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DESIGN AND IMPLEMENTATION OF ANFIS CONTROLLER BASED UPQC WITH RENEWABLE ENERGY BASED DISTRIBUTED GENERATION SYSTEM

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ABSTRACT:

This study investigates the performance of a renewable energy-based distributed generation system utilizing an Adaptive Neuro-Fuzzy Inference System (ANFIS) tuned Unified Power Quality Conditioner (UPQC). The system integrates photovoltaic (PV) and wind energy sources to address power quality issues and enhance the reliability of power distribution networks. The ANFIS-tuned UPQC is designed to dynamically optimize its control strategies, responding effectively to fluctuations in power generation and varying load demands. The main goals of this study are to determine how well the system compensates for reactive power loss and maintains voltage regulation, as well as how well it can reduce common power quality issues including harmonics, voltage sags, and swells. The research shows how well the ANFIS-tuned UPQC performs in providing a reliable and high-quality power supply through extensive simulation and analysis. Key findings indicate that the integration of ANFIS with UPQC not only enhances the power quality but also improves the overall efficiency and resilience of the distributed generation system. The system effectively utilizes renewable energy sources, reducing dependency on conventional power generation and contributing to environmental sustainability. The results highlight the potential of this advanced control strategy in promoting the widespread adoption of distributed generation systems based on renewable energy, ensuring both reliability and sustainability in modern power grids.

Keywords: Distributed generation system, unified power quality conditioner, artificial neural network, power quality, renewable energy sources, ANFIS Controller.

I. INTRODUCTION

Renewable energy sources have been developed and integrated into the power grid as a result of the growing worldwide need for energy and the negative environmental effects of fossil fuels. Due to their potential to lower greenhouse gas emissions and improve energy security, distributed generation (DG) technologies, such solar photovoltaic (PV) and wind energy, have acquired a lot of interest among other renewable energy technologies. However, the integration of renewable energy-based DG systems presents several technical challenges, primarily related to power quality and reliability. Issues such as voltage sags, swells, harmonics, and frequency deviations are common in renewable energy systems, affecting the stability and performance of the power grid. To address these challenges, advanced power quality improvement devices, such as the Unified Power Quality Conditioner (UPQC), have been developed. A flexible custom power tool called the Unified Power Quality Conditioner (UPQC) simultaneously addresses power quality problems relating to voltage and current. It consists of two voltage source inverters (VSIs) connected back-to-back through a common DC link: the series inverter, which compensates for voltage disturbances, and the shunt inverter, which addresses current-related issues. While the conventional UPQC can effectively enhance power quality, its performance largely depends on the control strategies employed. In this context, the Adaptive Neuro-Fuzzy Inference System (ANFIS) has emerged as a powerful tool for optimizing control strategies. ANFIS provides a reliable technique for managing nonlinearities and uncertainties in the power system by fusing the fuzzy logic reasoning methodology with the learning capabilities of neural networks. It is feasible to attain better performance in reducing power quality problems in distributed generation (DG) systems powered by renewable energy by fine-tuning the UPQC utilizing ANFIS. The performance of UPQCs has been substantially improved in recent years by the use of intelligent control mechanisms, such as the Adaptive Neuro-Fuzzy Inference System (ANFIS). By fusing the fuzzy logic approach with neural network learning capabilities, ANFIS provides a potent tool for handling the intricate and dynamic behaviour of renewable energy systems. By tuning the UPQC with ANFIS, the system can adaptively respond to changes in power generation and load conditions, optimizing its performance in real-time. The usefulness of the ANFIS-tuned UPQC in resolving power quality concerns is assessed in the study across a range of load scenarios and operating conditions. The performance metrics include voltage regulation, harmonic distortion, and overall system stability. Simulation results and experimental validations demonstrate the enhanced capabilities of the proposed approach,

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highlighting its potential for improving the reliability and efficiency of modern power grids.

II. CONTROL STRATEGIES

An ANFIS-tuned UPQC is utilized in a renewable energy-powered DG system to improve power quality and system reliability. The usual approach to managing such a system involves combining different control techniques to handle power flow, address power quality problems, and maintain stable operation. Here is a summary of the control tactics.

A. UNIFIED POWER QUALITY CONDITIONER

A Unified Power Quality Conditioner (UPQC) is an advanced device designed to enhance the quality of electrical power in a distribution network. It is a single unit that integrates the features of both a shunt active power filter and a series active power filter (APF). A UPQC's main objective is to minimize power quality problems, such as imbalances, harmonics, swells, and voltage dips, in order to provide a clean and reliable power source. In a UPQC, the series APF functions by injecting compensating voltages into the supply line, which is coupled in series with the line. This helps to correct voltage disturbances like sags (voltage drops) and swells (voltage rises). On the other hand, the shunt APF is connected in parallel with the load and works by injecting compensating currents to address issues such as load current harmonics, reactive power, and load unbalances.

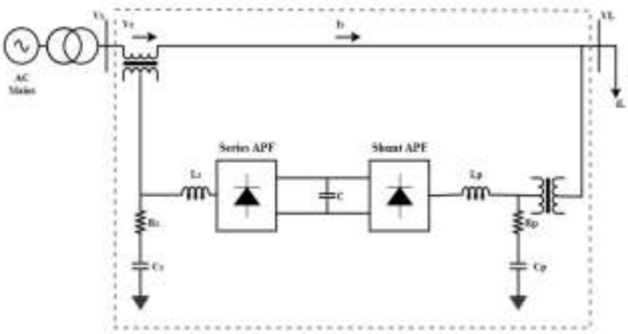

Figure 1. Circuit diagram of UPQC.

By simultaneously managing voltage and current quality, a UPQC enhances the reliability and efficiency of power systems, making it a crucial component in modern electrical distribution networks, particularly in industries with sensitive equipment or stringent power quality requirements.

1) SHUNT ACTIVE FILTER

A Shunt Active Filter (SAF) is an essential power electronic device used to improve the quality of power in electrical systems. It is connected in parallel with the load and operates by injecting compensating currents into the system to mitigate power quality issues such as harmonics, reactive power, and unbalanced loads.

The shunt active filter constantly monitors the current of the load in order to identify undesirable elements such as harmonics and reactive power. Once the unwanted components are recognized, the shunt active filter generates corrective currents. The Shunt active filter injects compensating currents into the power system that have the same magnitude as the detected harmonics and reactive power components, but opposite in phase. This method removes unwanted elements from the load current, resulting in a smoother and uniform current flow.

The goal of the Shunt active filter is to focus on and remove harmonics from the load current. Harmonics, which are higher frequency components, can lead to issues like equipment overheating and decreased efficiency. The shunt active filter maintains a sinusoidal current waveform by injecting compensating currents, preventing distortions. Reactive power, essential for inductive load operation, can lower the system's power factor and cause increased losses. The Static Synchronous Compensator (STATCOM) provides compensation for reactive power at the local level, which enhances power factor and lowers the apparent power consumption from the source. Unbalanced loads in three-phase systems can result in unequal currents in each phase, which may lead to issues like voltage imbalances and overheating of the neutral conductor. The SAF maintains load balance by introducing compensating currents to each phase, guaranteeing equal and balanced currents.

2) SERIES ACTIVE FILTER

A series active filter is a power electronic device that corrects problems like harmonics, voltage swells, and sags in order to enhance power quality in electrical systems. The series active filter is linked in series with the power line as opposed to the shunt active filter, which is connected in parallel with the load. It is essential to maintaining a steady and disturbance-free voltage supply to the load.

The Voltage supplied to the load is constantly monitored by the Series Active Filter. It identifies any changes from the expected voltage levels, like dips, spikes, or distortions caused by harmonics. The series active filter produces a compensating voltage when it detects a deviation in the voltage level. This compensating voltage is added in line with the supply voltage to offset the disturbance. The compensating voltage is directly added to the power line by the filter, which efficiently fixes the voltage sent to the load. This guarantees the load will get a consistent and sine-shaped voltage signal, no matter what disruptions occur in the power source.

A main purpose of the Series Active Filter is to reduce voltage disruptions like sags and swells. The SAF uses a compensating voltage to maintain the voltage level at the load within safe limits, safeguarding sensitive equipment from harm caused by voltage changes. The Series Active Filter also deals with voltage harmonics, which are voltage waveform distortions resulting from non-linear loads. Injecting a compensating voltage helps the filter remove harmonics, guaranteeing that the voltage delivered to the load is a clean sinusoidal waveform. The Series Active Filter can modify the phase angle of the voltage waveform to rectify any phase discrepancies, leading to a general enhancement of power quality.

