Enhancing Power Quality in Renewable Energy-Based Distributed Generation Systems through ANFIS-Tuned Unified Power Quality Conditioner (UPQC)

Abstract: With more and more renewable energy sources being integrated into power distribution networks, it is more important than ever to keep voltage stability and power quality at a high standard. In order to solve the problems with power quality in Distributed Generation (DG) systems, this study introduces an Adaptive Neuro-Fuzzy Inference System (ANFIS) governed Unified Power Quality Conditioner (UPQC). The study aims to bridge the gap in existing control strategies, which often struggle to maintain stable grid operation during renewable energy fluctuations and load disturbances. The suggested ANFIS-tuned UPQC system improves power quality overall and dynamically regulates voltage and current harmonics, two of the aforementioned problems. The ANFIS-tuned UPQC is compared to both traditional systems and other control approaches in this study, which makes use of modern simulation tools. In particular, the results show that voltage regulation and reduction of total harmonic distortion (THD) are significantly improved, even under circumstances of fluctuating load and grid faults. The findings underscore the effectiveness of the ANFIS-tuned UPQC in optimizing renewable energy integration, making it a robust solution for future power grids. This research presents an innovative approach to enhancing power quality, with potential applications in improving the efficiency and stability of renewable energy-based distribution systems.

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

I. INTRODUCTION

As the world's energy demand continues to rise, renewable power sources such as solar and wind have become more and more incorporated into contemporary power grids. While these sources contribute to cleaner and more sustainable energy production, their intermittent nature often causes fluctuations in power quality. Ensuring stable and high-quality power delivery, especially in distributed generation (DG) systems, is essential for maintaining the reliability of the electrical grid. A number of approaches have been devised to deal with these problems, but one of the most important is the Unified Power Quality Conditioner (UPQC), which helps to reduce the effects of voltage dips, spikes, and harmonics. The UPQC can improve its effectiveness in handling these disturbances by utilizing control systems like the Adaptive Neuro-Fuzzy Inference System (ANFIS), offering a strong solution for power quality enhancement. Previous studies have extensively explored the use of conventional control strategies like Proportional-Integral (PI) and Artificial Neural Networks (ANN) in improving power quality through UPQC systems. Researchers have demonstrated the efficacy of these methods in addressing voltage sags and harmonics in grids with high renewable energy penetration. For instance, traditional UPQC systems have been shown to effectively mitigate voltage imbalances and maintain power stability in fluctuating environments. However, limitations remain, particularly in dynamically adapting to varying grid conditions, which affects the overall performance during load disturbances and grid faults. While the integration of control strategies like ANN has enhanced UPQC performance, these methods often fall short in rapidly responding to changing grid conditions or fluctuating renewable energy output. Moreover, the inability of traditional controllers to handle non-linearities and uncertainties in power systems limits their effectiveness. This presents a need for more adaptive and intelligent control mechanisms. The gap in the literature lies in the lack of robust solutions that can efficiently integrate renewable energy sources while ensuring consistent power quality and system stability under varying operational conditions. The primary objective of this research is to develop and implement a UPQC system regulated by an ANFIS controller to improve power quality in renewable energy-based distributed generation systems. The study aims to demonstrate that the ANFIS-tuned UPQC offers superior performance over conventional controllers in reducing THD, stabilizing voltage, and maintaining reliable power quality during grid faults and load disturbances. This research focuses on the enhancement of power quality through the implementation of an ANFIS-tuned UPQC in renewable energy-based distributed generation systems. The study will primarily examine the system's performance under various operating conditions, including grid faults, load disturbances, and different renewable energy generation levels. The research does not cover other power quality conditioning systems, such as Dynamic Voltage Restorers (DVRs), and is limited to simulation-based results without experimental hardware testing.

II. LITERATURE REVIEW

The sustainable energy generation that could result from incorporating renewable energy sources into power systems has recently attracted a lot of attention. A number of approaches have been put forward to reduce power quality issues and improve the performance of hybrid renewable energy systems, with ANNs and UPQCs being the most prominent among them. This literature review highlights significant findings from recent studies while identifying existing gaps in the current body of knowledge. Rahman et al. [1] provide a comprehensive overview of methodologies employing ANNs for energy prediction in hybrid renewable energy systems. Their study emphasizes the effectiveness of neural networks in forecasting energy output but does not address the specific challenges related to integrating these predictions into real-time control systems for power quality management. Gupta and Seethalekshmi [2] present an innovative control method that combines ANNs with synchro squeezing wavelet transforms to manage power quality events in distributed generation systems. While their findings demonstrate the potential of this approach, they do not consider the impact of varying grid conditions or the scalability of their proposed method in larger systems. da Silva et al. [3] conduct a performance analysis of UPQC systems utilizing both conventional and dual/inverted power-line conditioning strategies. Although their research highlights performance differences, it lacks exploration of the adaptability of these systems under dynamic load conditions, which is critical for renewable energy integration. Mansor et al. [11] examines the design and functionality of a three-phase solar photovoltaic (PV) and battery energy storage system that incorporates UPQC. While the study's findings point to enhanced performance, it skirts the question of how battery cycling would affect the system's overall efficiency and lifetime. Amirullah et al. [14] propose a UPQC-PV-BES system controlled by fuzzy logic to enhance active power transfer. Although this approach shows promise in improving power quality, it does not delve into the operational complexities and real-time performance metrics necessary for practical implementation. Despite the advancements outlined in these studies, several critical gaps remain. Many existing control strategies, such as those discussed by Wu et al. [7] and Singh et al. [6], focus primarily on static scenarios and do not adequately address the system's dynamic response to rapid changes in load and generation. This limitation poses challenges in maintaining stable power quality in fluctuating environments, especially in rural or remote areas reliant on distributed generation systems [8]. There is a notable absence of studies that explore the integration of multiple renewable energy sources using advanced control mechanisms like ANFIS. Although Lei et al. [19] address the performance of grid-connected systems integrating hybrid wind-PV farms; the adaptability of their control techniques in a real-world context remains unexamined. The lack of research focused on real-time monitoring and control systems that leverage machine learning algorithms to predict and mitigate power quality disturbances in real-time is a significant gap. This limits the practical application of theoretical models developed in prior studies, such as those by Ray et al. [9] and Devassy and Singh [13]. While studies like those by Agarwal et al. [5] and Bouzelata et al. [15] present detailed simulations, there is a scarcity of empirical evidence validating these simulations through practical applications or field tests. The need for comprehensive evaluation methodologies that encompass both simulation and practical implementation is evident. In summary, while substantial progress has been made in the field of power quality improvement through the use of UPQC systems and advanced control strategies, significant gaps remain in addressing dynamic system responses, multi-source integration, real-time control, and comprehensive system evaluation. Future research should focus on developing adaptive solutions that can dynamically respond to the challenges posed by integrating renewable energy sources into existing power grids.

III. METHODOLOGY

1. System Modeling

The 3P4W distribution system is connected to the RE source based DGs by an ANN-based UPQC at a Hz of 60 and a voltage of 220 volts (L-L). There are three sections to the assembly.

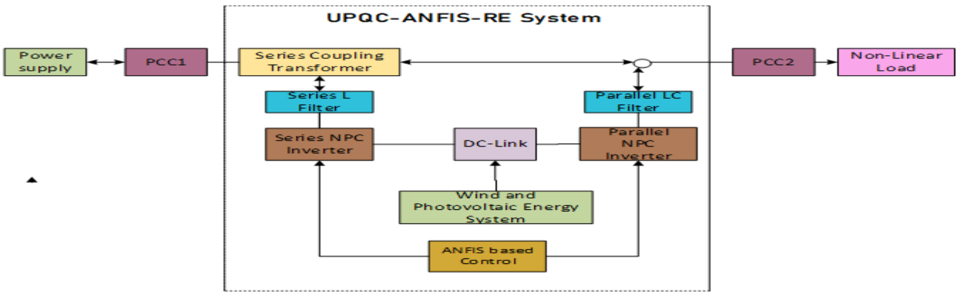


Fig.1. (a) proposed system block diagram

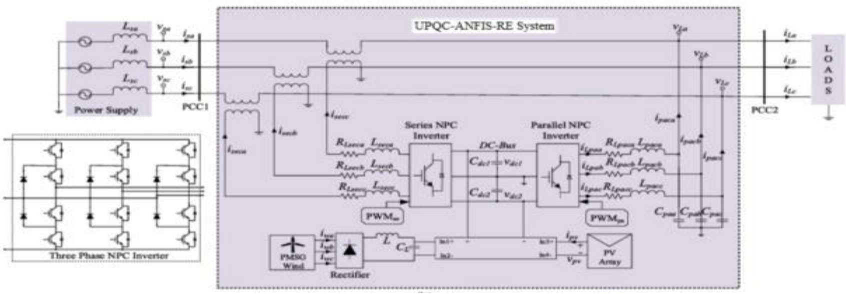


Fig. 1. (b) Proposed system circuit diagram

The first one is the DGS that uses wind and solar power in a single stage. On the other hand, you have the NPC series inverter, Lfilter(Lsec_abc) and the series coupling transformer, which are passive components. The third section concludes with LC filters (Lpac_abc and Cpa_abc) and a parallel NPC inverter. Clearly, the DC link is shared by DGs that utilize PV-wind and NPC inverters. At the same time, a local 3P4W system is created by connecting the capacitor's midway to the neutral conductor using its split configuration, which is part of the DC bus. 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

