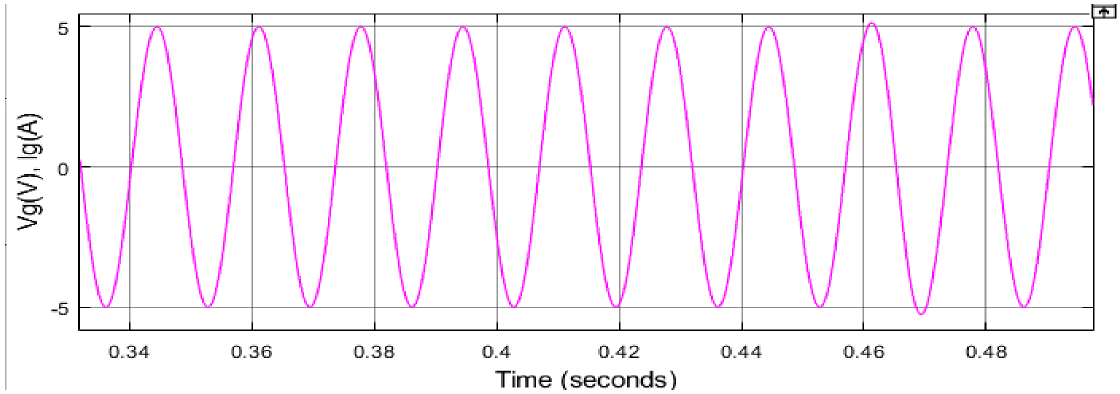

Fig 28 Grid Current of ANFIS

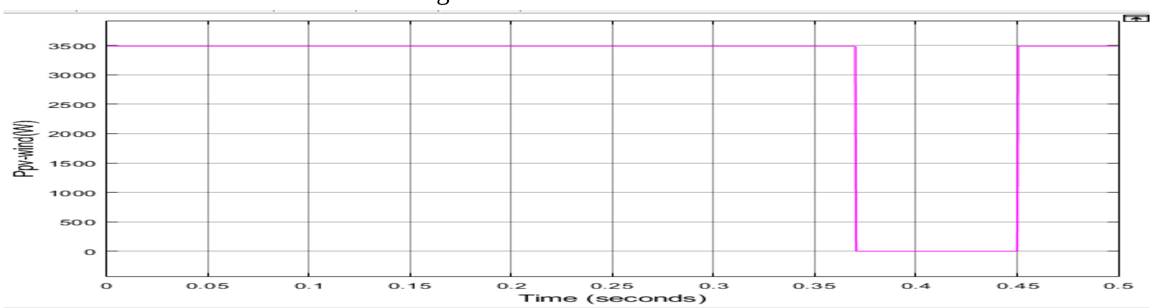

Fig 29 PV array and Wind turbine Power of ANFIS

These figures capture the transient response of the system when renewable sources are suddenly disconnected. ANFIS adapts quickly, restoring waveform balance and maintaining voltage quality. The resulting THD values remain low, proving its strength in handling abrupt disturbances.

6) *OPC 6: Sudden Load changes for OPC 4 UPQC-RE-ANN performs active power insertion along with active filtering with Ppv wind > PL*

When the load is suddenly removed, the system may face power imbalance. ANFIS shows faster damping of transient oscillations in grid and inverter currents compared to ANN, leading to a more stable post-event behaviour

