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INTELLIGENT POWER CONDITIONING IN RENEWABLE ENERGY MICROGRIDS USING ANFIS-BASED UPQC

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ABSTRACT: Renewable Energy Based integral part of modern power networks, but their intermittent and nonlinear characteristics Distributed Generation (DG) systems have become an often lead to significant power quality (PQ) issues such as voltage sag/swell, harmonic distortion, and unbalanced loading. In respose to these limitations, this paper presents an ANFIS-tuned Unified Power Quality Conditioner (UPQC) for enhanced PQ management in DG-integrated distribution systems. The suggestedcontrol approach employs an Adaptive Neuro-Fuzzy Inference System (ANFIS) to optimally tune the UPQC's series and shunt controllers, enabling fast dynamic response, improved harmonic compensation, and adaptive voltage regulation under varying operating conditions. The ANFIS model learns from system disturbances and continuously updates control parameters to ensure robust compensation performance even during rapid renewable generation fluctuations. The Results are validated through MATLAB/Simulink under multiple scenarios, including PV and wind-based DG variations, nonlinear loads, and grid disturbances. Results demonstrate that the ANFIS-tuned UPQC significantly reduces total harmonic distortion (THD), stabilizes terminal voltage, mitigates sag/swell events, and improves overall PQ compared to conventional PI and fuzzy controllers. The proposed system enhances reliability, power stability, and power quality of renewable-integrated distribution networks, making it suitable for smart-grid and microgrid applications.

Keywords: Adaptive Neuro-Fuzzy Inference System (ANFIS), Unified Power Quality Conditioner (UPQC), DC-Link Voltage Control, Smart Grid, Solar PV and Wind Energy, Total Harmonic Distortion (THD)

1. INTRODUCTION

The integration of renewable energy sources such as solar PV and wind into distribution networks has grown rapidly due to environmental concerns and the shift toward sustainable energy systems. Distributed generation (DG) enhances grid flexibility and reduces transmission losses, but its intermittent nature introduces significant power quality (PQ) issues. Variations in solar irradiance and wind speed lead to voltage fluctuations, frequency deviations, and power imbalance. Additionally, nonlinear loads generate harmonics, resulting in increased total harmonic distortion (THD), poor power factor, and reduced system performance.

To address these challenges, the Unified Power Quality Conditioner (UPQC) is widely used to mitigate both voltage and current disturbances. However, conventional controllers like PI and fuzzy logic have limitations such as slow response and poor adaptability under dynamic conditions. This work proposes an ANFIS-based UPQC controller, which combines neural network learning with fuzzy logic for adaptive control. The proposed system effectively improves harmonic reduction, voltage regulation, DC-link stability, and overall disturbance mitigation, ensuring better performance compared to traditional methods.

2. LITERATURE REVIEW

Numerous studies have contributed to PQ improvement in renewable energy–integrated systems. Studies focusing on PV and wind DG systems highlight the challenge of voltage instability and harmonic injection due to source intermittency. Conventional UPQC structures with PI and fuzzycontrol controllers have extensively reported, but their lack of adaptability limits their performance under dynamic conditions. Recent works emphasize intelligent controllers such as artificial neural networks (ANN), model predictive control (MPC), sliding mode control (SMC), and bio-inspired optimization–based designs. These methods enhance dynamic performance but often require complex tuning or suffer from increased computational burden.

ANFIS-based controllers have demonstrated potential in handling nonlinearities and uncertainties while offering fast adaptation. Despite this ,limitedresearch have done on ANFIS-tuned UPQC specifically for renewable energy–based DG systems. This study tackles this identified gap this gap by presenting a detailed analysis of ANFIS-UPQC performance and benchmarking it against conventional techniques.

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3. SYSTEM MODELING

A. Renewable Energy Based Distributed Generation System

The DG model consists of solar PV and wind energy conversion systems connected through voltage source inverters. Maximum Power Point Tracking (MPPT) using Perturb and Observe (P&O) for PV and Tip-Speed Ratio (TSR) control for wind ensure optimal power extraction.