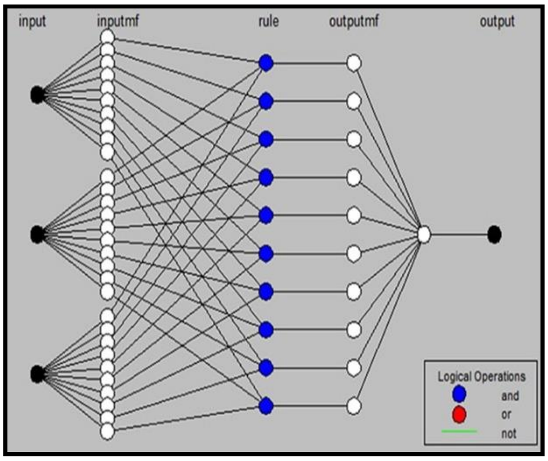


Fig.2. Structure of ANFIS controller

Rule1: If the values of x and y are A1 and B1, respectively, then
$f_1 = p_1x + q_1y + r_1$.
Rule2: With x= A2 and y= B2, then
$f_2 = p_2x + q_2y + r_2$.
What follows is an explanation of the ANFIS layers.
Layer 1: Each node of this layer is adaptive, the output is given by:
$\theta_i^1 = \mu_{Ai}(x)$ (1)
Node I takes X as input, Ai is the linguistic variable associated with it, and νAi is the membership function of Ai. Below ai, you can find μAi (x).
$\mu_{Ai}(x) = \exp\{-(\frac{x-ci}{ai})^2\}$ (2)
Layer 2: The Π symbols represent the fixed nodes. One way to represent the results of this layer is as.

θ_i^2 =ωi=μAi (x) *μBi (y) , i= 1,2 (3)

Layer 3: The nodes are too static. Their N classification suggests that they normalize the firing strengths of the previous layer. Normalized firing strength, as indicated by, is the output of the ith node.

θ_i^3= wi=$\frac{\omega i}{\omega 1-\omega 2}$ (4)

Layer 4: All of the nodes are adaptive. One thing that all the nodes in this layer do is multiply the normalized firing strength by a first-order polynomial. Therefore, the values that come out of this layer are

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

Layer 5: There is just one fixed node denoted by Γ. This node is responsible for adding up all the signals that come in. Going forward, the overall result of the model is provided by

θ_i^5 = overall –output = $\sum_i \omega_i f_i = \frac{\sum_i \omega i f i}{\sum_i \omega i}$ (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 distributed generation system for renewable energy is made more efficient and stable by combining the efforts of the ANFIS controller at the DC-bus voltage control with the ANN controllers, which provide precise and adaptive voltage regulation and accurate current management, respectively. Here, we build a hybrid green power system's power quality control using a UPQC that's based on neural networks. 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
Transistor series coupling resistances	R_T= 0.28 Ω
Turn ratio of the series transformer	n_T=1:1
PV Active Power	2.0 K W
PWM gain	C_{pwm} =0.0002
Inductive filters (parallel NPC inverter)	L_{pac} =1.73 Mh
Variations in internal resistance among inductors used in parallel NPC inverters	R_{pac}=0.2 Ω
Inductive filters (series NPC inverter)	L_{sec}= 1.75 mH
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
Capacitive filters (parallel NPC inverter)	C_{pac}=60Mf
Internal resistances of the parallel NPC inverter inductors	R_{sec}= 0.2Ω
Pitch angle of Blade	0 degree
PV Temperature	25° C
Irradiance	600 W/m2
Diode bridge rectifier operating with a resistive load in three phases (non-linear load)	R=40Ω

Speed of Wind	8 m/s
Active Power PMSG Wind Turbine	1.5 K W

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]. Grid electricity sent to the load. The DC-link relies on grid to maintain the necessary voltage levels.

