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ANFIS-BASED CONTROL STRATEGY FOR UPQC IN RENEWABLE ENERGY DISTRIBUTED GENERATION SYSTEMS

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Abstract: This research investigates the enhancement of power quality in renewable energy-based Distributed Generation (DG) systems by implementing a Unified Power Quality Conditioner (UPQC) regulated by an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. The proposed system is designed to improve voltage stability and overall power quality within distribution networks, especially those incorporating renewable energy sources. The performance of the ANFIS-tuned UPQC is compared against traditional systems without this configuration and other existing control strategies. Both simulation and experimental results reveal that the ANFIS-tuned UPQC significantly outperforms alternative methods, particularly in maintaining stability during grid faults and load disturbances. This research highlights the potential of the proposed system as a robust solution for integrating renewable energy into the power grid.

Index Terms: Distributed Generation (DG), Renewable Energy Sources (RES), Unified Power Quality Conditioner (UPQC), Adaptive Neuro-Fuzzy Inference System (ANFIS), Power Quality.

I. INTRODUCTION

The rapid integration of renewable energy sources (RES) into electrical grids presents both opportunities and challenges. On one hand, RES such as wind and solar photovoltaic (PV) systems offer clean and sustainable alternatives to traditional fossil fuels, reducing the carbon footprint and promoting environmental sustainability. On the other hand, the inherently intermittent and variable nature of these energy sources introduces significant power quality issues, particularly in the form of voltage sags, swells, harmonics, and other disturbances. These challenges are exacerbated in modern power systems, where maintaining a stable and reliable supply of electricity is crucial for both industrial and residential consumers. As the penetration of renewable energy increases, so does the need for advanced power quality management systems that can dynamically adapt to the fluctuations in power generation and load demands. Traditional power quality improvement devices, such as the Unified

Power Quality Conditioner (UPQC), have been employed to address these issues by providing simultaneous compensation for voltage and current disturbances. The UPQC achieves this by integrating series and shunt active power filters, which work together to mitigate both supply-side and load-side power quality problems. However, conventional UPQC systems face limitations when applied in environments with high levels of RES integration. These limitations stem from the static nature of traditional control strategies, which are not well-suited to handle the rapid and unpredictable changes associated with renewable energy generation. To overcome these challenges, there is a growing interest in integrating intelligent control systems with UPQC to enhance its adaptability and performance in dynamic grid conditions. In response to these challenges, this study proposes an advanced UPQC system enhanced with an Adaptive Neuro-Fuzzy Inference System (ANFIS) and supported by renewable energy sources. The proposed system, referred to as the UPQC-ANFIS-RE system, is designed to address the unique power quality issues associated with renewable energy integration while providing a robust and adaptive solution for modern power grids. The UPQC-ANFIS-RE system combines several key components: series and parallel Neutral Point Clamped (NPC) inverters, a series L filter, a parallel LC filter, and a DC-Link. These components are configured to work in harmony, ensuring that voltage and current disturbances are effectively mitigated. The series NPC inverter is responsible for compensating voltage sags and swells, while the parallel NPC inverter addresses harmonic distortions and reactive power compensation. The L and LC filters further enhance the system's ability to filter out unwanted harmonics and smooth out voltage fluctuations. At the core of the system is the ANFIS-based control mechanism, which provides the intelligence required to adapt to the constantly changing grid conditions. ANFIS, a hybrid system that combines the learning capabilities of neural networks with the fuzzy logic inference system, is particularly well-suited for this application. It allows the UPQC to dynamically adjust its operation in real-time, optimizing performance based on the current state of the grid and the characteristics of the connected renewable energy sources. The Integration of renewable energy sources into the UPQC system introduces additional complexity but also offers significant benefits. By incorporating wind and solar PV systems, the UPQC-ANFIS-RE system not only improves power quality but also contributes to the overall efficiency and sustainability of the grid. The renewable energy sources are connected through a DC-Link, which acts as a common interface between the inverters and the energy generation units. This setup enables the UPQC to utilize the available renewable energy to support its power quality compensation functions, further reducing the reliance on conventional energy sources. In this study, explore the implementation, and performance evaluation of the proposed UPQC-ANFIS-RE system. The system's architecture and operation are analyzed in detail, highlighting the interactions between the different components and the role of the ANFIS controller in ensuring optimal performance. Simulation results are presented to demonstrate the effectiveness of the system in various scenarios, including the presence of non-linear loads and the integration of renewable energy sources. Through this research, the aim to demonstrate that the UPQC-ANFIS-RE system represents a significant advancement in power quality management for modern electrical grids. Its ability to adapt to the dynamic conditions associated with renewable energy integration makes it a promising solution for the challenges facing today's power systems. The insights gained from this study will contribute to the ongoing development of intelligent power quality systems and support the broader transition towards more resilient and sustainable energy infrastructures.