B. Nonlinear Load Modelling

A three-phase diode rectifier with RL load is included to introduce harmonics into the system, providing realistic PQ disturbance scenarios.

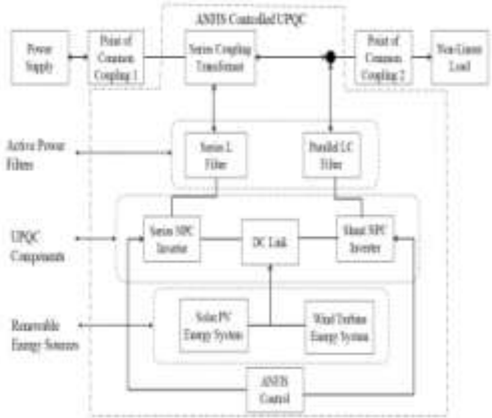


Fig 1. Block diagram of proposed system

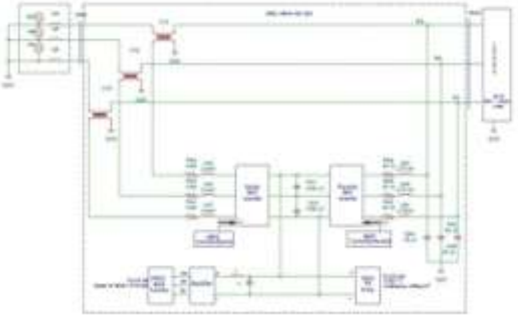


Fig 2. Circuit diagram of RES based ANFIStrained UPQC

4. MATHEMATICAL MODELING

A. Solar Photovoltaic (PV) Model

The single-diode model represents PV dynamics and is expressed as:

$$I_{PV} = I_{ph} - I_0\left(e^{\frac{V_{PV}+I_{PV}R_s}{aV_T}} - 1\right) - \frac{V_{PV} + I_{PV}R_s}{R_{sh}}$$

The output PV power is:

$$P_{PV} = V_{PV}I_{PV}$$

B. Wind Energy Conversion System (WECS) Model

Mechanical power:

$$P_m = \frac{1}{2}\rho A C_p(\lambda,\beta)v^3$$

Torque:

$$T_m = \frac{P_m}{\omega_t}$$

C. Nonlinear Load Model

$$I_L(t) = I_1\sin(\omega t) + \sum_{n=3,5,7,\dots} I_n \sin(n\omega t + \theta_n)$$

D. SAPF Dynamics

$$L_s\frac{di_s}{dt} = V_s - V_{inj} - R_s i_s$$

E. SHAPF Dynamics

$$L_f\frac{di_f}{dt} = V_{inv} - V_L - R_f i_f$$

F. DC-Link Voltage Model

$$C_{dc}\frac{dV_{dc}}{dt}=I_{sh}-I_{se}$$

UNIFIED POWER QUALITY CONDITIONER (UPQC)

The UPQC comprises:

- Series Active Power Filter (SAPF) for voltage compensation.
- Shunt Active Power Filter (SHAPF) for harmonic mitigation and reactive power support.
- A shared DC-link capacitor.

The device is installed between the distribution feeder and sensitive loads to regulate both voltage and current quality simultaneously.

ANFIS-TUNED CONTROL SSTRATEGY

A. ANFIS Structure

A Sugeno-type ANFIS framework employing hybrid learning (gradient descent + least squares) is used. Inputs include the error (e) and change in error (Δe) of the reference voltage or current.

B. Controller Functions

- Shunt Controller: Generates reference compensation currents.
- Series Controller: Produces reference injection voltages.
- Real-time parameter tuning improves robustness under DG variability.

C. Training Data Generation

The Data used for training are gathered from simulations under:

- Voltage sag/swell events.
- DG variability.
- Harmonic distortion from nonlinear loads.

ANFIS-TUNED CONTROL STRATEGY — Control Strategy Modelling

A. Control Objectives

The control aims to:

1. Compensate load current harmonics (shunt compensation).
2. Mitigate voltage sag/swell and deliver a clean sinusoidal load voltage (series compensation).
3. Maintain DC-link voltage at a reference V_{dc}^{ref} .
4. Ensure stable active/reactive power sharing between DG and grid.