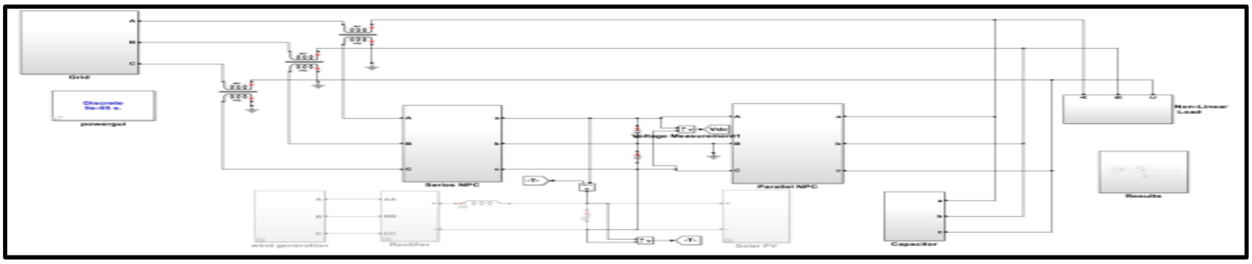


Fig.3. Simulink Model of UPQC-ANFIS-RE OPC 1

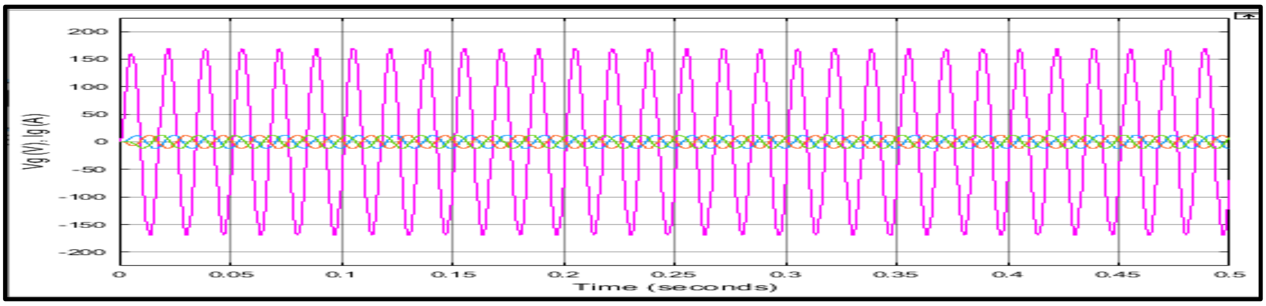


Fig.3.(a) Grid Voltage and Grid Current

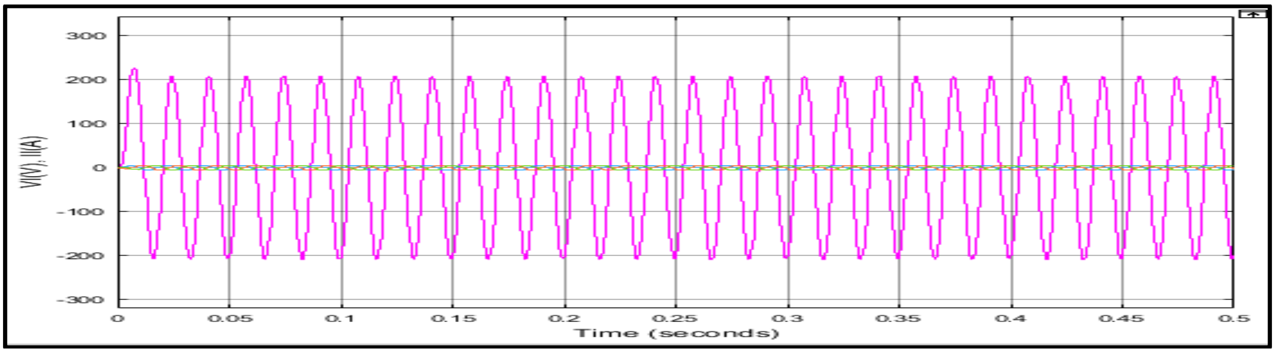


Fig 3.(b). Load Voltage and Load Current

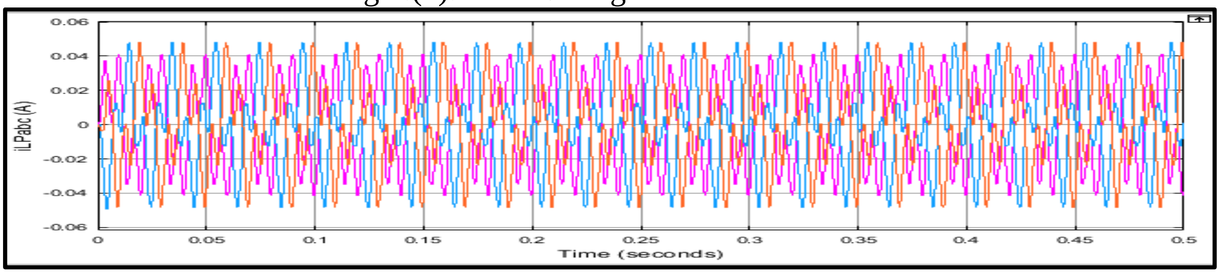


Fig .3. (c) Current at Parallel Inverter

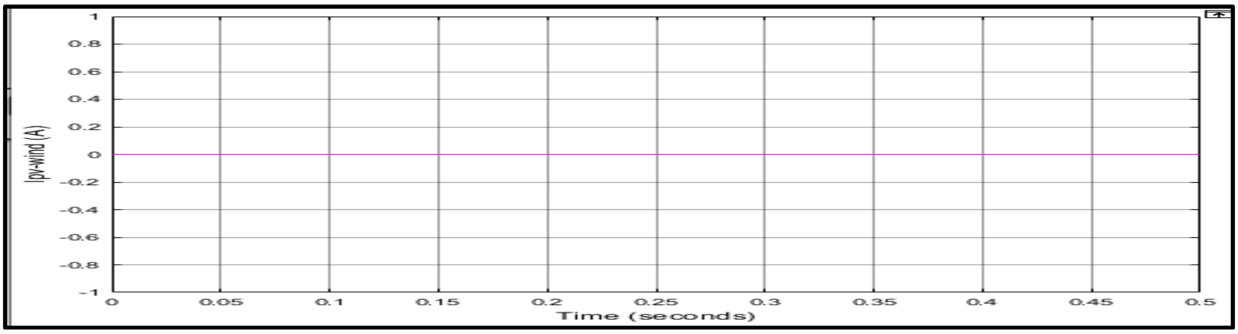


Fig.3.(d) Solar PV and Wind Turbine related Current

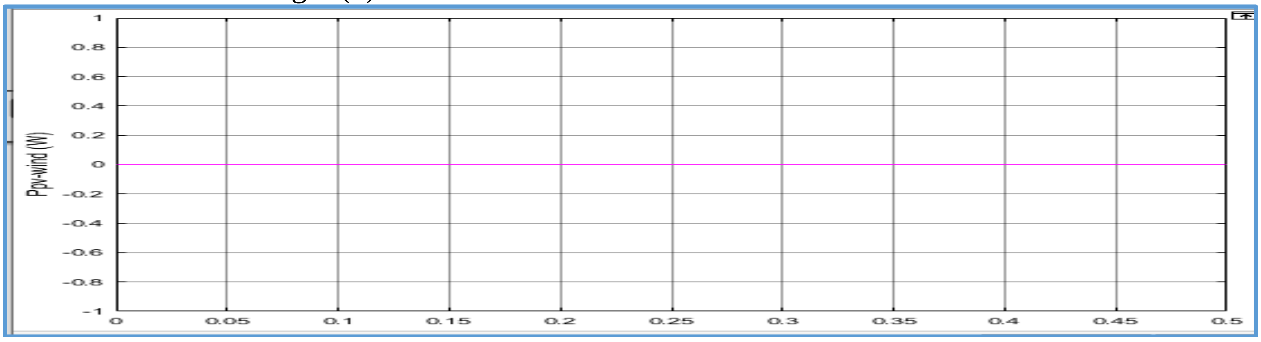


Fig.3.(e) Solar PV and Wind Turbine related Power

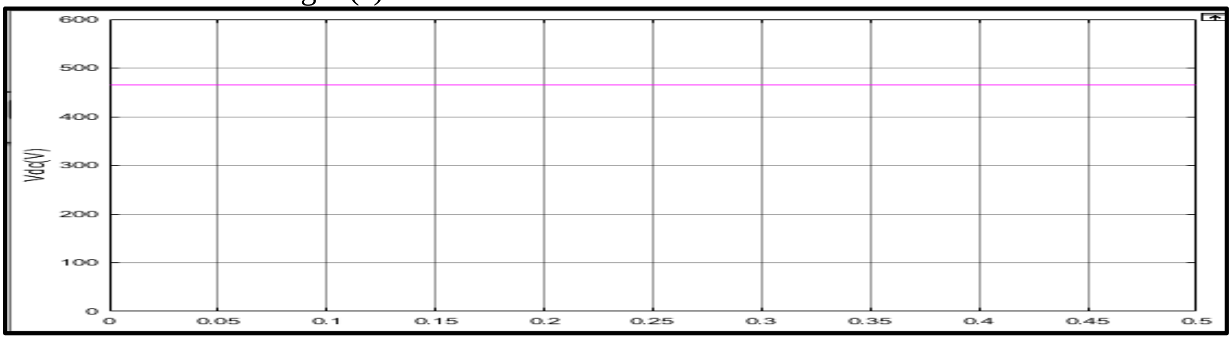
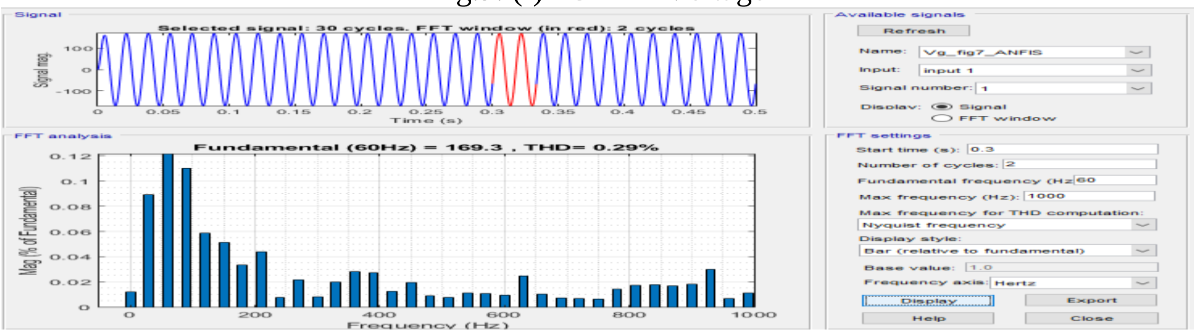
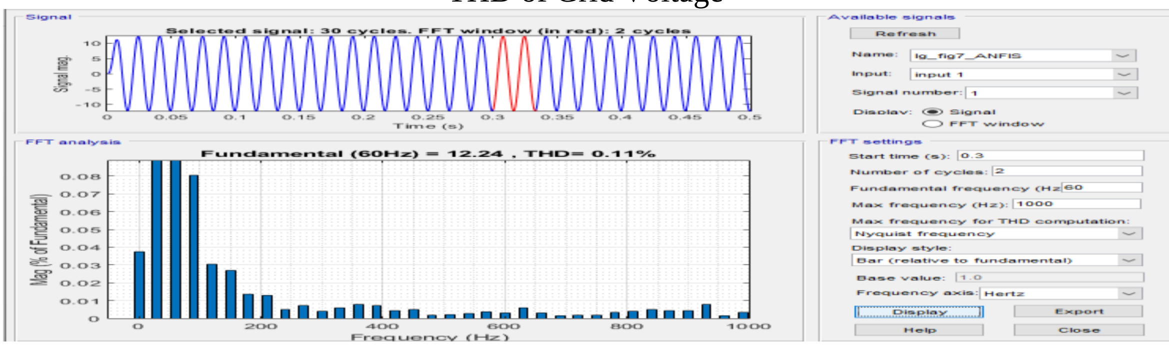