II. LITERATURE REVIEW

[1] M. M. Rahman, M. Shakeri, S. K. Tiong, F. Khatun, N. Amin, J. Pasupuleti, and M. K. Hasan,(2021) proposes a comprehensive review of machine learning (ML) based approaches, especially artificial neural networks (ANNs) in time series data prediction problems. According to literature, around 80% of the world's total energy demand is supplied either through fuel-based sources such as oil, gas, and coal or through nuclear-based sources.[2] N. Gupta and K. Seethalekshmi (2021)propose a new control scheme for UPQC in a grid with DG to reduce voltage issues and THD. They use SWT for PQ event detection, enhancing resolution. The study combines UPQC with ANN and SWT for better control. MATLAB simulations show that the ANN with SWT-based controller outperforms the ANN-based controller in accuracy and THD reduction. Performance analysis compares both controllers under different disturbances in time and frequency domains.[3]P. Ray, P. K. Ray, and S. K. Dash (2022) explore "Power quality enhancement and power flow analysis of a PV integrated UPQC system in a distribution network." The study investigates the integration of a Unified Power Quality Conditioner (UPQC) with photovoltaic (PV) systems to improve power quality in distribution networks. The authors analyze the system's ability to mitigate power quality issues such as voltage sags, swells, and harmonics while optimizing power flow.[4] A. Amirullah et al. (2019), titled "MATLAB/Simulink simulation of unified power quality conditioner-battery energy storage system supplied by PV-wind hybrid using fuzzy logic controller," the authors investigate a system that integrates a UPQC with battery energy storage, powered by a hybrid PV-wind source.[5]T. Lei et al. (2022) analyze a grid-connected system combining wind and PV energy with a Unified Power Quality Conditioner (UPQC). The study highlights the benefits of hybrid systems in enhancing reliability and efficiency. UPQC effectively mitigates power quality issues like voltage fluctuations and harmonics.[6] M. A. S. Masoum et al. (2021) evaluated the performance of ANFIS controllers against traditional PI controllers in UPQC applications with wind turbine generators. The results indicated superior performance of ANFIS in terms of response time, accuracy, and adaptability to changing wind conditions.[7] N. Zanib et al. The research delves into enhancing power quality in a hybrid distributed generation system by employing a unified power quality conditioner (UPQC). This research, published in May 2022 in the Computational Modeling in Engineering and Sciences journal, focuses on analyzing and improving power quality within such a system.[8]A. Amirullah, O. Penang sang, and A. Soeprijanto, published in 2019, use MATLAB/Simulink to simulate a UPQC with a battery energy storage system powered by a PV-wind hybrid. They employ a fuzzy logic controller for system management, focusing on power quality improvement in renewable energy setups.

Modeling Complexity of ANFIS modeling and the need for extensive training data pose challenges in real-world applications. Computational Requirements ANFIS controllers may require significant computational resources, especially for real-time implementation. Integration with Advanced grid technologies future research directions include integrating ANFIS controllers with advanced grid technologies such as microgrids and smart grids to enhance overall grid resilience and reliability. The integration of ANFIS controllers with UPQC systems in combination with RES-based distributed generation represents a promising approach for improving power quality and grid stability. Continued research and development efforts are essential to address challenges related to modeling complexity, computational requirements, and real-time implementation, thereby unlocking the full potential of these integrated systems in future smart grid applications.

III . METHODOLOGY

1. System Modeling

The RE source based DGs are coupled to the 3P4W distribution system with a frequency of 220 volts (L-L) and 60 Hz via ANN-based UPQC. The assembly is divided into three portions.

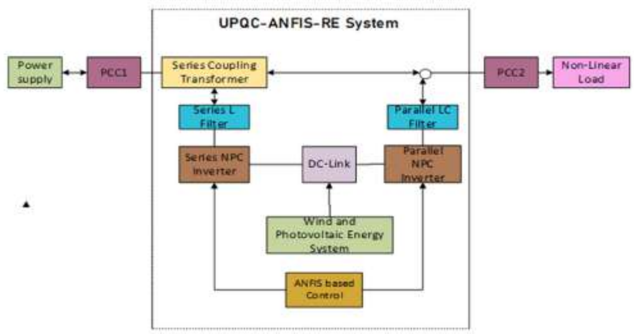


Fig.1. (a) Block Diagram of proposed system

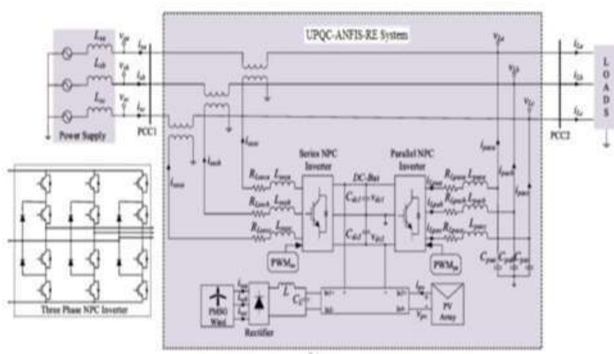


Fig. 1. (b) Circuit diagram of proposed system

The first consists of the DGS based on single stage photovoltaic and wind turbines. The second consists of the NPC series inverter and the passive elements ($L_{filter}(L_{sec\_abc})$) and series coupling transformer. Lastly, the third portion consists of a parallel NPC inverter and filter elements (LC filters (L_{pac_abc} and C_{pa_abc})) As may be seen, DGsbasedonPV-windandNPCinverterssharetheidenticalDClink. Meanwhile the split arrangement of capacitor is utilized, its midpoint of the DC bus must be attached to the neutral conductor which makes local 3P4W system. The system includes a photovoltaic network with twenty modules in series and a wind turbine generator connected to a UPQC via a rectifier. The MPPT algorithm is crucial for maximizing power output in varying weather. The UPQC-ANN-RE system uses the DC bus voltage determined by MPPT, with a maximum of 600V for optimal operation at STC. The system operates outside the maximum power point when the voltage drops below 460V.

2. ANFIS Controller

ANFIS combines Fuzzy Logic and Neural Networks for optimization. It needs input and output data to train and compute output values for given inputs. Controllers are crucial when PID methods fall short. ANFIS is key for systems with nonlinear dynamics or uncertain models, adapting well to changing environments.ANFIS's fundamental architecture combines five layers of ANN along with sugeno fuzzy model. The input values are represented by the first layer of an ANN's structure, then the input values get fuzzified by the second layer, the fuzzy rule evaluation is represented by the third and fourth layers, and defuzzification is represented by the last layer.

A. Working of the ANFIS controller

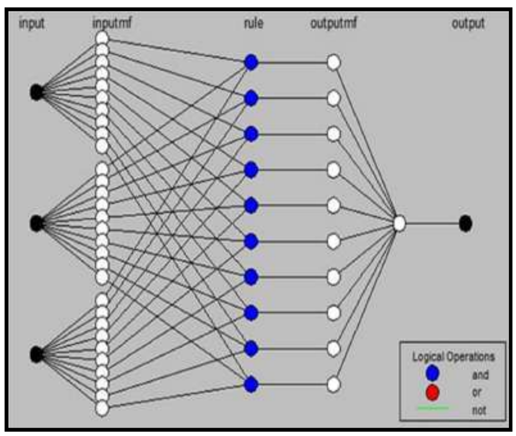


Fig.2. Structure of ANFIS controller

Rule1:If x is A_1 and y is B_1,then

$$f_1 = p_1x + q_1y + r_1.$$

Rule2:If x is A_2 and y is B_2,then

$$f_2 = p_2x + q_2y + r_2.$$

The description of ANFIS layers is given below.