B. ARTIFICIAL NEURAL NETWORK

An Artificial Neural Network (ANN) is a computerized representation influenced by the design and operation of the human brain. Its purpose is to identify patterns, acquire knowledge from data, and take actions based on the acquired knowledge. ANNs are commonly utilized in different fields such as image and speech recognition, natural language processing, and predictive analytics.

An artificial neural network is made up of layers of interconnected nodes, which are also referred to as neurons. Usually, these layers are categorized into three primary types:

Input layer: The initial layer in the network is the input layer. It gets the original data and transfers it to the next layer. Every node in the input layer denotes a characteristic or quality of the data.

Hidden layer: Hidden layers serve as the bridge between the input and output layers. These layers handle the input data by implementing different changes. Every neuron in a concealed layer gets input from the layer before, analyses it, and transmits the result to the layer ahead. The number of hidden layers and neurons in each layer can vary depending on the complexity of the task.

Output layer: The final result is generated by the output layer. The number of neurons in the output layer typically corresponds to the number of classes or outcomes the model is designed to predict.

Each neuron in the network performs a weighted sum of its inputs and passes the result through a nonlinear activation function.

1. Neuron Model:

The basic mathematical operation for a neuron j in an ANN can be described as:

$$y_j = f(\sum_{i=1}^{n} w_{ji}\, x_i + b_j) \qquad (1)$$

Where:

x_i is the input to the neuron.

w_{ji} is the weight between the i^{th} input and j^{th} neuron.

b_j is the bias term.

f(.) is the activation function.

y_j is the output function.

The activation function introduces nonlinearity, allowing the ANN to model complex, nonlinear relationships.

2. Network output:

For an ANN controller with L layers, the output of the network can be expressed as a series pf matrix multiplications and activations and activation functions applied at each layer. Let $X^{(0)}$ be the input to the network, and the network computes the output through layers as follows:

$$X^{(l+1)}= f(W^{(l)}x^{(l)}+ b^{(l)}) \qquad (2)$$

Where:

$x^{(l)}$ is the vector of neuron activations in layer *l*,

$W^{(l)}$ is the weight matrix for layer *l,*

$b^{(l)}$ is the bias vector for later *l*.

The final output layer computes the control signal y as:

$$y= W^{(L)}X^{(L-1)} + b^{(L)} \qquad (3)$$

This output can represent control actions in a control system.

3. Training the ANN:

The weights $W^{(l)}$ and biases $b^{(l)}$ are learned through a process called training, typically using a supervised learning method such as backpropagation combined with gradient descent.

The network minimizes a loss function (L), which measures the error between the predicted output and the desired control action. The loss function is typically defined as the mean squared error for a regression-based control task.

$$L = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \qquad (4)$$

Where:

y_i is the true control output for the i^{th} training sample.

$\hat{y}_i$ is the predicted output by the network for the same sample.

The weights are updated iteratively using the gradient of the loss function with respect to the weights, following the rules:

$$W^{(l)} \leftarrow W^{(l)} - \eta\, \frac{\partial L}{\partial W^{(l)}} \qquad (5)$$

Where η is the learning rate.

4. ANN as a controller

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In a control system, the ANN controller receives system state information as unput and produces control signals to drive the system toward a desired state.

For example, consider a dynamic system described by the following differential equation.

$$\dot{x}(t) = f\,(x(f), u(t)) \quad (6)$$

Where:

x(t) is the state of the system at time t.

u(t) is the control input.

f(.) is the system dynamics.

The ANN controller is the trained to approximate the optimal control law u(t) that drives the system toward a target state x_{target}.

In this scenario, the control signal u(t) is generated by the ANN based on the current state x(t).

$$u(t) = ANN\,(x(t)) \quad (7)$$

The ANN approximates the mapping between the systems state and the required control input to achieve the control objective.

The Artificial Neural Network (ANN) controller is a powerful tool in control systems, designed to learn and adapt to complex, nonlinear behaviours that are often difficult for traditional controllers to manage. By mimicking the way biological neural networks process information, ANN controllers can handle uncertainties, nonlinearities, and dynamic environments, making them suitable for a wide range of applications, from robotics to power systems.

ANN controllers excel in adaptability, as they can improve their performance over time through training, allowing them to handle varying system conditions without needing explicit mathematical models of the controlled process. However, the success of an ANN controller relies heavily on the quality and quantity of data used for training, as well as the design of the network architecture.

In conclusion, ANN controllers offer flexibility and robustness in managing complex systems, especially where conventional control methods fall short. While their implementation can be computationally demanding and requires careful tuning, their ability to learn and generalize makes them a valuable tool for modern control systems.

C. FUZZY LOGIC SYSTEM

An algorithmic method for handling imprecision and ambiguity in decision-making is called a fuzzy logic system, which imitates human reasoning. Fuzzy logic permits degrees of truth, which means that values can range from 0 to 1, in contrast to classical binary logic, which takes variables to be either true (1) or false (0).

Fuzzification: Fuzzification is the process of converting precise input values into fuzzy sets and allocating membership degrees to each input to indicate its relative contribution to different categories. Decision-making in complicated situations is made possible by fuzzy logic systems' ability to handle imprecise or uncertain facts.

Rule base: A fuzzy logic controller that employs a rule-based system is a framework that employs a series of "if-then" rules to produce fuzzy logic-based choices. Fuzzy logic allows for reasoning with degrees of truth, where values can be partially true and partially false, in contrast to classical logic, which only works with true or false values. A fuzzy logic controller's rule base, which helps translate input conditions into output decisions, is its central component.

Inference Engine: The degree of truth for every rule is assessed by the inference engine as it processes the rule base. It determines the contribution of each rule to the output by combining the membership values of the input variables using fuzzy operators.

Defuzzification: Defuzzification in a fuzzy logic controller is the process of converting fuzzy output sets into a single crisp value. After the inference engine processes the fuzzy rules and generates fuzzy output sets, these outputs need to be translated into a specific, actionable value that can be used by the system.

D. ANFIS CONTROLLER

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid control system that blends fuzzy logic reasoning with neural network learning. The benefits of both methodologies are combined in ANFIS to efficiently model intricate, nonlinear systems.

1. Structure of ANFIS Controller

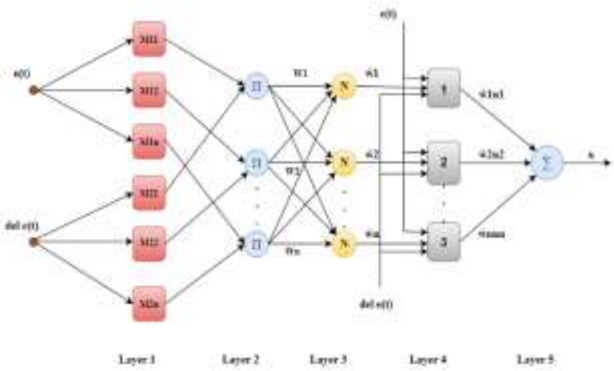

Figure.2 Schematic diagram of ANFIS architecture.

The adaptive neuro-fuzzy inference system is a hybrid automated/machine learning model, involves another Takagi–Sugeno fuzzy logic. ANFIS method is proved to be of a good balance between the neural network and fuzzy logic, so it has widely used in control models - successful. The way makes use of a predetermined observation data set and the input/ output to be able to build a fuzzy interference program. Back propagation is used during the training process to learn the membership function parameters. Figure.1 depicts a suggested architecture for the ANFIS. The structure consists of five layers of the ANFIS structure, two error inputs e and Δe, and one output (u), which represents the control signal for blade pitch control.

The adaptive neuro-fuzzy inference system generally consists of five layers:

Layer 1 (Input Layer): The input layer represents the input variables. Each neuron in this layer corresponds to one input variable and passes it to the next layer without any modification.

Layer 2 (Fuzzification Layer): This layer applies membership functions to the input data. Each neuron in this layer represents a membership function, which translates crisp input values into fuzzy values (degrees of membership).

Layer 3 (Normalization Layer): Each node calculates the normalized firing strength.

Layer 4 (Defuzzification Layer): Each node calculates a weighted output.