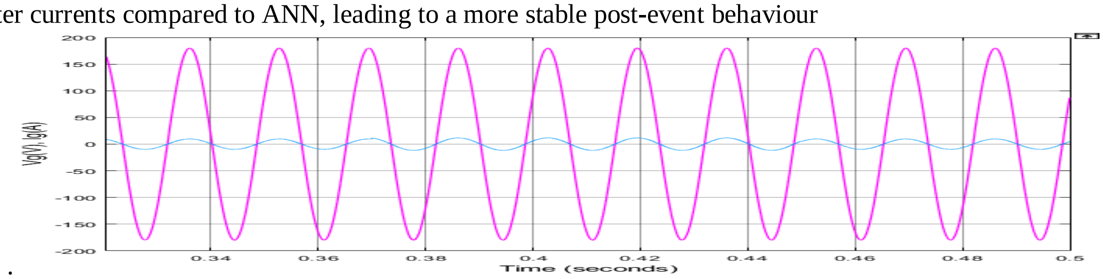

Fig 30 Grid Voltage and Grid Current of ANFIS

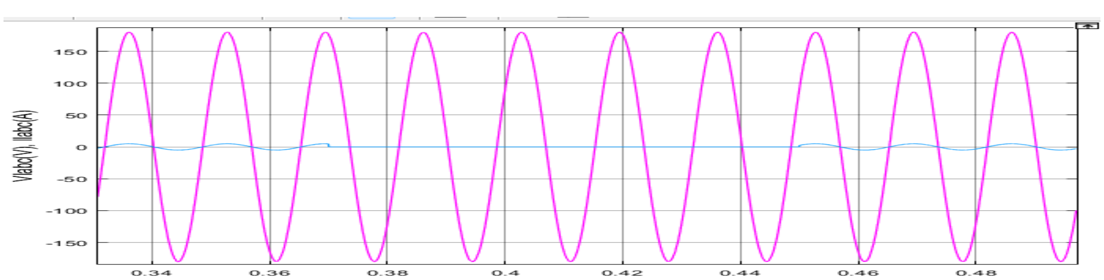

Fig 31 Load Voltage and Load Current of ANFIS

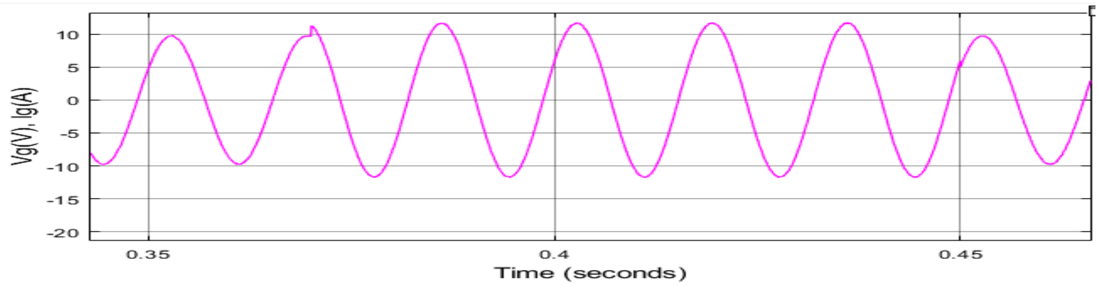

Fig 32 Grid Current of ANFIS

The graphs display the inverter and grid behavior during unexpected load disconnection. ANFIS provides quick correction, preventing overshoot and reducing oscillations. The cleaner voltage and current waveforms confirm enhanced control and power quality during sudden changes. These results confirm that the proposed ANFIS-tuned UPQC system offers a reliable, adaptive, and efficient solution for enhancing the power quality and stability of renewable energy-based distributed generation networks.

A. *THD Analysis*

Compared with ANN, the ANFIS-based control consistently achieves lower THD values in all operating cases.

	Grid Voltage		Grid Current		Load Voltage		Load Current	
	ANN	ANFIS	ANN	ANFIS	ANN	ANFIS	ANN	ANFIS
OPC 1	0.74	0.29	2.01	0.11	3.02	1.5	28.83	16.78
OPC 2	1.6	0.48	2.42	0.48	1.96	0.48	-	-
OPC 3	1.6	0.27	5.22	0.42	2.06	0.31	27.30	17.15
OPC 4	1.44	0.27	1.39	0.17	1.94	0.31	26.88	16.79
OPC 5	0.48	0.18	0.4	0.17	0.92	0.23	-	-
OPC 6	0.51	0.29	1.18	0.91	0.58	0.34	-	-

- In OPC 1, grid voltage THD improves from 0.74% to 0.29% and grid current from 2.01% to 0.11%, while load voltage drops from 3.02% to 1.5% and load current from 28.83% to 16.78%.
- In OPC 2, grid voltage reduces from 1.6% to 0.48% and grid current from 2.42% to 0.48%, with load voltage improving from 1.96% to 0.48%.
- In OPC 3, grid voltage decreases from 1.6% to 0.27% and grid current from 5.22% to 0.42%, while load voltage drops from 2.06% to 0.31% and load current from 27.30% to 17.15%.
- In OPC 4, grid voltage improves from 1.44% to 0.27% and grid current from 1.39% to 0.17%, with load voltage reducing from 1.94% to 0.31% and load current from 26.88% to 16.79%.
- In OPC 5, grid voltage decreases from 0.48% to 0.18% and grid current from 0.40% to 0.17%, while load voltage improves from 0.36% to 0.21%.
- In OPC 6, grid voltage drops from 0.51% to 0.29% and grid current from 1.18% to 0.91%, with load voltage reducing from 0.58% to 0.34%.