B. Signal Transformations

Use Clarke and Park transforms for control design.

Clarke (abc → $\alpha\beta$)

$$\begin{bmatrix}x_\alpha\\x_\beta\end{bmatrix}=\frac{2}{3}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}x_a\\x_b\\x_c\end{bmatrix}$$

Park ($\alpha\beta$ → dq)

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix}$$

where $\theta$is from the PLL.

C. Shunt Controller Modelling (Current Compensation)

Reference current (instantaneous p–q):

$$\begin{bmatrix} i_\alpha^{ref} \\ i_\beta^{ref} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} P_{load} - P^* \\ Q^{ref} \end{bmatrix}$$

P^*= active power to be supplied by DG/grid; Q^{ref} usually 0 for unity PF.

Inner current controller (dq frame PI): Transform measured currents to i_d, i_q. Errors:

$$e_d = i_d^{ref} - i_d, e_q = i_q^{ref} - i_q$$

PI outputs in dq:

$$v_d^* = K_{p_d} e_d + K_{i_d} \int e_d \, dt + v_d^{ff}$$
$$v_q^* = K_{p_q} e_q + K_{i_q} \int e_q \, dt + v_q^{ff}$$

where $v_{d,q}^{ff}$are feedforward decoupling terms (e.g., $\omega L i_q, \ -\omega L i_d$).

ANFIS role: ANFIS maps $(e, \Delta e) \rightarrow \left(K_p, K_i\right)$in real time:

$$[\, K_p, K_i \,] = \mathscr{F}_{ANFIS}(e, \Delta e)$$

so gains adapt to disturbances. Inverse Park/Clarke transform converts $v_d^*, v_q^*$to PWM gating.

D. Series Controller Modelling (Voltage Compensation)

Voltage reference / injection:

$$v_{inj,\alpha\beta}^{ref} = v_{s,\alpha\beta}^{ref} - v_{L,\alpha\beta}$$

Convert to dq and compute errors:

$$e_{vd} = v_d^{ref} - v_d, e_{vq} = v_q^{ref} - v_q$$

Series PI control (ANFIS-tuned):

$$v_{sd}^* = K_{p_{sd}} e_{vd} + K_{i_{sd}} \int e_{vd} \, dt$$
$$v_{sq}^* = K_{p_{sq}} e_{vq} + K_{i_{sq}} \int e_{vq} \, dt$$

ANFIS provides adaptive $K_p, K_i$for series loop. Transform back to abc and apply via PWM.

E. DC-Link Voltage Control

DC error:

$$e_{dc} = V_{dc}^{ref} - V_{dc}$$

PI controller provides shunt power reference:

$$P_{sh}^{ref} = K_{p_{dc}} e_{dc} + K_{i_{dc}} \int e_{dc}\, dt$$

ANFIS adaptively tunes $K_{p_{dc}}, K_{i_{dc}}$ from $(e_{dc}, \Delta e_{dc})$. DC dynamics:

$$C_{dc} \frac{dV_{dc}}{dt} = I_{sh} - I_{se} - \frac{V_{dc}}{R_{loss}}$$

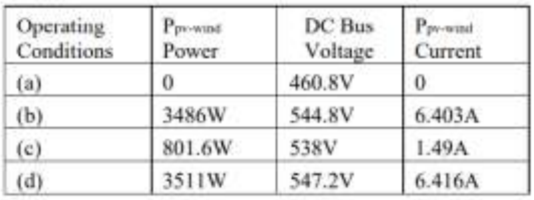
(R_{loss} models leakage/converter losses).