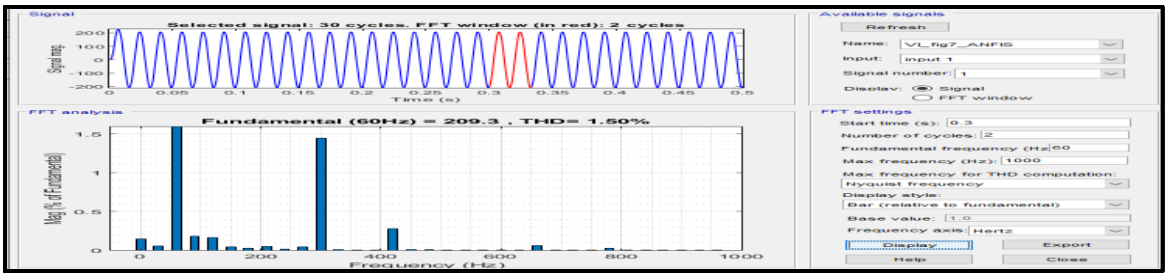
Fig.3. (f)DC Link Voltage



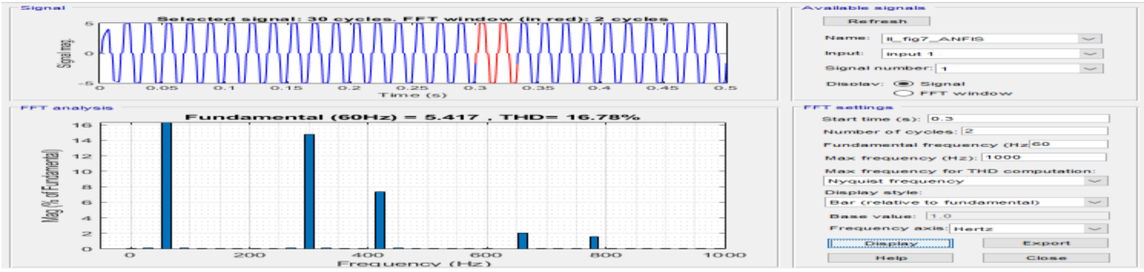
THD of Grid Voltage



THD of Grid Current



THD of Load Voltage



THD of Load Current

Active/real power-line conditioning is the sole function of UPQC-ANFIS-RE OPC-1, as shown in figure 3, where Ppv−wind = 0W and Vs

Grid current and voltage total harmonic distortion Measurements of power usage and voltage at the load

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B. UPQC-ANFIS-RE OPC 2

The load is not necessary for the UPQC-ANFIS-RE system to operate. Using grid power, the UPQC system maintains its DC-link voltage and stays in a monitoring condition even when the load is disconnected. 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.