Layer 1: Each node of this layer is adaptive, the output is given by:

$$\theta_i^1 = \mu_{Ai}(x) \quad (1)$$

Where, the input of node I is X, the associated linguistic variable is Ai and μ_{Ai} is the membership function of Ai. μ_{Ai} (x) is given below a_i

$$\mu_{Ai}(x) = \exp\{-(\frac{x-ci}{ai})^2\} \quad (2)$$

Layer 2: The nodes are fixed nodes denoted as Π. The outputs of this layer can be symbolized as.

$\theta_i^2 = \omega_i = \mu_{Ai}(x) * \mu_{Bi}(y)$, i= 1,2 (3)

Layer 3: The nodes are too fixed nodes. They are categorized with N, indicating that they play a normalization role to the firing strengths from the preceding layer. The output from the ith node is the normalized firing strength given by

$$\theta_i^3 = w_i = \frac{\omega i}{\omega 1 - \omega 2} \quad (4)$$

Layer 4: The nodes are adaptive nodes. The output of each node in this layer is simply the product of the normalized firing strength and a first order polynomial. Thus, the outputs of this layer are given by

$$\theta_i^4 = \omega_i f_i = \omega_i (p_i x + q_i y + r_i) \quad (5)$$

Layer 5: There is only solitary fixed node characterized with Σ. This node performs the summation of all entering signals. Henceforth, the general output of the model is given by

$$\theta_i^5 = \text{overall} - \text{output} = \sum_i \omega_i f_i = \frac{\sum i \omega i f i}{\sum i \omega i} \quad (6)$$

B. ANFIS Controller at the DC-Bus Voltage Control

The ANFIS controller dynamically adjusts the control parameters to maintain a constant DC bus voltage by processing input variables (e.g., voltage, current, environmental conditions). It is used at the DC-Bus Voltage Control to regulate the DC bus voltage, ensuring stable operation and efficient energy transfer.PLL synchronizes with the grid voltage to provide phase information (sin and cos of the phase angle.abc to d transformation now coverts three phase currents to the direct axis component. Low pass filter filters out high frequency noise from the direct-axis current. Feed forward current loop improves dynamic response by adding a feed forward component to the current control loop. Current summation point combines the ANFIS controller output, filtered current and feed-forward current.d-q-0 transformation converts the direct axis current to the d-q-0 reference frame. ANN current controllers take the reference currents and generate precise control signals. These control signals are transformed to the d-q-0 frame for accurate inverter control.PWM controller converts the ANN output into PWM signals, driving the series NPC inverter. The inverter injects compensating voltage to counteract supply voltage disturbances, ensuring stable load voltage.

C. ANN Current Controllers

The ANN controllers regulate system currents, ensuring they align with desired values for stable power distribution. They track reference currents like i_{secq}, i_{secb}, i_{secc}, adjusting actual currents accordingly. ANN's adaptive learning enables it to handle system changes, maintaining precise current control in dynamic settings. ANN controllers handle system nonlinearities for precise control, improving distributed generation performance. The ANFIS controller at the DC-bus voltage control provides adaptive and precise voltage regulation, while the ANN controllers ensure accurate current control, enhancing the efficiency and stability of the renewable energy distributed generation system. In this paper ,a neural network-based UPQC is developed to improve the power quality of a hybrid green power system. The UPQC is configured with the following settings:ANN-30 hidden layers, 5000epochs,1input and 1 output for error controllers. The network parameters utilized during the systems training structure of ANN model 1:30:1,training algorithm "trainlm",activation function purelin,train mean squared error 6.03e-07,correlation coefficient R[Training-1,Testing-1].

3. Simulation Setup

Simulation Environment: The simulation is conducted in MATLAB/Simulink, modeling the grid, load, RES, and UPQC with ANFIS control. The setup evaluates system performance under different operational scenarios.

Operational Scenarios

Scenario 1 (OPC 1): Nighttime operation with no solar power and wind power, acting purely as a UPQC-ANFIS system.

Scenario 2 (OPC 2): Operation without load, where UPQC maintains DC-link voltage using grid power.

Scenario 3 (OPC 3): Low renewable energy generation, with the grid providing primary power while UPQC mitigates power quality issues.

Scenario 4 (OPC 4): High renewable energy generation, reducing grid power reliance and enhancing efficiency.

Table 1: Parameters Assumed in the Simulation

Nominal unity voltage(RMS)	V_s = 127.27 V
Unity grid frequency	F_s =60 Hz
Leakage inductance of series coupling transfer	L_T= 0.3mH
Resistances of series coupling transformer	R_T= 0.28 Ω
Turn ratio of the series transformer	n_T=1:1
Inductive filters (series NPC inverter)	L_{sec}= 1.75 mH
Internal resistances of the parallel NPC inverter inductors	R_{sec}= 0.2Ω
Inductive filters (parallel NPC inverter)	L_{pac} =1.73 Mh
Internal resistances of the parallel NPC inverter inductors	R_{pac}=0.2 Ω
Capacitive filters (parallel NPC inverter)	C_{pac}=60Mf
DC-Bus equipment capacitance	C_{dc} =4700Mf
DC-Bus Voltage (MPP in STC)	V_{dc} =616 V
Minimum DC -Bus Voltage	V_{dc}=460 V

PWM gain	C_{pwm} =0.0002
PV Active Power	2.0 K W
PV Temperature	25° C
Irradiance	600 W/m2
Active Power PMSG Wind Turbine	1.5 K W
Speed of Wind	8 m/s
Pitch angle of Blade	0 degree
Three phase Diode bridge rectifier with resistive Load (Non-Linear Load)	R=40Ω

IV. SIMULATION RESULTS

A. UPQC-ANFIS-RE OPC 1

UPQC-ANFIS-RE OPC-1comes when its nighttime and there's no solar power, so the model acts just as a UPQC-ANFIS system with no solar and no wind [$P_{pv-wind}$ = 0 W].The power supplied by the grid to the load. The DC-link relies on grid to maintain the necessary voltage levels.