F. ANFIS Architecture & Learning

- Inputs: error $e$and change-in-error Δe.
- MFs: Gaussian/bell (3–5 per input).
- Consequent: linear/singleton gives gain value.
- Training: hybrid (least squares for consequents + gradient descent for premises).
- Online adaptation: incremental updates at each control cycle (ensure inference time << sampling period)

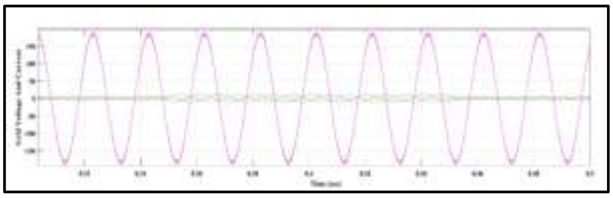
5. SIMULATION RESULTS

The below are results of proposed system and table shows different operating conditions.



Operating Conditions	$P_{pv\text{-}wind}$ Power	DC Bus Voltage	$P_{pv\text{-}wind}$ Current
(a)	0	460.8V	0
(b)	3486W	544.8V	6.403A
(c)	801.6W	538V	1.49A
(d)	3511W	547.2V	6.416A

Table 1. Table of operational Power



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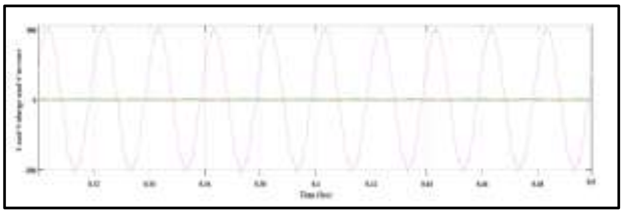

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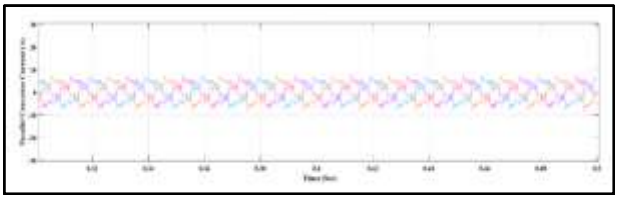

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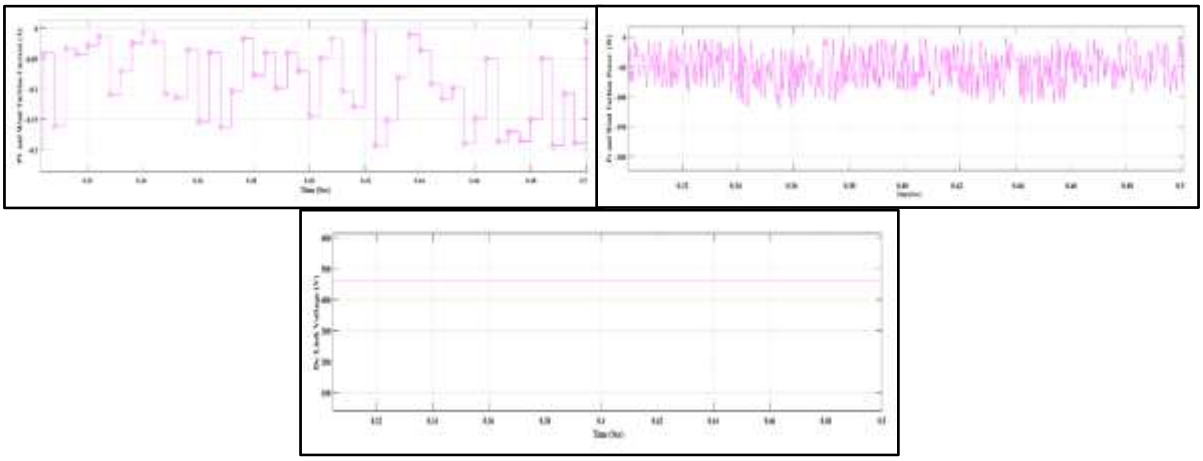
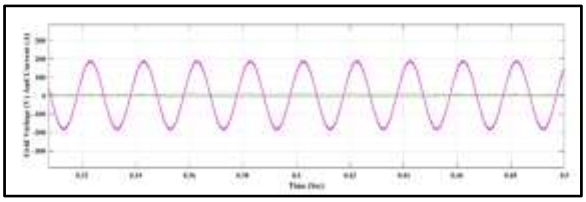


(d)

FIGURE 3 . Operating condition (OPC)1: UPQC-ANFIS providing active/real powercompensation withPpv−wind = 0 W i,e. no PV and Wind and Vs < VL (a) Grid Voltage and current ; (b) LoadVoltage and current ; (c) Parallel NPC Invertercurrents; (d) Current of PV array and Wind turbine , Power and DC link voltage profiles.