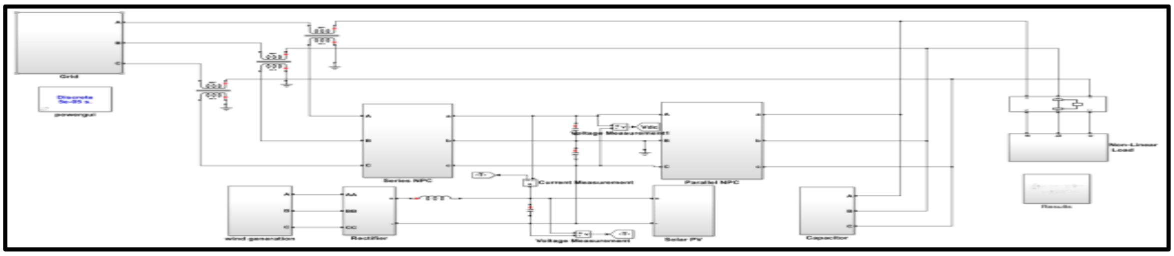


Fig .4. Simulink Model of UPQC-ANFIS-RE OPC 2

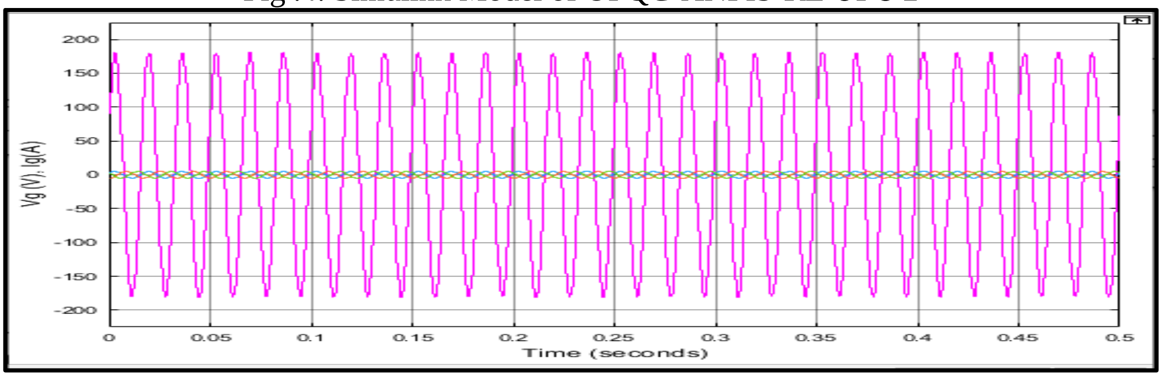


Fig .4. (a) Grid Voltage and Grid Current

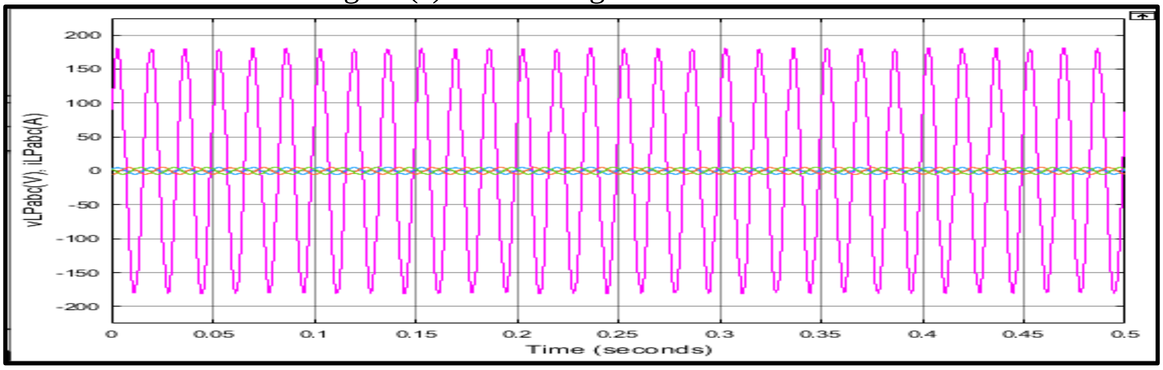


Fig.4.(b) Parallel Inverter Voltage and Current

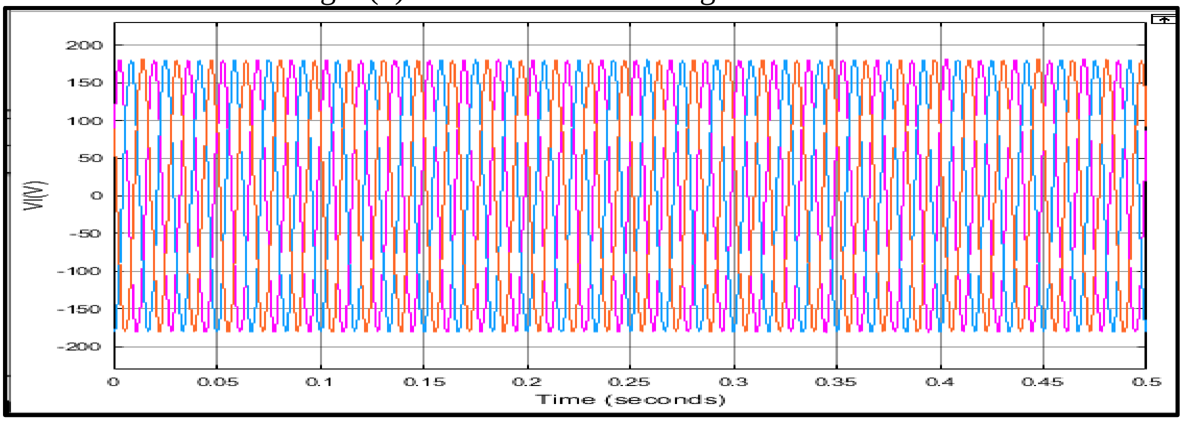


Fig.4.(c) Load Voltage

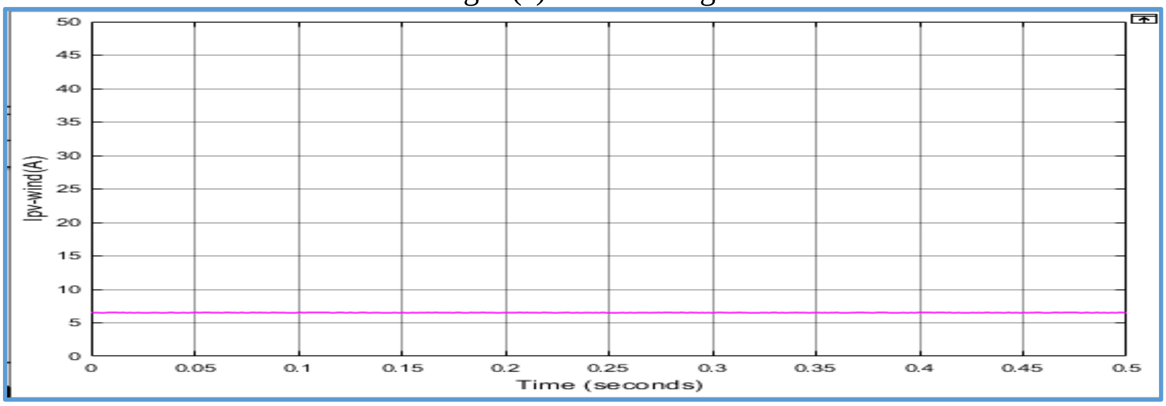


Fig.4. (d) Solar PV and Wind Turbine related Current

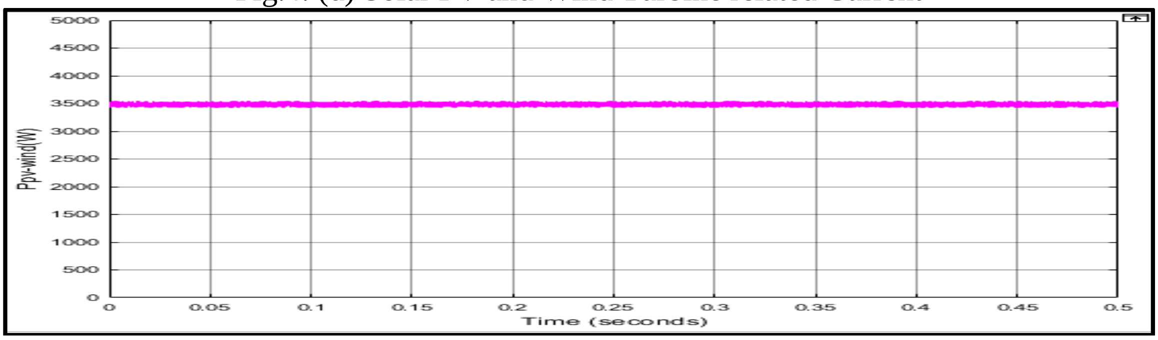


Fig.4. (e) Solar PV and Wind Turbine related Power

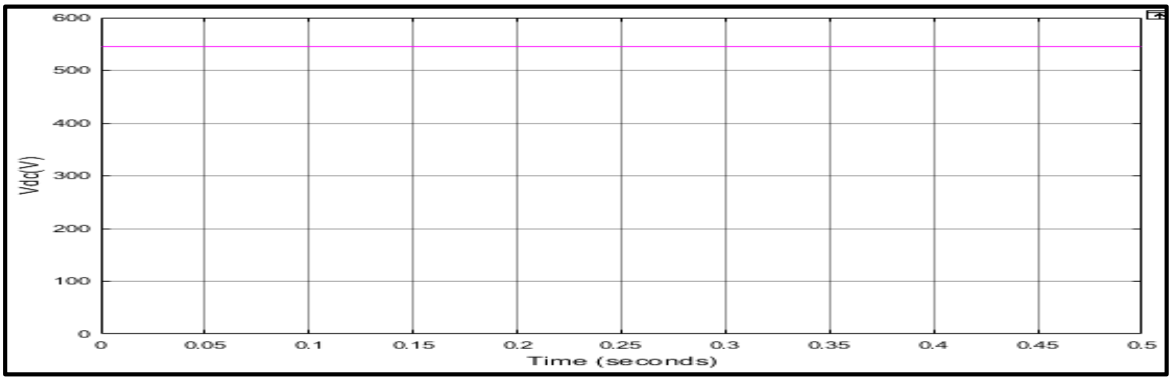
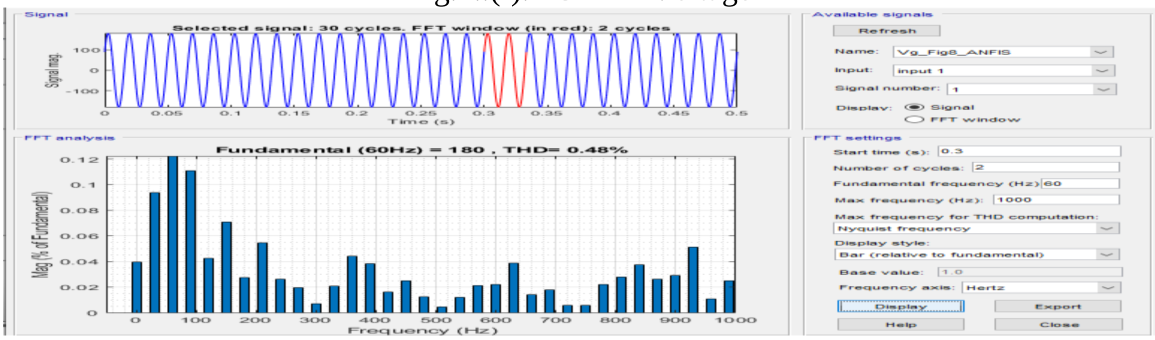