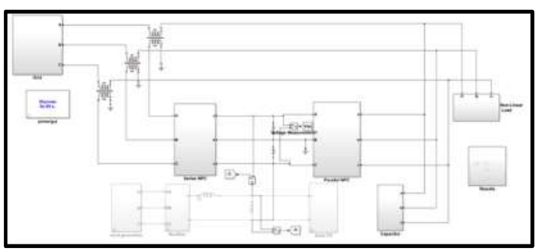


Fig.3. Simulink Model of UPQC-ANFIS-RE OPC 1

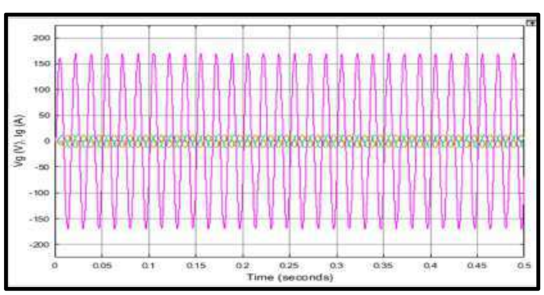


Fig.3.(a) Grid Voltage and Grid Current

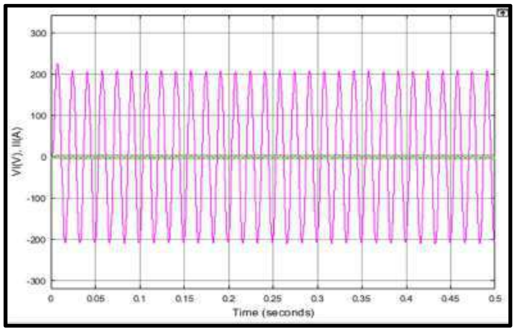


Fig 3.(b). Load Voltage and Load Current

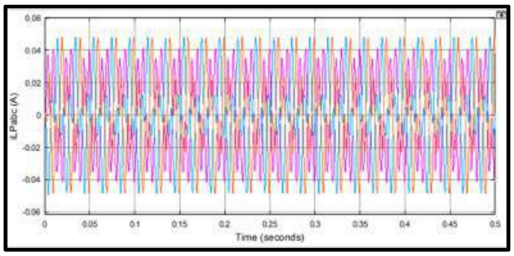


Fig .3. (c) Current at Parallel Inverter

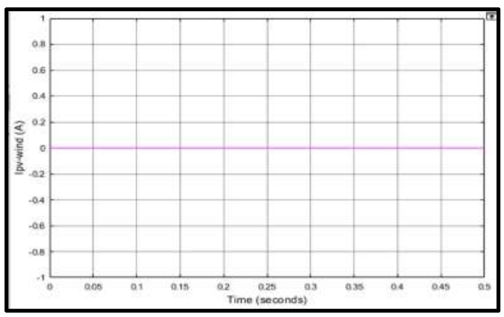


Fig.3.(d) Solar PV and Wind Turbine related Current

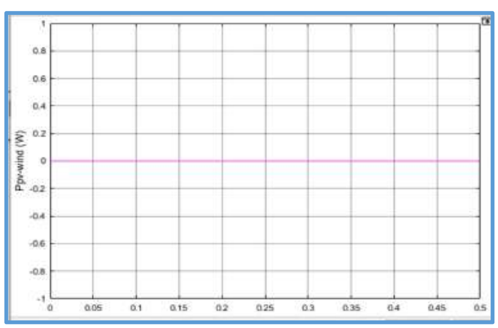


Fig.3.(e) Solar PV and Wind Turbine related Power

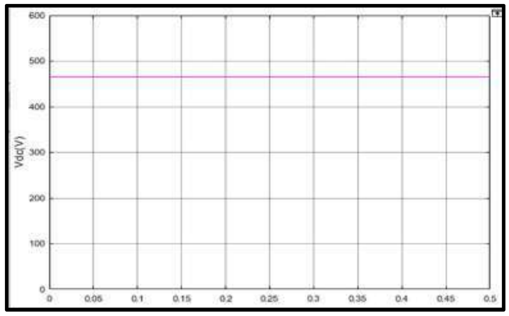
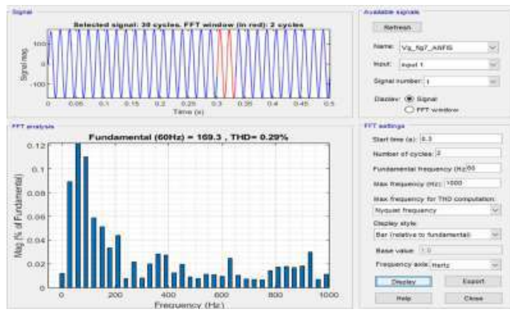
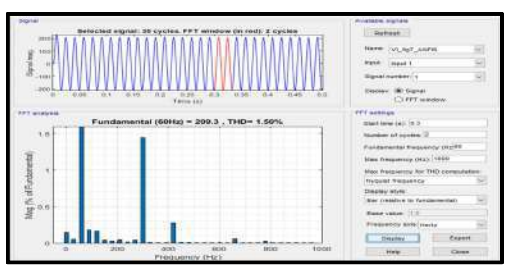


Fig.3. (f)DC Link Voltage

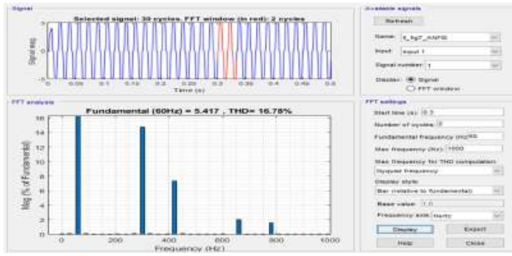


THD of Grid Voltage

THD of Grid Current



THD of Load Voltage



THD of Load Current

UPQC-ANFIS-RE OPC-1 only performs active/real power-line conditioning with $P_{pv-wind}$ =0W and Vs<$V_L$illustrated in figure 3.(a) Voltage and current of Grid; (b) Voltage and current of load; (c) currents of Parallel NPC Inverter; (d) PV array and Wind turbine current;(e)PV array and Wind turbine Power;(f) DC link voltages.