Layer 5 (Output Layer): Computes the overall output as the sum of all incoming signals.

The fuzzy if-then rules in the Sugano fuzzy model, which the ANFIS algorithm employs, are expressed in Eq.

$$R_n = if\ M_{1i}(e)\ and\ M_{2i}(\Delta e), then\ f = p_n e(t) + q_n \Delta e(t) + r_n \quad (8)$$

where n is the quantity of rules. The linear parameters of the subsequent component of the n^{th} rules are p_n, q_n, r_n while M_{1i} and M_{2i} are fuzzy membership functions.

The degrees of membership functions in the first layer of Adaptive Neuro Fuzzy Inference system, which symbolizes the fundamental Fuzzification, are established by the input variable. Every node in this layer represents an adaptive node function that is defined by Equation.

$$M_{1i} = \frac{1}{1+\left[\frac{x-c_i}{a_i}\right]} b_i \quad (9)$$

The parameter set is represented by $(a_{i,} b_{i,} c_i)$.

The second layer is the inference layer, where every node that has the π label is based on a fuzzy rule's firing strength. This layer's w_i outputs can be characterized as follows:

$$w_i = M_{1i}(e) \times M_{2i}(\Delta e) \quad (10)$$

To normalize the computed firing strengths from the previous layer, apply a normalization layer in the third layer.

$$\overline{w_i} = \frac{w_i}{\sum_i (w_i)} \quad (11)$$

The third layer's normalized values are the input values for layer four. Each node in this layer functions as an adaptable mode, and its node function is defined by Equation.

$$\overline{w_i} u = \overline{w_i}(p_i e + q_i \Delta e + r_i) \quad (12)$$

Where the (p, q, r) represents the consequent parameter set and u is the control signal.

The final layer is the output layer, which computes the total of all incoming signals to Defuzzifier the consequent section of rules.

$$\sum_i (\overline{w_i} u) = \frac{\sum_i w_i u}{\sum_i w_i} \quad (13)$$

III. UPQC-ANFIS-RE TOPOLOGY

Utilizing renewable energy sources, the distributed generation systems are incorporated into a four-wire, three-phase distribution network that runs at 60 Hz and 220 volts line-to-line. An Adaptive Neuro-Fuzzy Inference System (ANFIS)-based Unified Power Quality Conditioner (UPQC) is used to manage these systems. Three primary sections comprise the setup:

Decentralized Power Generation: The solar panels and wind turbines in this area operate separately to produce electricity.

Inverter and Coupling: In this instance, the power flow is managed by a series coupling transformer, passive components, and an NPC (Neutral Point Clamped) series inverter.

Inverter and Filtering: An NPC inverter and parallel-arranged filter elements are featured in the last part. The distributed energy system, which consists of wind turbine and solar (PV) generators, and the NPC inverters are connected by a shared DC link. To create a local three-phase, four-wire system, a split capacitor design is used, with the neutral conductor and the DC bus's midpoint connected.

The distributed generators are made up of a variable-speed permanent magnet synchronous generator (PMSG) wind turbine and a solar array with twenty modules connected in series. They do not feature energy storage. This arrangement generates electricity, which is subsequently connected via an AC/DC bridge rectifier to the DC link of the UPQC.

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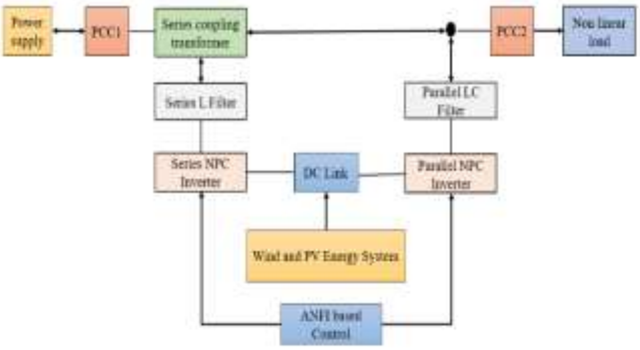

Figure 3. Block diagram of ANFIS Controller based UPQC with Renewable energy system.

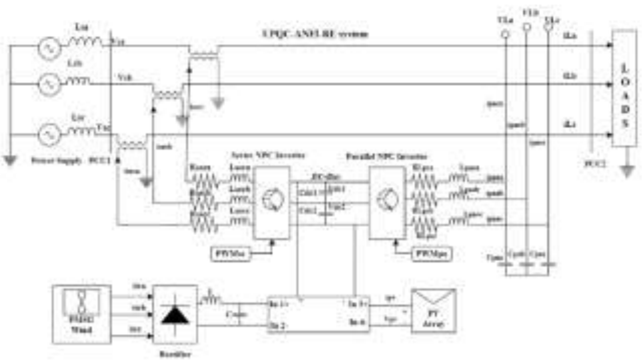

Figure 4. Circuit diagram of ANFIS Controller based UPQC with Renewable energy system.

The MPPT algorithm plays a crucial role in maximizing power output in various weather conditions. Hence, a hybrid power quality improvement solution that integrates Unified Power Quality Conditioner (UPQC), Adaptive Neuro-Fuzzy Inference System (ANFIS), and renewable energy source (RE) system is created to operate based on the DC bus voltage V_{dc} calculated from the Maximum Power Point Tracking process. Therefore, the DC bus's voltage peak reaches approximately 600 V, enabling the system to function optimally during standard testing at Maximum Power Point. The system's minimum operating voltage remains consistent at 460 V, meaning that when this voltage is reached, the system operates beyond the Maximum Power Point.

A. SERIES NPC FILTER

The series NPC (Neutral Point Clamped) filter in a Unified Power Quality Conditioner (UPQC) plays a crucial role in improving the quality of power in an electrical system. In UPQC, the series filter is responsible for mitigating voltage-based issues such as sags, swells, and harmonics in the supply voltage. The NPC topology, often used in multilevel converters, helps to improve the filter's performance by reducing the voltage stress on components and enhancing the quality of voltage compensation. It also allows for higher voltage operation with lower harmonic distortion, ensuring the load receives a clean and stable voltage.

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is used as a smart control mechanism in the context of a renewable energy system. For dynamic and non-linear situations such as renewable energy sources, ANFIS combines the reasoning powers of fuzzy logic with the learning capabilities of neural networks. ANFIS assists in managing power flow in a UPQC system, assisting in the efficient management of power quality concerns such harmonics, voltage fluctuations, and reactive power. Better stability and reliability in the power system as a whole are made possible by this intelligent control, which guarantees optimal performance and adaptation to changing conditions in the integration of renewable energy.

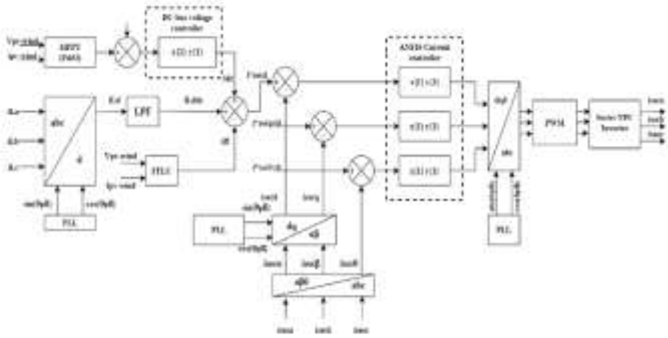

Figure 5. Control strategy of series converter.

From the dq to the abc axes, the load currents are assessed and transformed.

. The present i_{Ld} n can therefore be simply determined as follows:

$$i_{Ld} = \sqrt{\frac{3}{2}}[\cos\theta - \frac{1}{2}\cos\theta + \frac{\sqrt{3}}{2}\sin\theta - \frac{1}{2}\cos\theta + \frac{\sqrt{3}}{2}\sin\theta] \times \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (14)$$

The load current harmonic and real components, represented by $\cos\theta$ and $\sin\theta$, create the current vector i_{Ld} s. These components act as coordinates for the rotating unit vector.