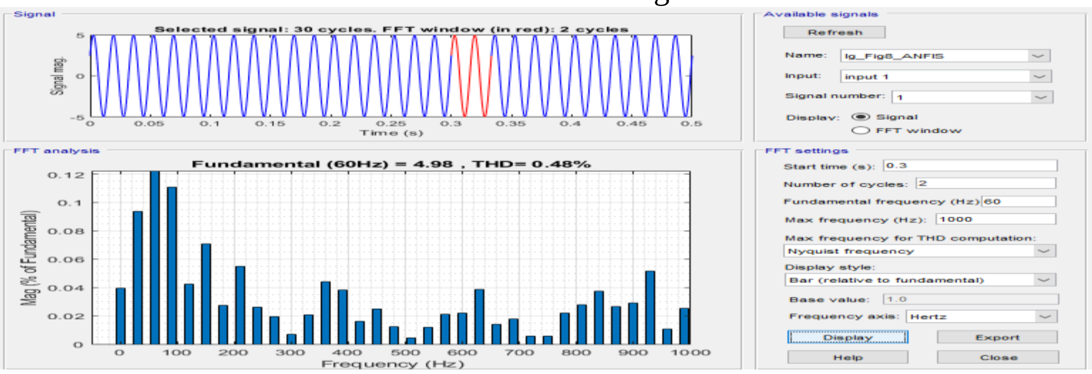


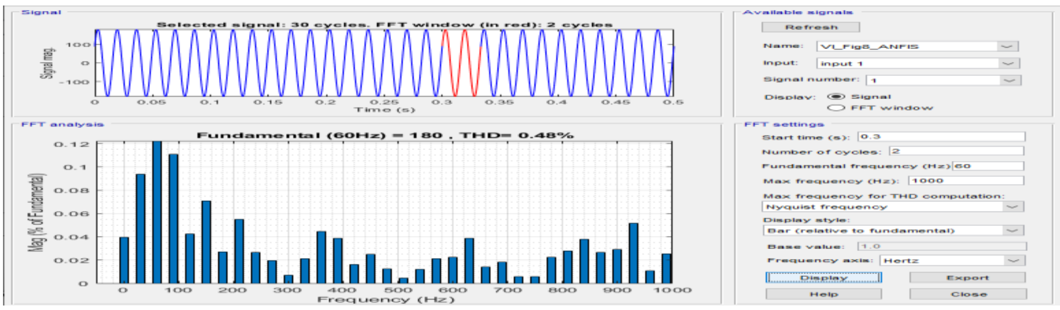
Fig.4..(f).DC Link Voltage



THD of Grid Voltage



THD of Grid Current



THD of Load Voltage

The UPQC-ANFIS-RE OPC-2 actively feeds power into the utility grid with PL=0W and Ppv−wind=3500W, as shown in figure 4.(a) Power from the grid and the wind turbine, (b) Voltage at the load, (c) Voltage at the parallel NPC inverter, (d) Current in the PV array, (e) Power from the wind turbine, and (f) Voltages at the DC links.
THD of the grid's current and voltage Power consumption and voltage at the load.

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.