THD of grid voltage and current THD of load voltage and current.

B. UPQC-ANFIS-RE OPC 2

UPQC-ANFIS-RE system functions without the load. When the load is disconnected the UPQC system continues to maintain its DC-link voltage using grid power and remains in a monitory state.The series and parallel inverters do not actively inject compensating voltage or current as there is no load demand.The Renewable energy sources are generation power they will continue to feed power into the DC-bus (or) fed into the grid.

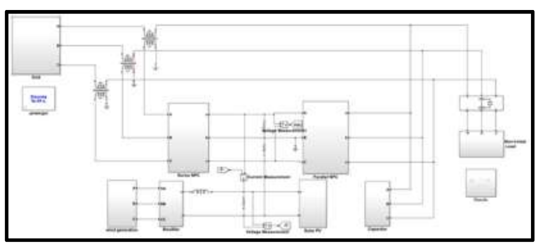


Fig .4. Simulink Model of UPQC-ANFIS-RE OPC 2

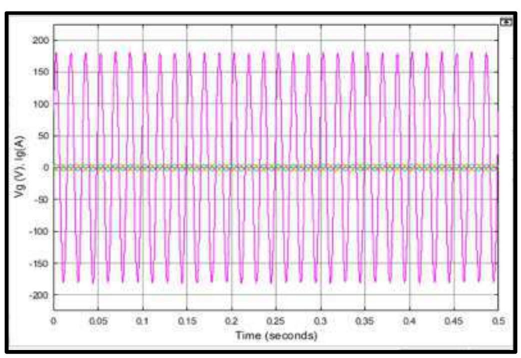


Fig .4. (a) Grid Voltage and Grid Current

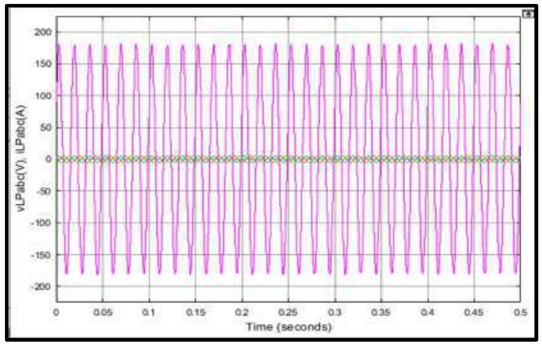


Fig.4.(b) Parallel Inverter Voltage and Current

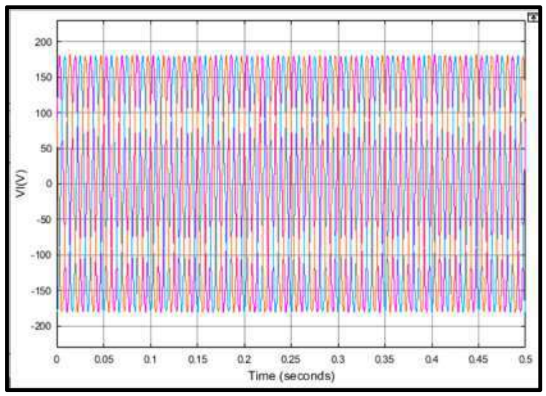


Fig.4.(c) Load Voltage

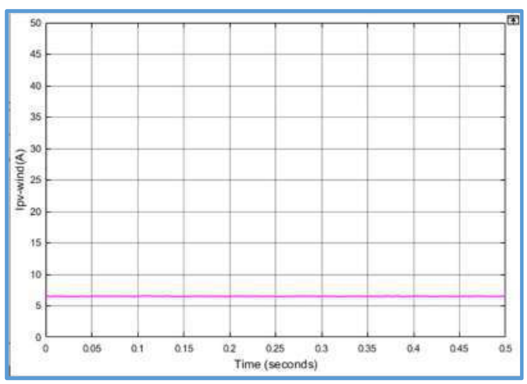


Fig.4. (d) Solar PV and Wind Turbine related Current

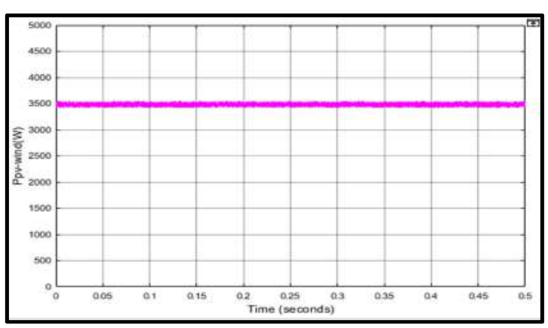


Fig.4. (e) Solar PV and Wind Turbine related Power

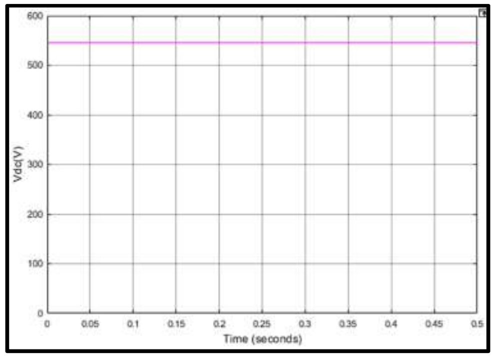
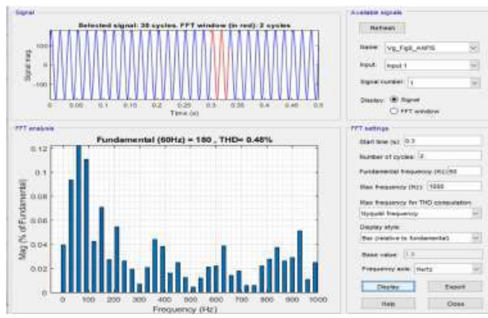
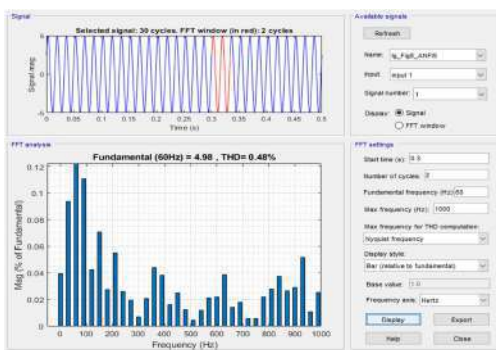


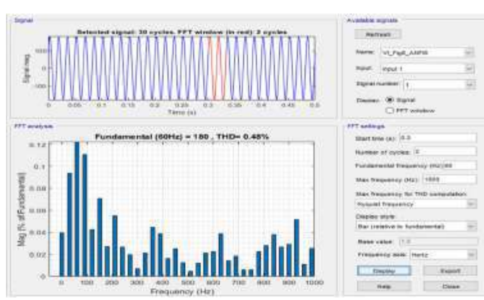
Fig.4..(f).DC Link Voltage



THD of Grid Voltage



THD of Grid Current



THD of Load Voltage

UPQC-ANFIS-RE OPC-2 performs simply active power insertion in the utility grid with PL=0W and $P_{pv-wind}$=3500W illustrated in figure 4:(a) Voltage and current of Grid; (b) Voltage of load; (c) Voltage of Load

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and currents of Parallel NPC Inverter; (d) PV array and Wind turbine current;(e)PV array and Wind turbine Power;(f) DC link voltages.

THD of grid voltage and current THD of load voltage and current.

C. UPQC-ANFIS-RE OPC 3

When the renewable energy sources producing low power in the given UPQC-ANFIS-RE system, the system continues to operate with the grid providing the primary power to maintain the DC-link voltage. The system remains effective in mitigating power quality issues and delivering stable, quality power to the load.