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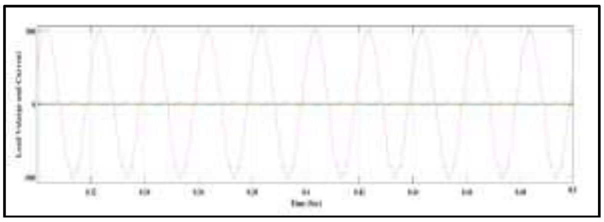

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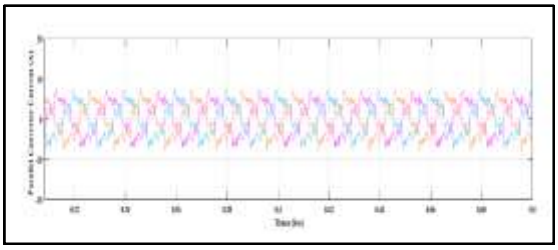

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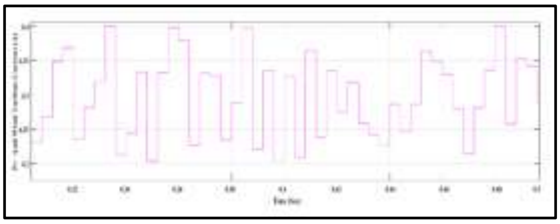
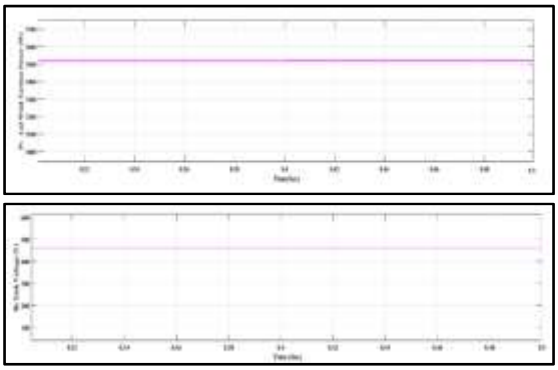
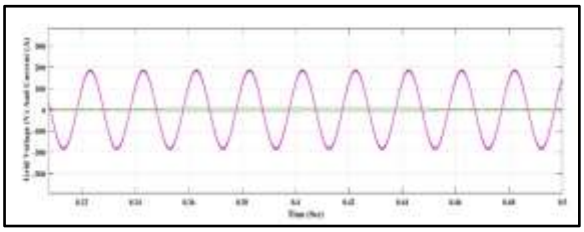




(d)

FIGURE 4. Operating condition (OPC)2:UPQC with ANFIS based RESprovide active power insertion into the grid with Zero load power i.e, $P_L = 0$Wand PV -Wind generation$P_{pv-wind} = 3500$ W: (a) Grid Voltage and current ; (b)Load Voltage and current ; (c) Parallel NPC Invertercurrents; (d) PV array and Wind turbine current, Power and DC link voltage responses.



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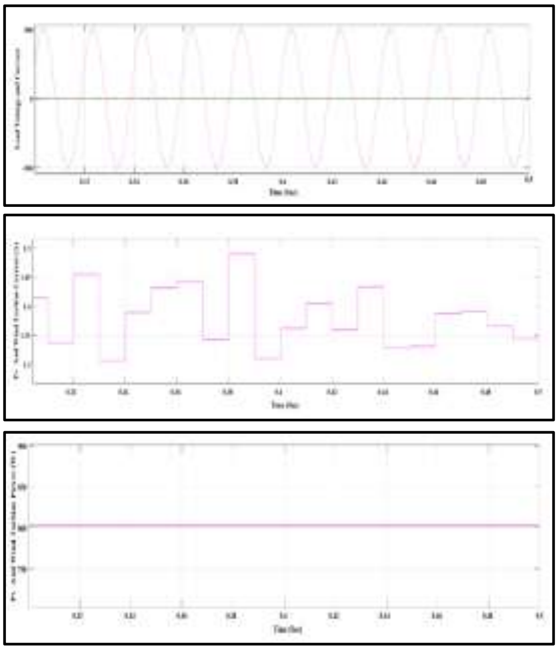