The low pass filter is used to obtain the average value of i_{Ld} ($i_{Ld_{dc}}$), guaranteeing that ($i_{Ld_{dc}}$) represents the actual components of the abc load currents. Lastly, the NPC series inverter input currents on the d-axis are referenced by:

$$i_{secd} = i_{Ld_{dc}} + i_{dc} - i_{ff} \quad (15)$$

In this context, i_{dc} represents the DC link voltage output from the ANN controller, while i_{ff} denotes the feedforward current. The i_{dc} signal indicates the amount of real power managed by the NPC series inverter to maintain UPQC power stability and regulate the DC bus voltage. To provide energy stability and regulate the power flow through the ANFIS Controller based UPQC with distributed generation based on renewable energy, i_{dc} modifies the magnitude of i_{sec}^{*}. Alongside i_{dc} the feedforward current i_{ff} helps accelerate energy balance. Given that balanced and sinusoidal currents are desired in the power grid, both the zero-sequence component i_{sec0}^{*} and the quadrature current i_{secq} are maintained at zero.

B. PARALLEL NPC FILTER

A Parallel Neutral Point Clamped (NPC) inverter is a sophisticated multilevel inverter structure employed in power electronics to convert DC power into high-grade AC power. This configuration combines the advantages of the NPC structure with parallel operation to boost performance, expand power capacity, and increase reliability.

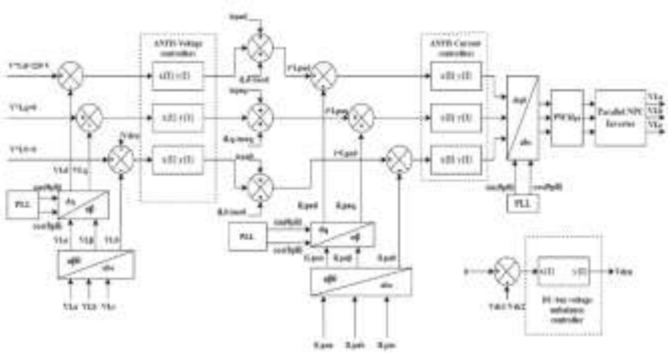

Figure 6. Control strategy of parallel converter.

In this configuration, the parallel NPC converter operates in shunt with the grid and load, injecting compensating currents to correct current imbalances, eliminate harmonics, and regulate reactive power flow. The NPC topology offers a multilevel structure that minimizes harmonic distortion and reduces switching losses, making it suitable for high-voltage applications in renewable energy-based power systems.

Current Compensation: It injects compensating currents to filter out harmonics and balance the load current.

Reactive Power Compensation: It helps improve the system's power factor by compensating for reactive power.

Integration of Renewable Energy: It manages the flow of power from renewable sources, optimizing energy usage.

ANFIS Control: The ANFIS controller dynamically adjusts the NPC converter's operation to meet real-time power quality needs.

The mathematical modelling of the parallel NPC converter focuses on current control, DC link voltage regulation, and power flow management. The NPC converter uses three voltage levels-positive, zero (neutral), and negative-allowing more precise current control.

1. Current Injection Model:

The parallel NPC Converter injects compensating current i_{inj}, into the system to improve the quality of current. The relationship between the source current i_S, load current i_L, and compensating current i_{inj} is given by:

$$i_S = i_L - i_{inj} \tag{16}$$

Here, i_S represents the current flowing from the grid, which the converter ensures is free of harmonics and reactive power components. i_{inj} is the current injected by the NPC converter to compensate for any disturbances.

2. Load and Compensating Current:

The converter aims to cancel out the harmonic and reactive components of the load current. The compensating current i_{inj} is calculated by subtracting the reference current i_{ref} from the actual load current i_L:

$$i_{inj} = i_L - i_{ref} \tag{17}$$

Usually, the reference current comes from a control algorithm that finds the optimal current waveform and keeps track of the power quality of the system.

3. DC Bus Voltage Regulation:

The voltage of the DC bus V_{dc} must remain constant in order to secure the proper operation of the NPC converter. To manage the DC bus voltage, a proportional-integral (PI) controller is frequently utilized. The controller takes the difference between the reference DC voltage V_{dc}^{ref} and the actual DC voltage V_{dc} and adjusts the injected current accordingly:

$$V_{dc}(t) = V_{dc}^{ref} - K_p\left(V_{dc}^{ref} - V_{dc}(t)\right) - K_i \int V_{dc}^{ref} - V_{dc}(t))dt \tag{18}$$

Where:

K_p represents the Proportional gain.

K_i represents the integral gain.

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This equation maintains the stability of the DC link, which is critical for the proper functioning of the multilevel inverter.

4. Modulation of Switching Devices:

The NPC converter uses Pulse Width Modulation (PWM) to switch between voltage levels. The switching function, S(t), determines which voltage level is applied at any given time.

5. Harmonic Filtering:

The harmonic components of the load current can be expressed using Fourier analysis as:

$$i_L(t) = I_1 \sin(wt) + \sum_{n=2}^{\infty} I_n \sin(nwt + \varphi_n) \quad (19)$$

Where I_1 represents the fundamental frequency component and I_n represents the amplitude of the n^{th} harmonic. The NPC converter injects current to cancel out these harmonic components, ensuring that the source current remains sinusoidal.

6. Power Injection and Energy Balance:

The DC link voltage and the compensating current determine the power injected by the NPC converter (P_{inj}).

$$P_{inj} = V_{dc}.i_{inj} \quad (20)$$

The injected power helps in balancing the system's reactive power and compensating for the load's harmonic distortions. The total power flow in the system is adjusted to maintain stability and ensure proper power quality.

The parallel NPC converter is a crucial component for improving current quality by compensating for harmonics, reactive power, and load imbalances. Its mathematical model involves current injection equations, DC bus voltage regulation, harmonic filtering, and control of switching devices. By using multilevel conversion, the NPC topology reduces switching losses and harmonic distortion, providing efficient and reliable power quality improvement in high-voltage applications.

IV. UPQC-ANFIS-RE SYSTEM-BASED ACTIVE POWER FLOW

Table 1. The UPQC-ANFIS-RE system's active power flow is regulated by certain conditions.

Operating conditions		RMS Voltage	PV and Wind power	Load Power
a	1	Vs > VL	Ppv-wind = 0	PL not equal to ZERO
	2	Vs < VL		
b	1	Vs > VL	Ppv-wind > 0	PL = 0
	2	Vs < VL		
c	1	Vs > VL	Ppv-wind < PL	PL > 0
	2	Vs < VL		
d	1	Vs > VL	Ppv-wind > PL	PL > 0
	2	Vs < VL		

The table describes the operating conditions of system where renewable energy sources, specifically photovoltaic (PV) and wind power, interact with a power grid. It illustrates how different conditions of voltage and power generations from these renewable sources affect the load voltage.

1. Operating conditions: Each condition is denoted by a letter (a, b, c, d) and numbered into two rows, indicating two sub-cases under each operating condition

2. RMS Voltage: This refers to the Root Mean Square (RMS) voltage at the source (V_S). It compares the source voltage (V_S) to the load voltage (V_L) in two scenarios:

3. PV and Wind Power: This column represents the amount of power generated by PV and wind systems. The table shows different cases, such as:

$\boldsymbol{P_{PV-Wind} = 0}$**:** No power is generated from PV or Wind sources.

$\boldsymbol{P_{PV-Wind} > 0}$: There is some power generation from PV or Wind.

$\boldsymbol{P_{PV-Wind} < P_L}$**:** The power generated by PV and Wind is less than the load power demand (P_L).

$\boldsymbol{P_{PV-Wind} > P_L}$**:** The power generation from PV and Wind exceeds the load power demand.

4. Load Power: This shows whether the load power is equal to zero or greater than zero, depending on the conditions of power supply and demand. $P_L > 0$ indicates there is load power present, while $P_L = 0$ means no load power is available.

V. OPERATING CONDITIONS

When solar PV and wind turbines are not in operation, the energy flow is referred to as operating condition (a). At that point, the grid supplies the series inverter with the real power required, and the parallel inverter supplies the load.

In Operating Condition (b), there is no power required at the load; this is the actual power being conveyed. In this case, all of the electrical power is still mostly controlled by the parallel converter but is transferred to the grid via the DC bus.

When the power generated by the wind turbine and photovoltaic array is sufficient to meet the load needs, the actual power transmission is represented by operating condition (c). The extra energy required by these loads in this scenario needs to be transferred via a parallel and series converter from the utility grid to the load.

When the energy generated by the wind turbine and PV system surpasses the total energy needed by the loads, operating condition (d) occurs. In this case, any energy that is not used by the load and is transferred from the DC bus to the utility grid is considered excess.