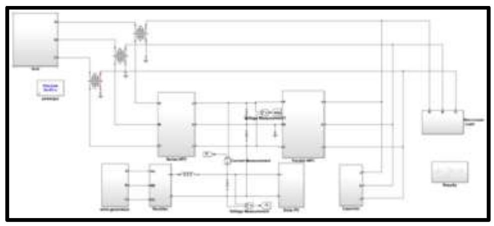


Fig.5. Simulink Model of UPQC-ANFIS-RE OPC 3

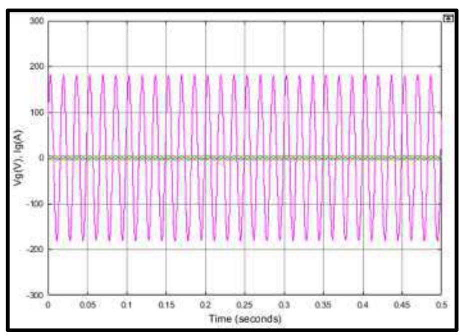


Fig.5 (a) Grid Voltage and Grid Current

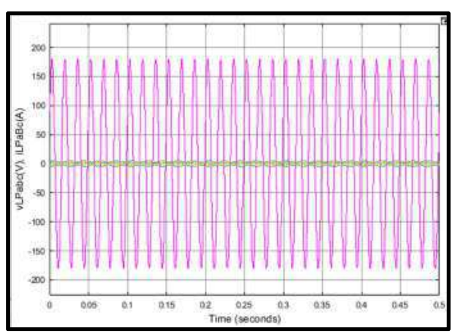


Fig.5.(b) Parallel Inverter Voltage and Current

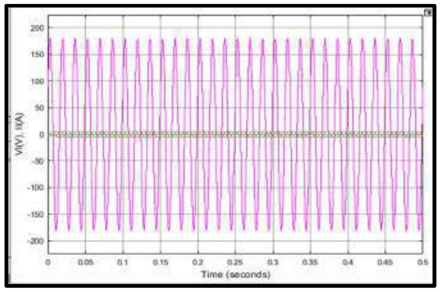


Fig.5. (c) Load Voltage and Load Current

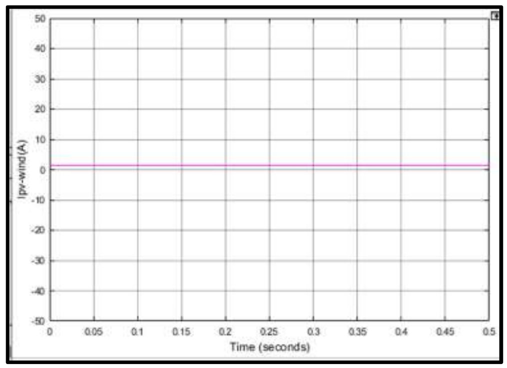


Fig.5.(d) Solar PV and Wind Turbine related Current

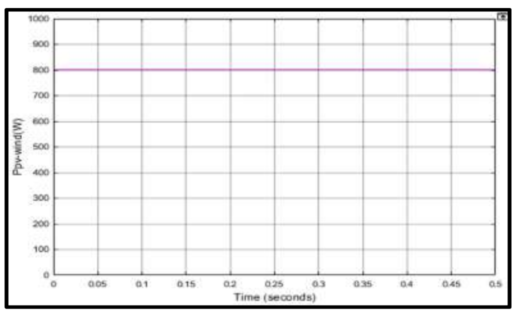


Fig.5. (f)Solar PV and Wind Turbine related Power

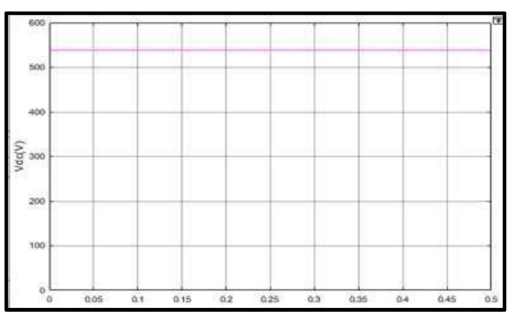
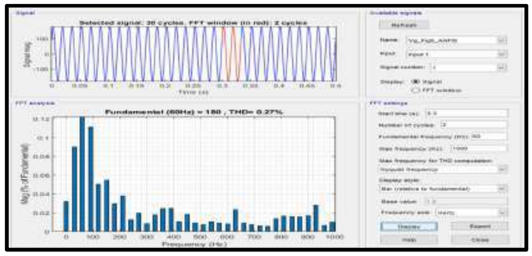
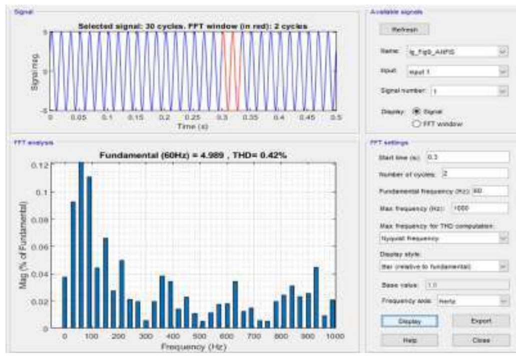


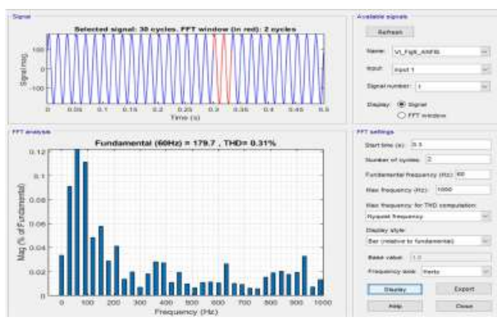
Fig.5.(g)DC Link Voltage



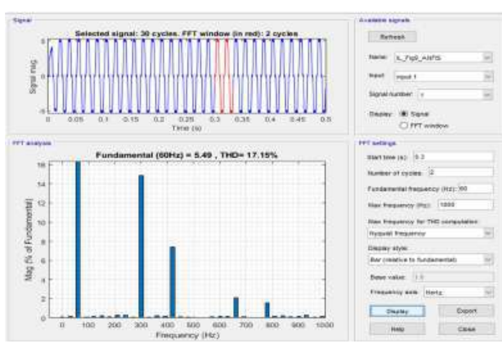
THD of Grid Voltage



THD of Grid Current



THD of Load Voltage



THD of Load Current

UPQC-ANFIS-REOPC-3 performs active power insertion along with active filtering with Ppv−wind< PL illustrated in figure5. (a) Voltage and current of Grid;(b) Voltage of Load and Parallel NPC Inverter currents (c) Voltage and current of load (d) PV array and Wind turbine current;(e)PV array and Wind turbine Power;(f) DC link voltages.

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THD of grid voltage and current (f)THD of load voltage and current.

D.UPQC-ANFIS-RE OPC 4

When the RES in the given UPQC-ANFIS-RE system produce high power, the system contribute significantly to the DC-bus. Support its compensating function. The system reliance on grid power is minimized and it effectively addresses power quality issues by injecting compensating voltage and current as needed. RES enhancing the overall efficiency and sustainability of the power.