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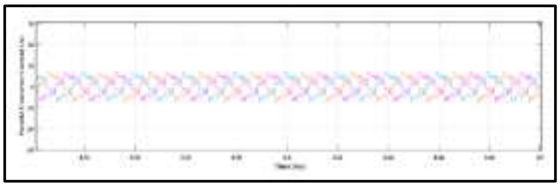
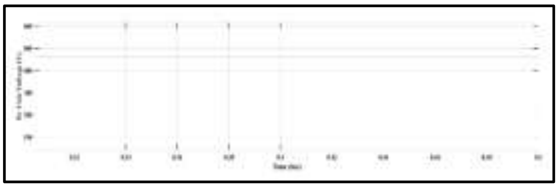
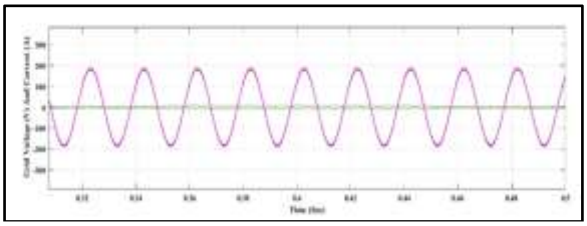




(d)

(c)

FIGURE 5 .Operating condition(OPC)-3UPQC with ANFIS based RES performs active power injection into gridcombined with active filtering,with PV-Wind generation less than load demand i.e,Ppv−wind < PL: (a) Grid Voltage and current ; (b)Load Voltage and current ; (c) Load Voltage and Parallel NPC Inverter currents; (d) PV array and Wind turbine current, Power andDC link voltage waveforms.



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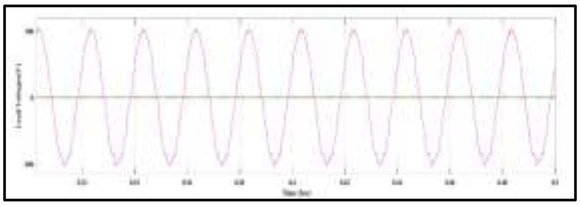

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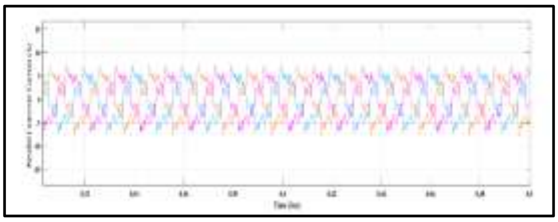