VI. SIMULATION RESULTS

The performance of the UPQC-ANFI-RE system is evaluated by simulating the system using MATLAB/SIMULINK software. The system simulations rely on the diagram shown in Figure 4 for implementation. The parallel and series PWM converters are parts of the three-level NPC inverters. The load and component of the load is a three-phase diode bridge rectifier with R load. The solver's step size for the simulation is 5 seconds.

Four operating conditions are used to examine the suggested model. Operating condition 1 takes place at night, when solar radiation is absent, leading to the model functioning only as a UPQC-ANFIS-RE, with $P_{pv-wind} = 0\,W$. The UPQC-ANFIS-RE system in operating condition 2 only provides active power to the utility grid while it is not under load. Operating condition 3 occurs when $P_{pv-wind} < P_L$ due to solar insolation and the load attached to the UPQC-ANFIS-RE system requiring energy. In conclusion, operating condition 4 is comparable to operating condition 3 and happens when $P_{pv-wind} > P_L$.

Figure 7. Simulation flowchart.

The flowchart outlines the operational steps of a Unified Power Quality Conditioner (UPQC) system integrated with Adaptive Neuro-Fuzzy Inference System (ANFIS) and powered by Renewable Energy (RE) in MATLAB/Simulink environment.

The system is simulated under the necessary conditions using MATLAB/Simulink in order to acquire the waveforms of PV and Wind turbine Power ($P_{pv-wind}$), grid voltage (V_g), grid current (i_g), load voltage (V_L), load current (i_L), Parallel NPC inverter currents (i_{pac}), DC link voltage (V_{dc}). The flowchart that is provided explains the suggested systems procedure in detail.

A parameters table. 2 is essential in organizing and defining the variables in the simulation of an ANFIS-based UPQC integrated with a renewable energy-based distributed generation system. Below is a breakdown of the usual parameters that may be incorporated in a table like this.

Table 2. Parameters assumed in the simulation.

S.no	Parameter	values
1	Nominal utility voltage (RMS)	$V_s = 127.27$ V
2	Utility grid frequency	$f_s = 60$ Hz
3	Leakage inductance of series coupling transformer	$L_T = 0.3$ mH
4	Resistance of series coupling transformer	$R_T = 0.28$ ohm
5	Turns ration of the series transformer	$n_T = 1:1$

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6	Inductive filter (series NPC inverter)	$L_{sec} = 1.75$ mH
7	Internal resistance of the series NPC inverter inductors	$R_{sec} = 0.2$ ohm
8	Inductive filter (parallel NPC inverter)	$L_{pac} = 1.73$ mH
9	Internal resistance of the parallel NPC inverter inductors	R_{pac}=0.2 ohm
10	Capacitive filter (parallel NPC inverter)	C_{pac}= 60 μF
11	dc-bus equivalent capacitance	$C_{dc} = 4700\ \mu F$
12	dc-bus voltage (MPP in STC)	V_{dc}= 616 V
13	Minimum dc-bus voltage	V_{dc}^{*}= 460 V
14	PWM gain	C_{pwm} = 0.0002
	Photovoltaic	
15	Active power	2.0 KW
16	Temperature	25 ℃
17	Irradiance	600 w/m^2
	PMSG wind turbine	
18	Active power	1.5 KW
19	Speed of wind	8 m/s
20	Pitch angle of blade	0 degree
	Load	
21	resistive load	R=40 ohms

This table assists in structurally arranging the parameters utilized in simulations and offers a clear comprehension of how each parameter impacts the overall efficiency of the ANFIS-based UPQC combined with renewable energy sources.

A. OPERATING CONDITION-1

The operating condition 1 means that there is no active power being generated from photovoltaic (PV) or wind energy sources. Put simply, the system is not receiving any power from the renewable energy sources. This might be because of insufficient sunlight or wind, or the system being disconnected for maintenance or other causes.

In this case, VS stands for the source voltage, while VL stands for the load voltage. This situation means that the voltage from the source is less than the voltage from the load. This scenario may be the result of different factors, like voltage decline in the transmission cables or other problems impacting the voltage distribution.

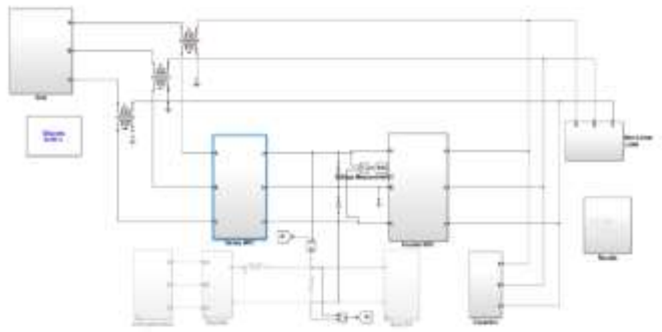

Figure 8. ANFIS Controller based UPQC with RE System with $P_{pv-wind} = 0\ w$ and $V_S < V_L$.

The power from renewable energy sources $P_{pv-wind} = 0\ W$, indicating the systems photovoltaic (PV) and wind energy sources ate not generating power.

The supply voltage (V_S) is less than the load voltage (V_L), meaning that the voltage on the supply side has dipped below the desired level required by the load.

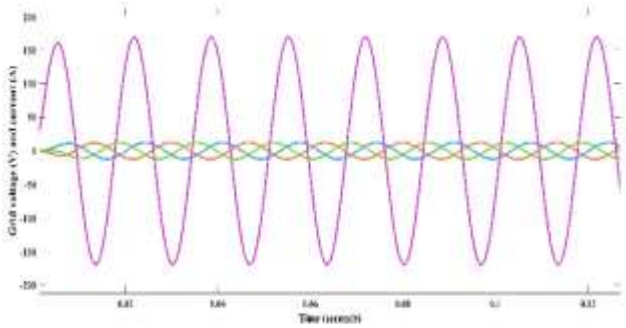

Figure 8. (A)

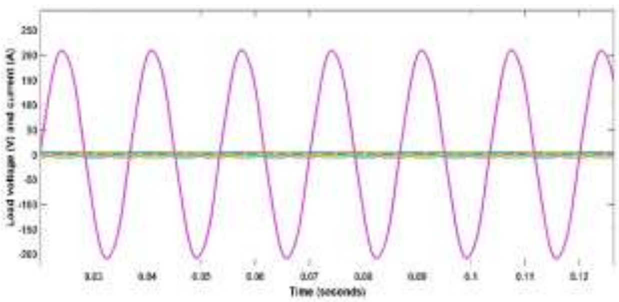

Figure 8. (B)

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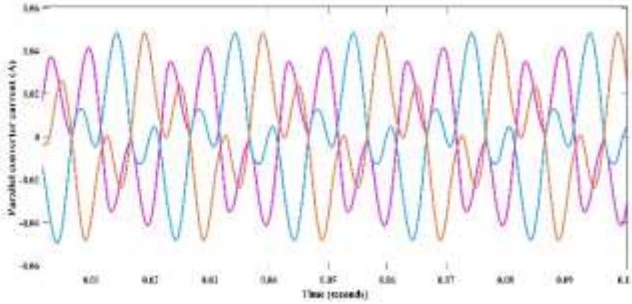

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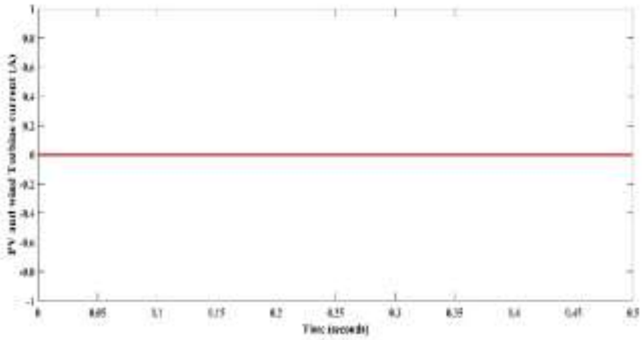

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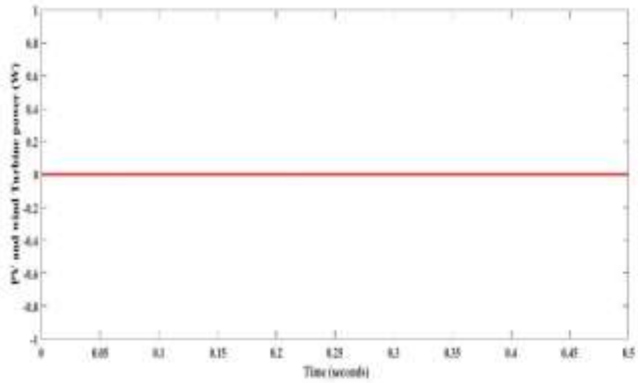