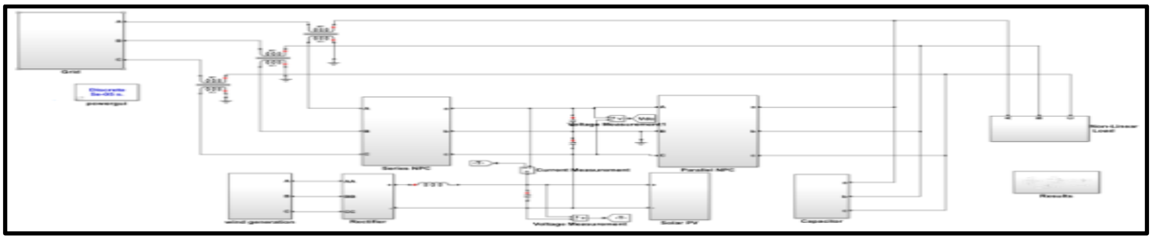


Fig.5. Simulink Model of UPQC-ANFIS-RE OPC 3

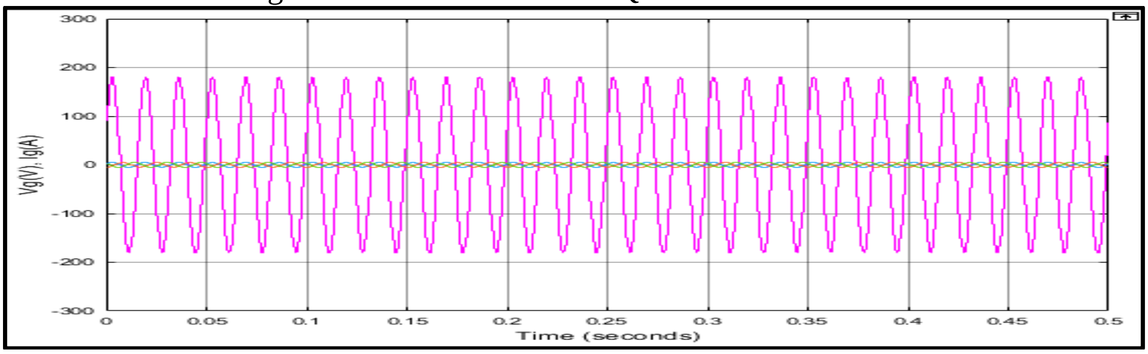


Fig.5 (a) Grid Voltage and Grid Current

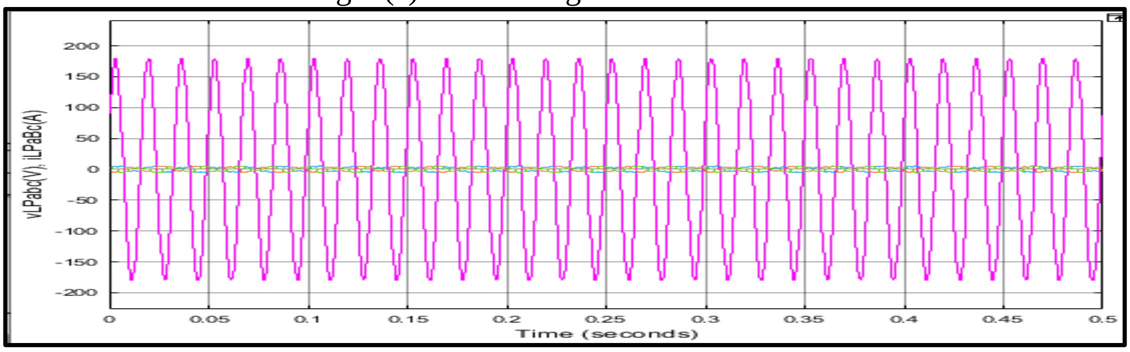


Fig.5.(b) Parallel Inverter Voltage and Current

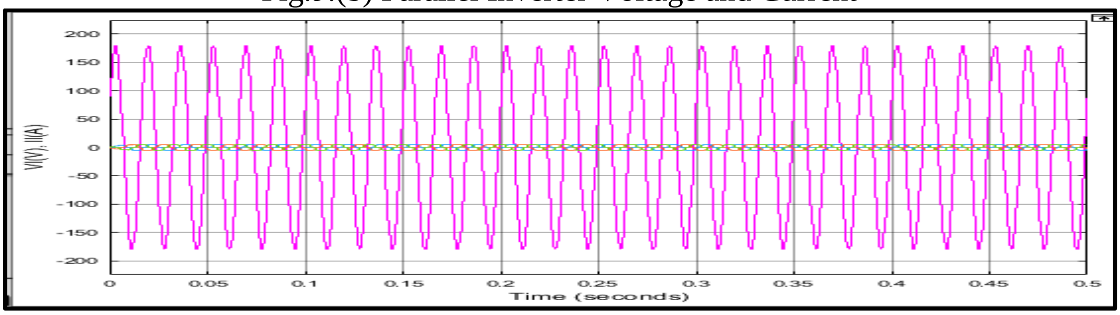


Fig.5. (c) Load Voltage and Load Current

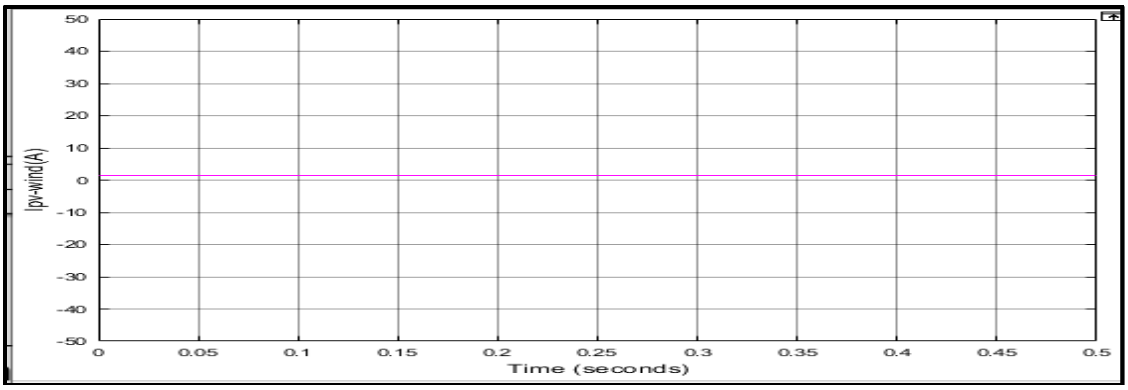


Fig.5.(d) Solar PV and Wind Turbine related Current

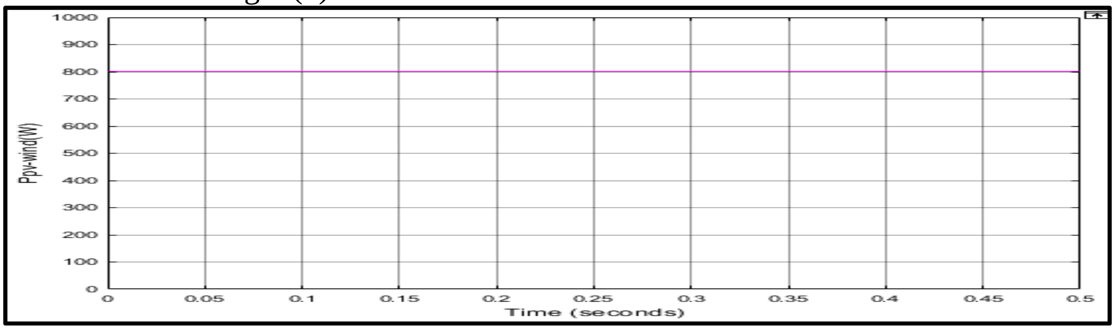


Fig.5. (f)Solar PV and Wind Turbine related Power

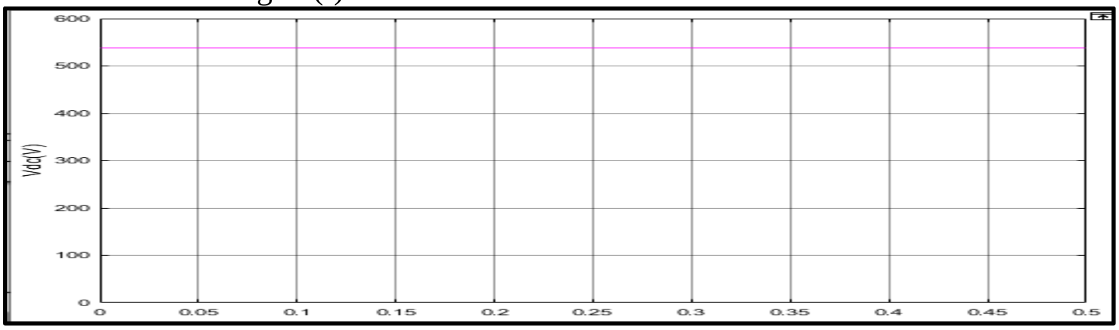
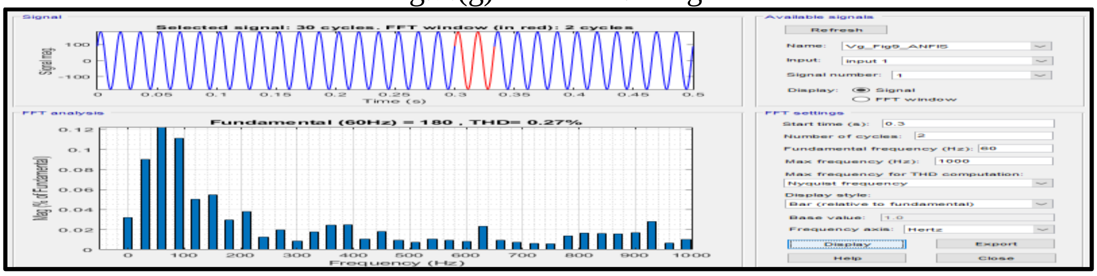
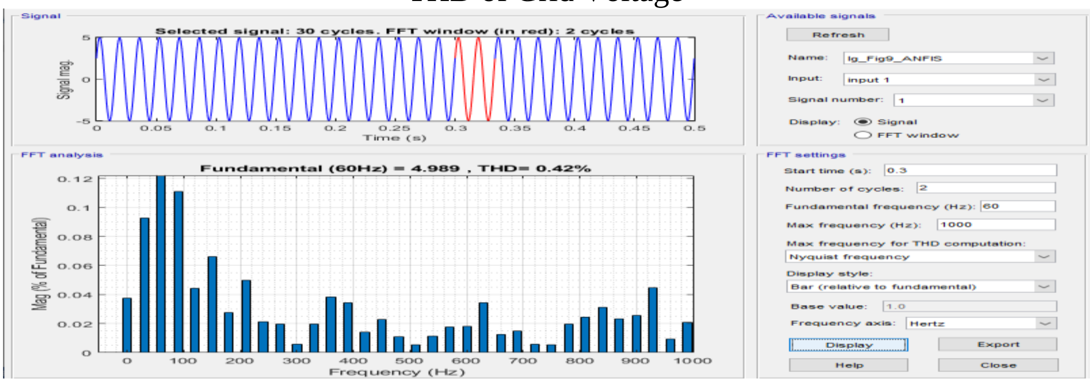


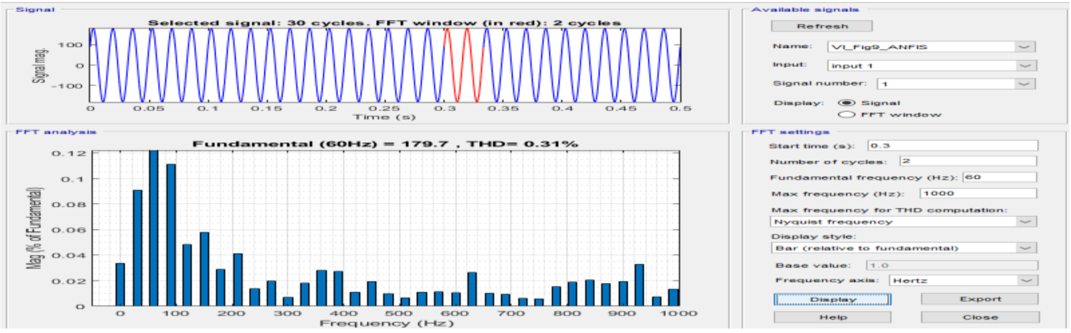
Fig.5.(g)DC Link Voltage



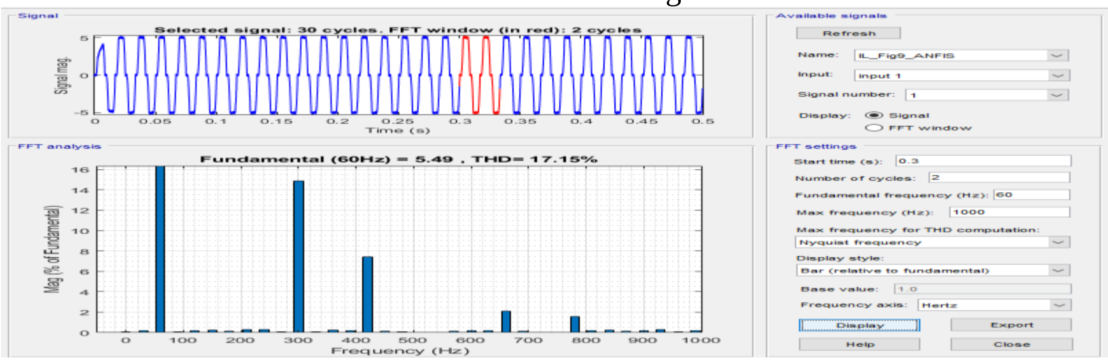
THD of Grid Voltage



THD of Grid Current



THD of Load Voltage



THD of Load Current

Figure 5 shows the process of active power insertion and active filtering through UPQC-ANFIS-REOPC-3 with Ppv−wind< PL. the grid's voltage and current; the load's voltage; and the currents flowing through parallel NPC inverters (a) Load voltage and current (c) Power from PV arrays and wind turbines (d) Grid voltage and current (e) Voltages across DC connections.
voltage and current on the grid (f) on a THD scalePower consumption and voltage at the load.

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.