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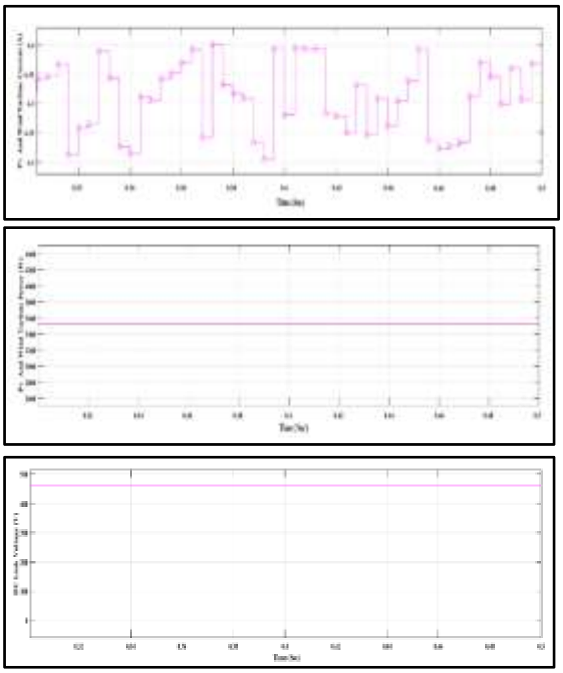
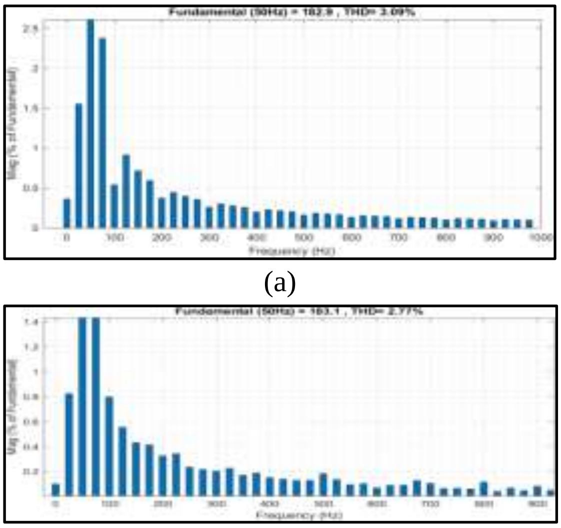


(d)

FIGURE 6 . Operating condition(OPC)-4: UPQC with ANFIS based RES provides active power injection combined with active filtering, with PV-Wind generation exceeding load demand i.e, Ppv−wind > PL: (a)

Grid Voltage and current; (b)Load Voltage and current ; (c) Load Voltage and Parallel NPC Inverter currents; (d) PV array and Wind turbine current, Power and DC link voltages waveforms

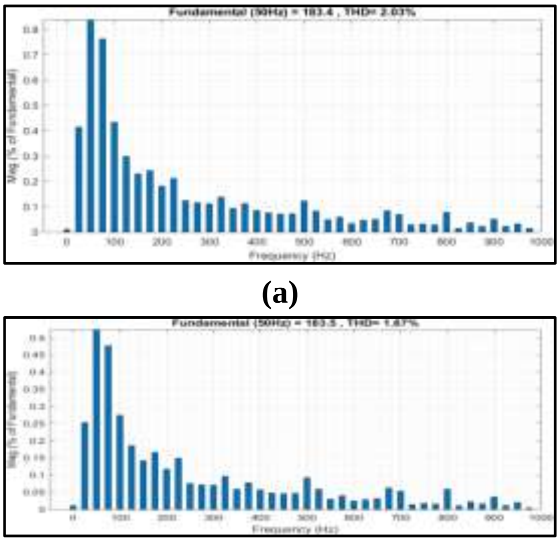
THDanalysis :



(a)

(b)

FIGURE8.THD(%) of (a) Load Voltage is 3.09% and (b) Grid Voltage is 2.77% in ANN tuned UPQC



(a)

(b)

FIGURE 9 .THD(%) of (a) Load Voltage is 2.03% and (b) Grid Voltage is 1.67% in ANFIS tuned UPQC

6. CONCLUSION

The proposed ANFIS controller effectively combines the learning capability of neural networks with the linguistic reasoning of fuzzy systems, enabling real-time adaptation to varying operating conditions.

The Outcomes from Simulation confirm that the ANFIS-based UPQC outperforms conventional PI- and fuzzy-controlled UPQC structures. The proposed system provides faster dynamic response, superior harmonic compensation, improved DC-link voltage regulation, and enhanced mitigation of voltage dips and overvoltage events. It ensures stable operation during rapid fluctuations in PV irradiance and wind speed, regulating load voltage within permissible limits and achieving THD levels compliant with IEEE-519 standards.

Overall, the ANFIS-tuned UPQC significantly strengthens the reliability, Quality Power, and resilience of renewable energy–supported distribution systems. The methodology is highly suitable for smart grids, microgrids, and future decentralized energy frameworks where adaptive and intelligent control is essential. Future work may explore hardware implementation, real-time control using DSP/FPGA platforms, and optimization-based ANFIS tuning for further performance improvement.

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