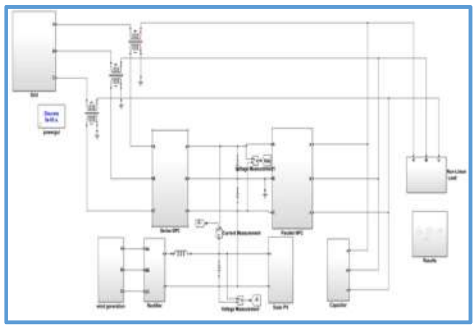


Fig.6.Simulink Model of UPQC-ANFIS-RE OPC 4

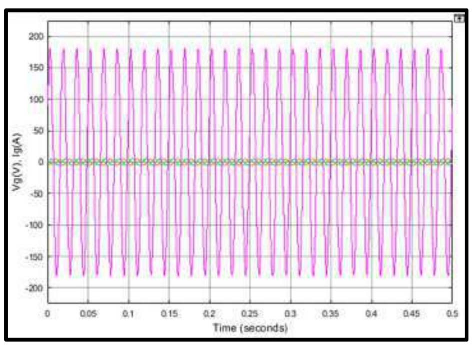


Fig.6.(a) Grid Voltage and Grid Current

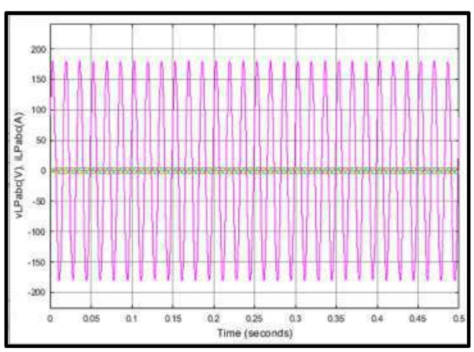


Fig.6.(b) Parallel Inverter Voltage and Current

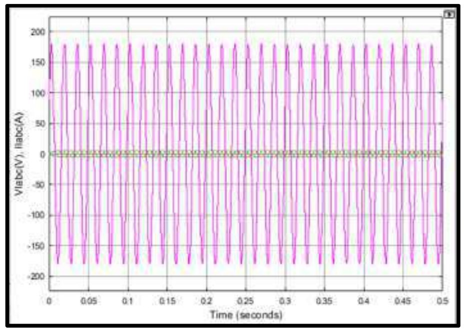


Fig.6. (c) Load Voltage and Load Current

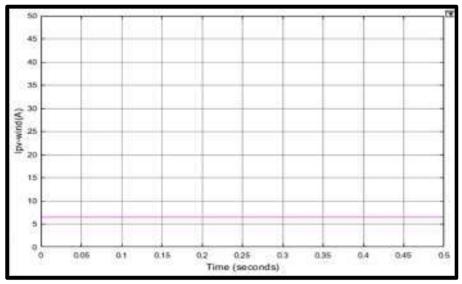


Fig.6. (d) Solar PV and Wind Turbine related Current

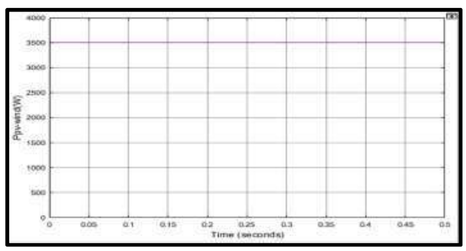


Fig .6.(e) Solar PV and Wind Turbine related Power

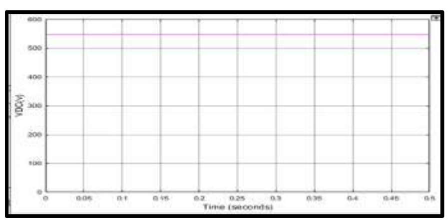
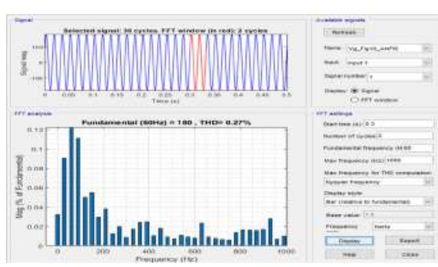
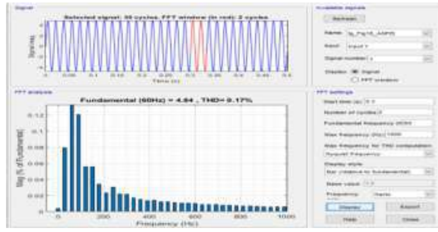


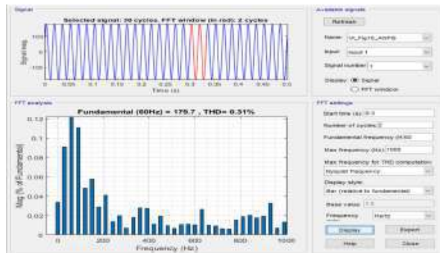
Fig.6.(f)DC Link Voltage



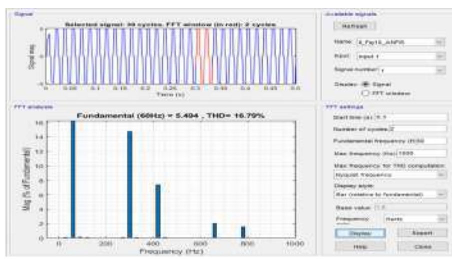
THD of Grid Voltage



THD of Grid Current



THD of Load Voltage



THD of Load Current

UPQC-ANFIS-REOPC-4 performs active power insertion along with active filtering with $P_{pv-wind} > P_L$ illustrated in figure 6: (a) Voltage and current of Grid;(b) Voltage of Load and Parallel NPC Inverter currents (c) Voltage and current of load;(d) PV array and Wind turbine current;(e)PV array and Wind turbine Power; (f)DC link voltages.

THD of grid voltage and current,THD of load voltage and current.

Table-2:Comparison of ANN Controller and ANFIS Controller in THDs (Total Harmonic Distortions)

Parameter	**By using ANN Controller**	**By using ANFIS Controller**
Grid Voltage_Fig-3	0.74%	0.29%
Grid Current_Fig-3	2.01%	0.11%
Load Voltage_Fig-3	3.02%	1.50%
Load Current_Fig-3	28.83%	16.78%
Grid Voltage_Fig-4	1.60%	0.48%

Grid Current_Fig-4	2.42%	0.48%
Load Voltage_Fig-4	1.96%	0.48%
Grid Voltage_Fig-5	1.60%	0.27%
Grid Current_Fig-5	5.22%	0.42%
Load Voltage_Fig-5	2.06%	0.31%
Load Current_Fig-5	27.30%	17.15%