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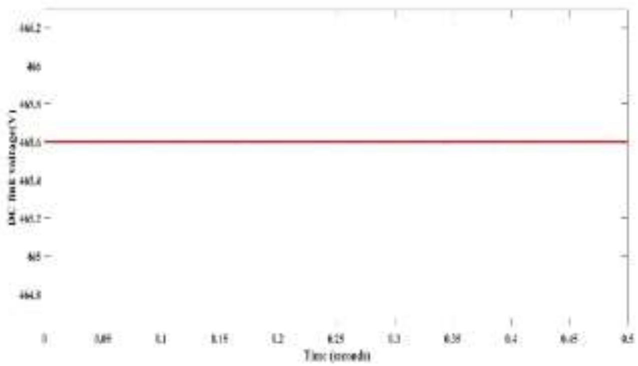

Figure 8. (F)

With $P_{pv-wind}$=0 W, the renewable energy sources are not contributing any active power. The system relies on the UPQC-ANFI to manage the power quality.

The condition $V_S < V_L$ indicates that the source voltage is lower than the load voltage, which is a typical voltage sag scenario.

B. OPERATING CONDITION-2

Operating condition 2 indicates that the load attached to the system is not utilizing any power (P_L=0 W). In simpler terms, the load does not require any active power supply.

The generation of 3500 watts of power from renewable sources like solar panels or wind turbines is represented by $P_{pv-wind}$=3500 w.

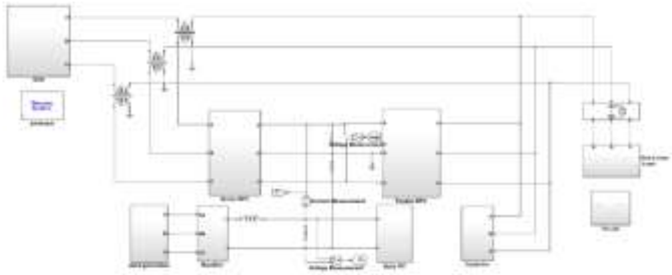

Figure 9. ANFIS Controller based UPQC with RE System with $P_{L=}$ 0 W and $P_{pv-wind} = 3500W.$

Figure 9, labelled OPC 2 (Operating condition 2), demonstrates a scenario where the ANFIS Controller based UPQC with RE system performs active power insertion into the utility gird. This occurs under the following specific conditions:

In this case, the load connected to the system is not drawing any power. This can happen when the system is in a no-load condition or during periods of very low demand.

In this operating condition, the ANFIS Controller based UPQC with RE System takes the generated power from the renewable sources and inject it into the utility grid. This is an essential functionality because it prevents the renewable energy from going to waste. By feeding this excess power back into the grid, the system enhances energy efficiency and supports grid stability.

The NPC (Neutral Point Clamped) converters play a key role in this operation. NPC converters are a type of multilevel converter that help improve voltage quality and minimize switching losses.

The series converter is responsible for injecting the renewable energy directly into the utility grid. It ensures that the power is transferred efficiently and that the voltage levels are properly adjusted to match the grid's requirements. It also compensates for any voltage imbalances or fluctuations on the grid side, maintaining stable power flow during the insertion process.

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The parallel converter is used to control the current and ensure that the power flow into the grid is smooth and free from harmonic distortions. It helps regulate the active power and ensure that the energy fed into the grid complies with grid standards, minimizing issues such as harmonic injection or reactive power imbalances.

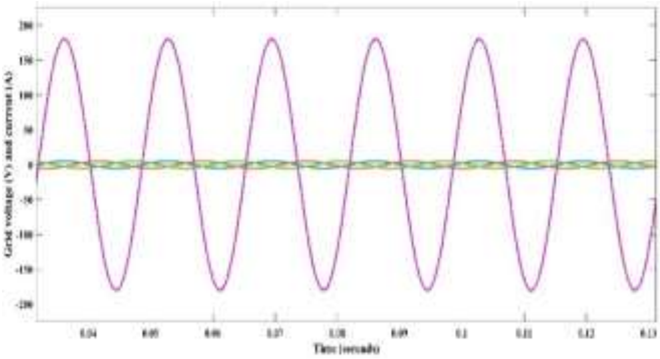


Figure 9. (A)

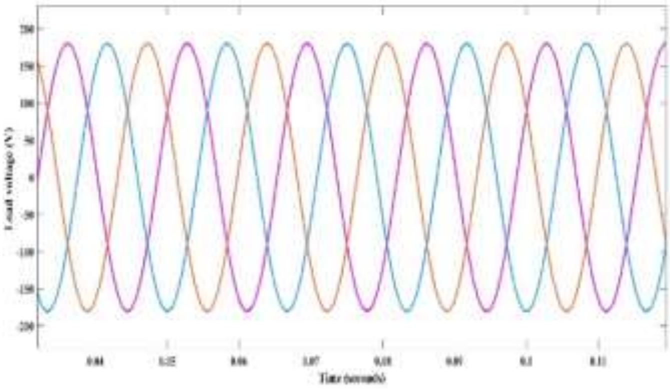
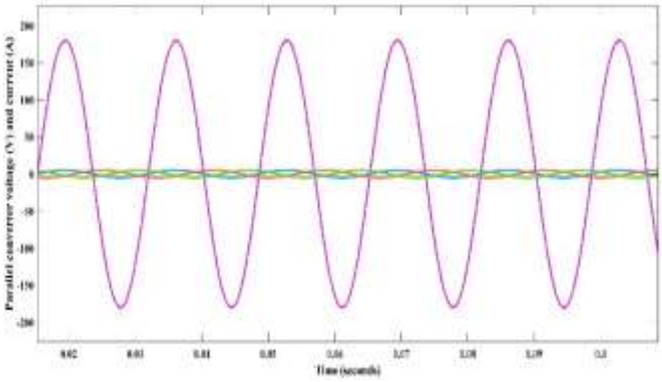


Figure 9. (B)



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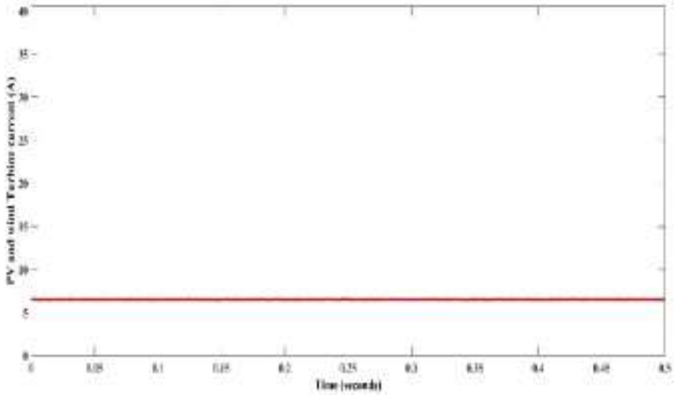

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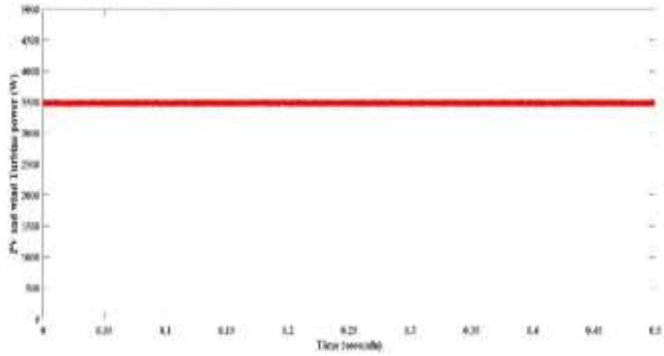

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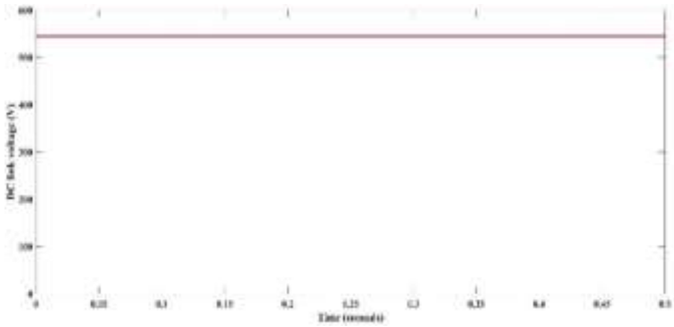

Figure 9. (F)

C. OPERATING CONDITION-3

Operating condition 3 occurs when the renewable energy sources generate less active power than the load requires. In this situation, the UPQC-ANFI is in charge of controlling and improving the power distribution. Extra active power needs to be added to the system to match the load's needs, bridging the difference between the power produced by renewable sources and the total power needed by the load.