VI. CONCLUSION

The proposed Unified Power Quality Conditioner (UPQC) developed for a hybrid renewable energy system comprising solar PV and wind sources. A key contribution lies in replacing the conventional Artificial Neural Network (ANN) used in the series controller with an Adaptive Neuro-Fuzzy Inference System (ANFIS), aiming to enhance the system's dynamic response and power quality performance. Simulation results under six different operating power conditions—including varying load profiles, generation states, and transient disturbances—demonstrate that the ANFIS-based controller consistently achieves better harmonic mitigation compared to the ANN-based approach. Improvements in Total Harmonic Distortion (THD) were observed across grid voltage, grid current, load voltage, and load current waveforms. The enhanced control strategy ensures smoother voltage regulation, stable current flow, and greater resilience under dynamic conditions. Overall, the proposed ANFIS-enhanced UPQC provides a reliable and effective solution for maintaining power quality in distributed generation systems integrated with renewable energy sources.

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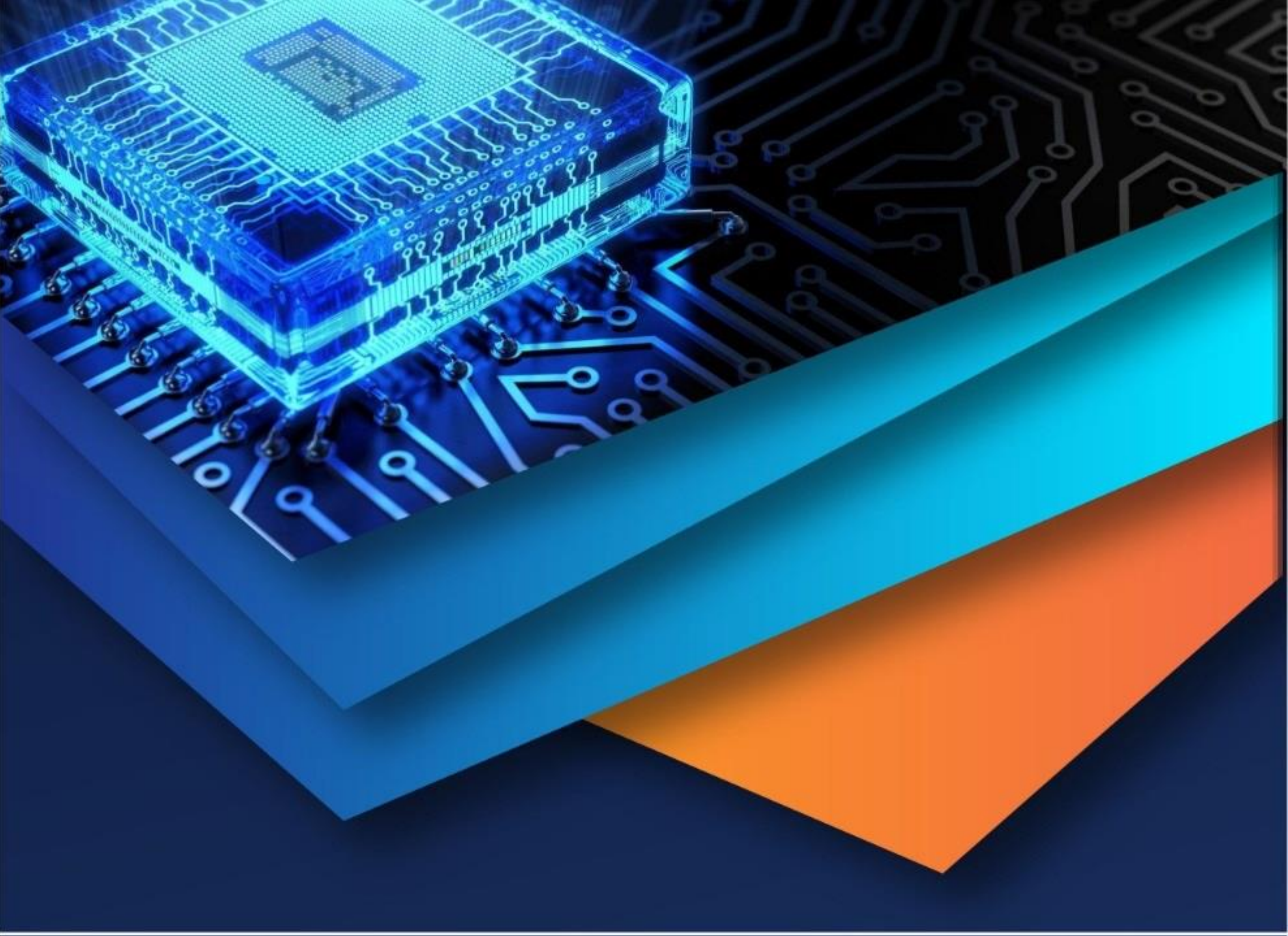

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