Grid Voltage_Fig-6	1.44%	0.27%
Grid Current_Fig-6	1.39%	0.17%
Load Voltage_Fig-6	1.94%	0.31%
Load Current_Fig-6	26.88%	16.79%

V. CONCLUSION

In this research, investigated the performance of a renewable energy-based distributed generation (DG) system using a Unified Power Quality Conditioner (UPQC) with an ANFIS (Adaptive Neuro-Fuzzy Inference System) controller. The objective was to enhance power quality and stabilize voltage in the distribution network, particularly in the presence of renewable energy sources. The simulation and experimental results demonstrate that the proposed UPQC with ANFIS controller significantly improves the power quality and stability of the renewable energy-based DG system, particularly during grid faults and load disturbances, as compared to the other control strategies. The proposed system effectively mitigated voltage and current harmonics, reduced power losses, and maintained voltage at the point of common coupling (PCC) within acceptable limits. Furthermore, the proposed system exhibited excellent performance in handling the unbalanced and nonlinear loads commonly encountered in practical distribution systems. The results indicate that the proposed UPQC with ANFIS controller can be considered as a promising solution for renewable energy integration in the power grid. In conclusion, the proposed system offers significant advantages over other control strategies in terms of power quality enhancement and voltage stabilization in the distribution network. It provides a cost-effective and efficient means of improving power quality, reducing power losses, and ensuring stable and reliable power supply in the presence of renewable energy sources.

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