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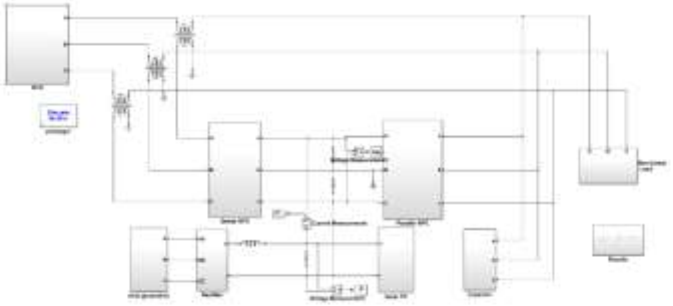


Figure 10. ANFIS Controller based UPQC with RE System $P_{pv-wind} < P_L$.

The power generated from the renewable energy sources (solar and wind) is insufficient to meet the total power demand of the connected load. In this situation, the system has to manage the available renewable power while still ensuring that the load's power requirements are met.

Active power injection of the UPQC-ANFIS-RE system takes the power generated from the renewable sources ($P_{pv-wind}$) and injects into the system to supply part of the load power demand. This injection helps reduce the amount of power that needs to be drawn from the utility gird. However, science the renewable energy is less than the load demand, the system compensates by drawing the remaining power from the grid to ensure that the load is fully supplied.

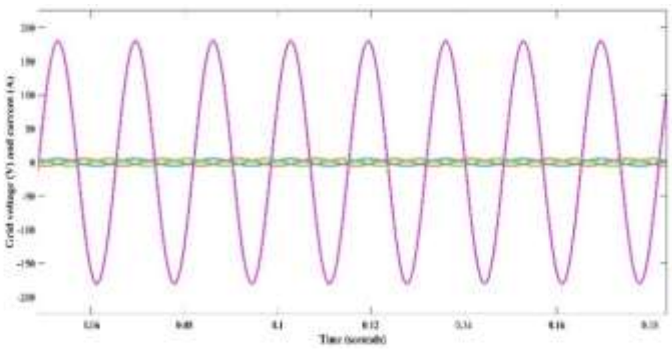
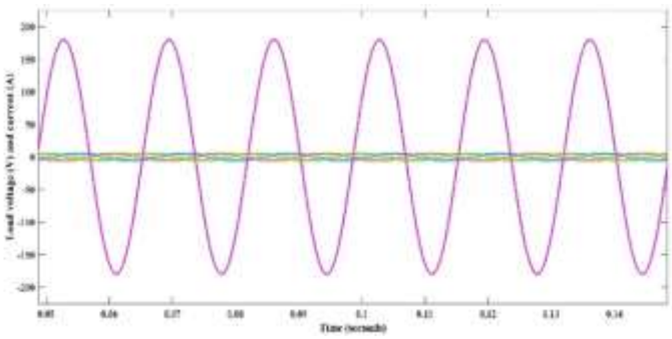


Figure 10. (A)



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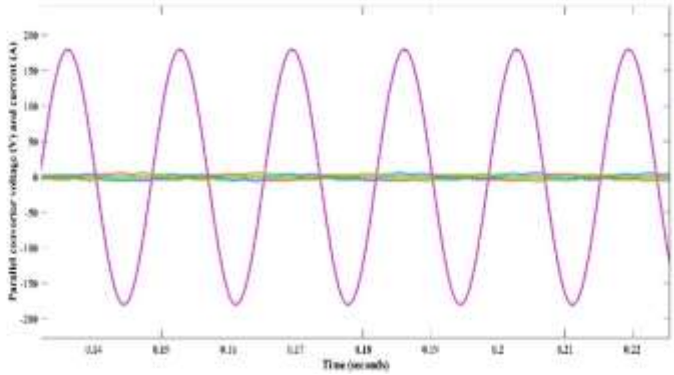

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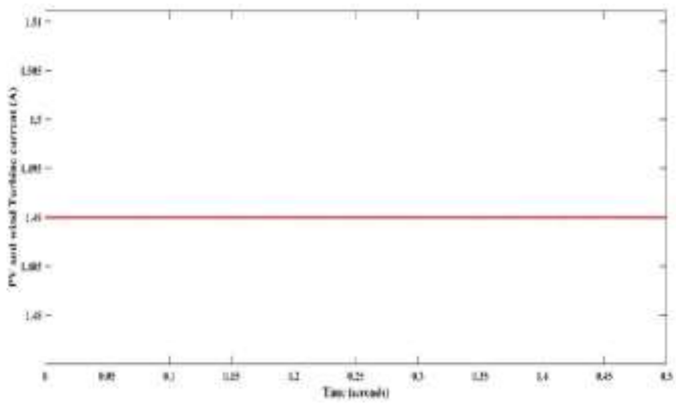

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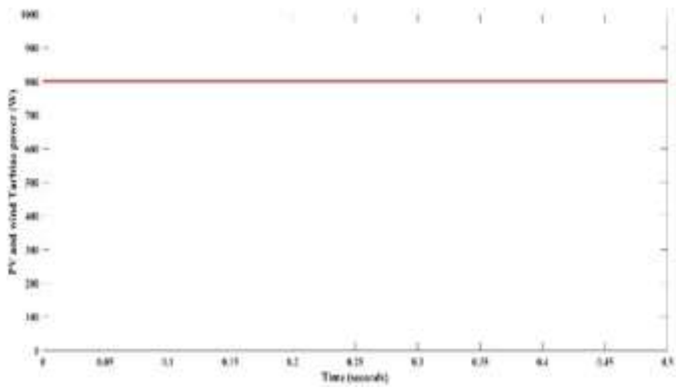

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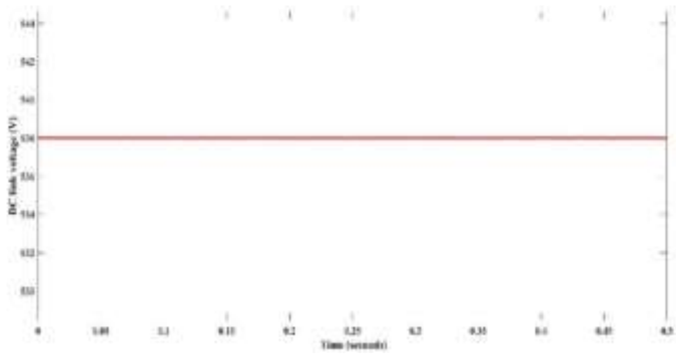


Figure 10. (F)

D. OPERATING CONDITION-4

In this scenario, the renewable energy sources are generating an excess of active power compared to the necessary load.

The renewable sources are producing excess power compared to the load requirements, the UPQC-ANFI-RE is responsible for controlling this surplus. Depending on the design and operational needs, the surplus energy can be pumped into the utility grid or stored by the system. This aids in equalizing the power distribution and preventing any excess from going to waste.

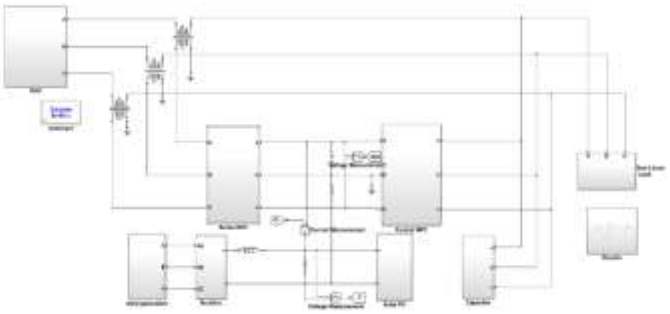


Figure 11. ANFIS Controller based UPQC with RE System with $P_{pv-wind} > P_L$.

The series NPC converter compensates for voltage disturbances, while the parallel NPC converter performs current harmonics filtering and provides reactive power compensation. During conditions where the renewable energy power generation exceeds the load demand, the surplus power is inserted into the grid, while the UPQC ensures the quality of both voltage and current through active filtering. This active filtering helps in reducing harmonics and maintaining power quality, ensuring stable operation despite the variations in load or generation.

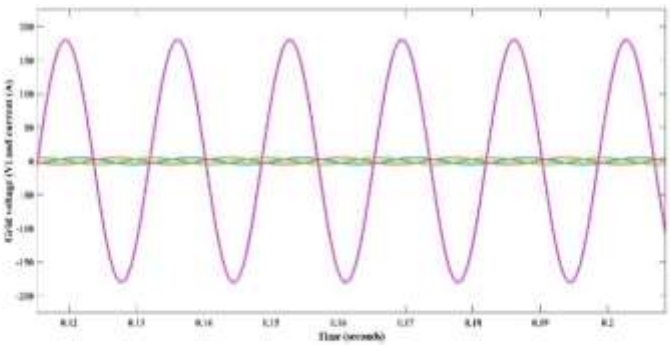
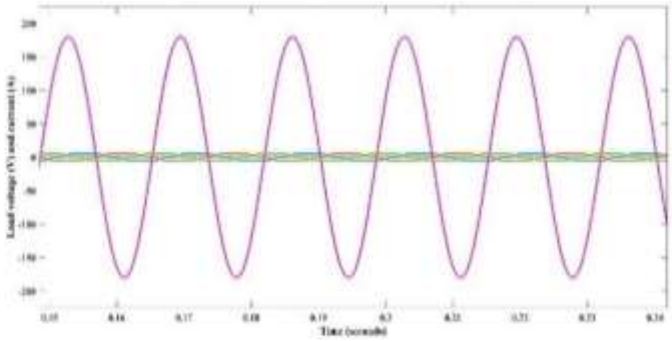


Figure 11. (A)



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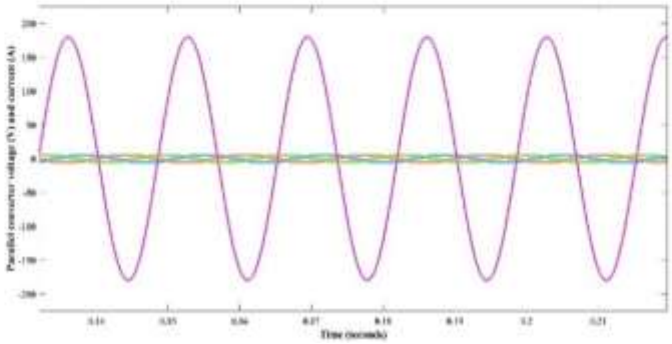

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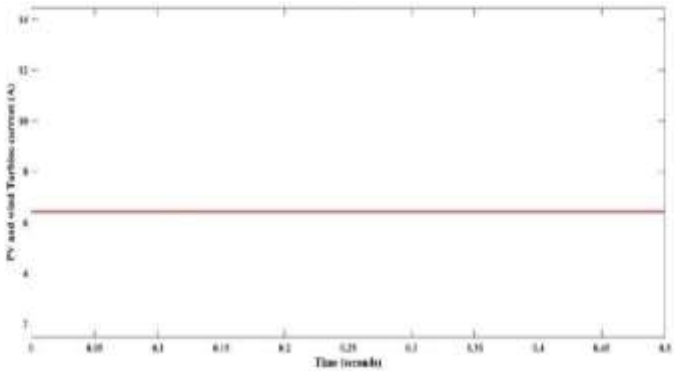

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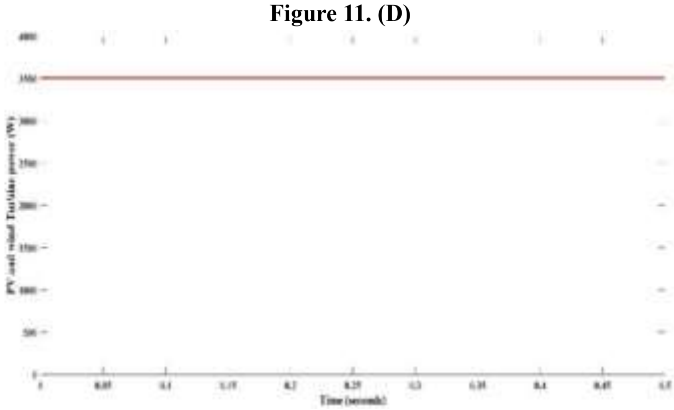

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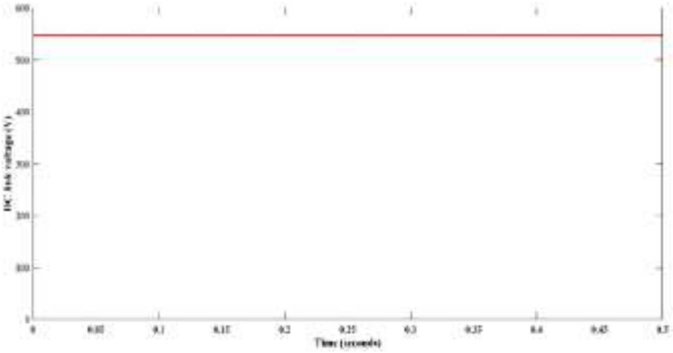

Figure 11. (F)

(A) Voltage and Current of Grid, (B) Voltage and Current of Load, (C) Voltage and currents of parallel Inverter, (D) Current of Solar PV and wind Turbine, (E) Power of Solar PV and Wind Turbine, (F) DC link voltage

Table 3. Harmonics of UPQC-ANFIS-RE System

Operating conditions	Grid voltage THD (%)	Grid current THD (%)	Load voltage THD (%)	Load current THD (%)
ANN Controller				
Condition-1	0.74	2.01	3.02	28.83
Condition-2	1.60	2.42	1.96	…
Condition-3	1.60	5.22	2.06	27.30
Condition-4	1.44	1.39	1.94	26.88
ANFIS Controller				
Condition-1	0.29	0.11	1.50	16.78
Condition-2	0.48	0.48	0.48	…
Condition-3	0.27	0.42	0.31	17.15
Condition-4	0.27	0.17	0.31	16.79

VII. COMPARISON

Comparing Traditional UPQC, Artificial Neural Network (ANN) Tuned UPQC, and Adaptive Neuro-Fuzzy Inference System (ANFIS) Tuned UPQC involves evaluating their effectiveness in managing power quality, their adaptability, and their implementation complexities. Here's a detailed comparison in table 4.

Table 4. comparison of Traditional UPQC, ANN Tuned UPQC and ANFIS Tuned UPQC.

Conditions	Tradition UPQC	ANN Tuned UPQC	ANFIS Tuned UPQC
Nominal voltage (V)	Fluctuating	Improved	Stable
Voltage deviation (V)	High	Medium	Slow
THD (%)	High	Reduced	Significantly Low
Power Factor	Low	Improved	High
Settling Time (sec)	High	Reduced	Minimal
Overshoot	High	Medium	Low
Stability	Low	Improved	High

VIII. CONCLUSION

This research focused on analysing the effectiveness of a DG system powered by renewable energy, which incorporates a UPQC and an ANFIS controller. The goal was to improve power quality and maintain voltage stability in the distribution grid, especially with the inclusion of renewable energy sources. The results from both simulations and experiments show that the suggested UPQC with ANFIS controller greatly enhances the power quality and stability of the renewable energy-based DG system, especially in situations like grid faults and load disturbances, in comparison to alternative control approaches.

The suggested system successfully controlled voltage and current harmonics, minimized power losses, and kept voltage at the point of common coupling (PCC) within acceptable levels. Moreover, the suggested system showed great effectiveness in dealing with the uneven and nonlinear loads typically found in real-world distribution systems. The findings suggest that the suggested UPQC with ANFIS controller shows promise for incorporating renewable energy into the power grid. In summary, the suggested system provides notable benefits compared to alternative control methods for improving power quality and stabilizing voltage in the distribution network. It offers a cost-efficient and effective way to enhance power quality, minimize power losses, and guarantee a steady and dependable power supply alongside renewable energy sources.

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