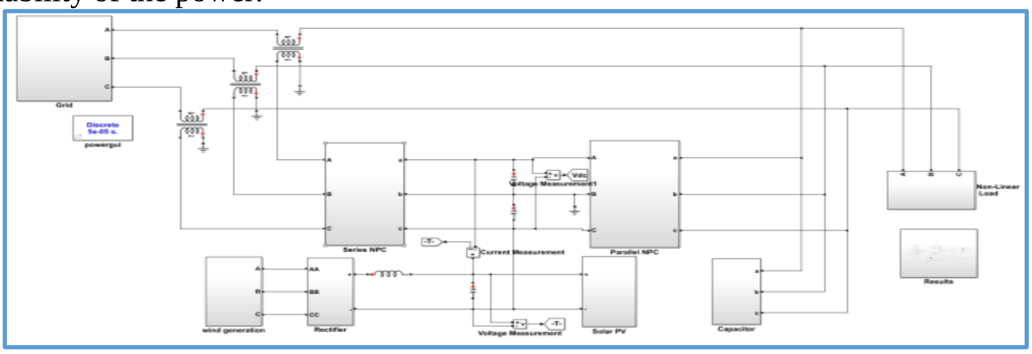


Fig.6.Simulink Model of UPQC-ANFIS-RE OPC 4

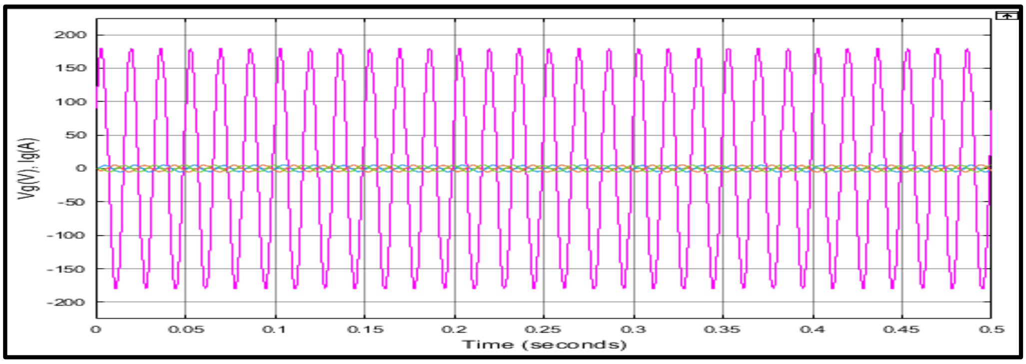


Fig.6.(a) Grid Voltage and Grid Current

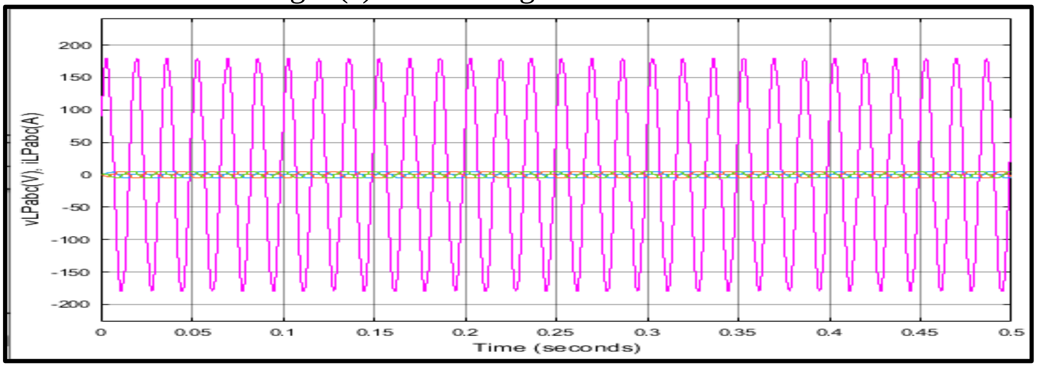


Fig.6.(b) Parallel Inverter Voltage and Current

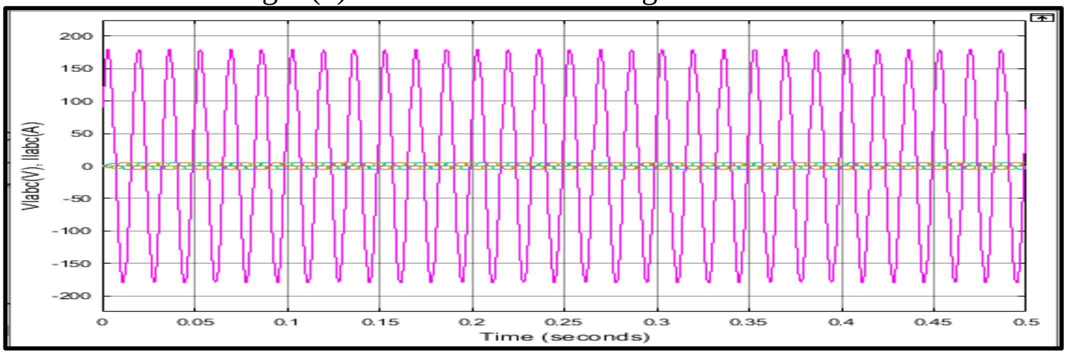


Fig.6. (c) Load Voltage and Load Current

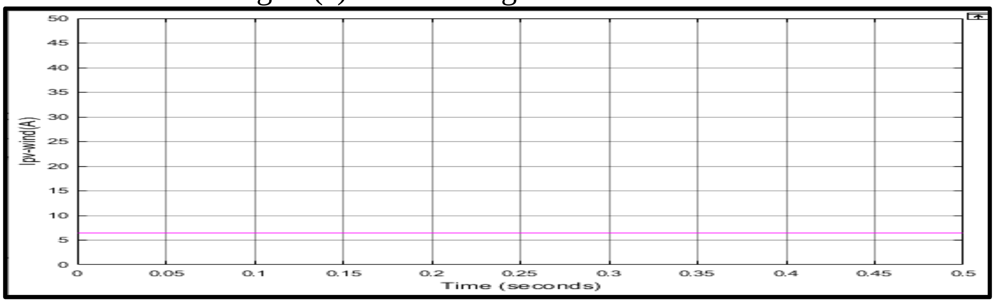


Fig.6. (d) Solar PV and Wind Turbine related Current

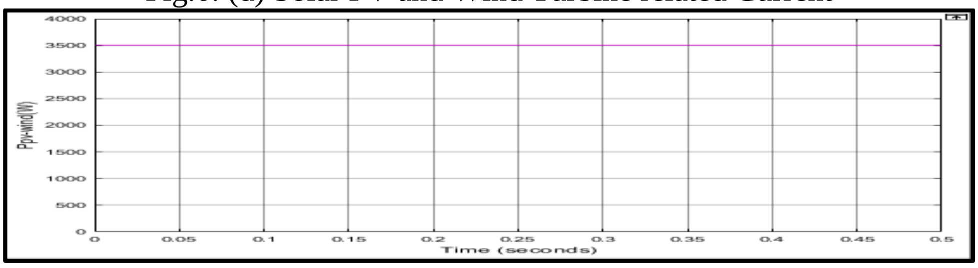


Fig .6.(e) Solar PV and Wind Turbine related Power

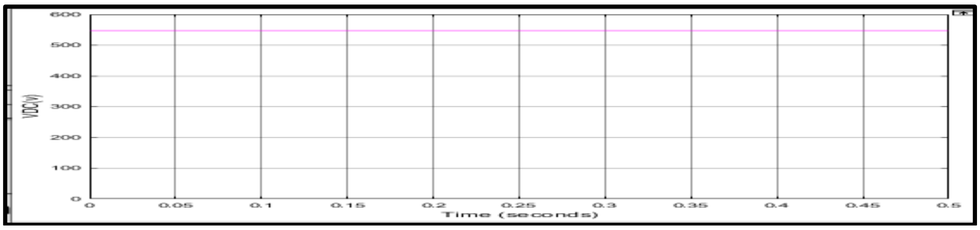
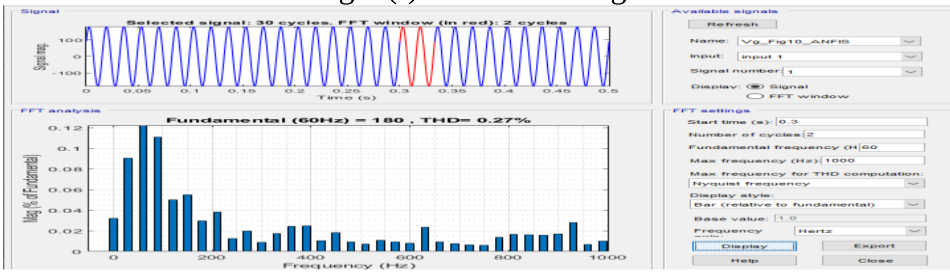
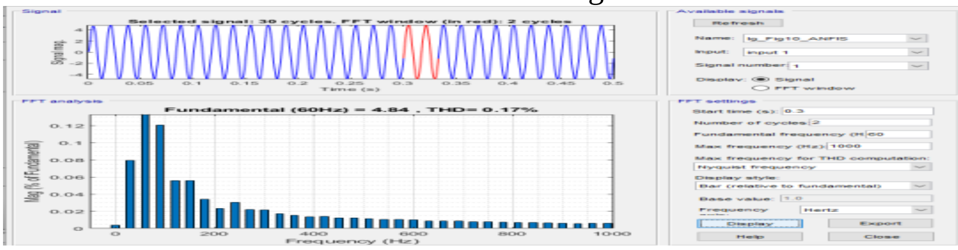


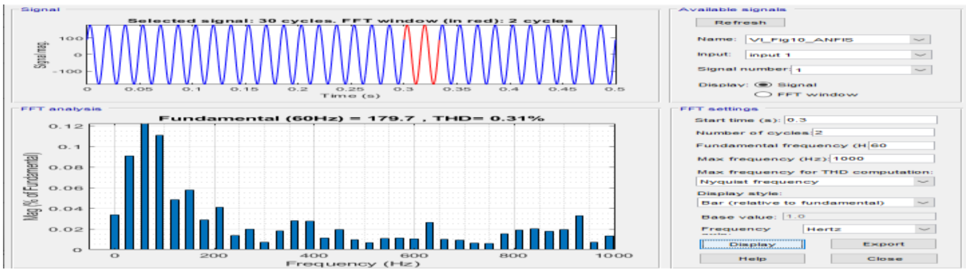
Fig.6.(f)DC Link Voltage



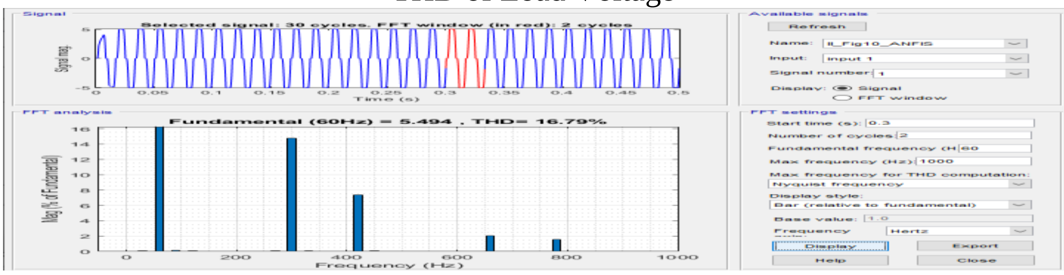
THD of Grid Voltage



THD of Grid Current



THD of Load Voltage



THD of Load Current

Figure 6 shows how UPQC-ANFIS-REOPC-4 utilizes Ppv−wind> PL to accomplish active power insertion and active filtering. the grid's voltage and current; the load's voltage; and the currents flowing through parallel NPC inverters (c)Load voltage and current; (d)Power from PV arrays and wind turbines; (e)Voltages across DC links; and (f)Load voltage and current. 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

A distributed generation (DG) system that relies on renewable energy sources and employs a controller based on the ANFIS was studied in this study. It was especially important to improve power quality and stabilize voltage in the distribution network when renewable energy sources were present. From what we can tell from both the simulations and the experiments, the suggested UPQC with ANFIS controller is the best control strategy for renewable energy-based DG systems in terms of power quality and stability, especially in the face of grid failures and load disruptions. Voltage at the point of common coupling (PCC) was kept below acceptable limits, power losses were decreased, and harmonics in both voltage and current were effectively suppressed by the suggested system. And when it came to dealing with the nonlinear and imbalanced loads that are typical in real-world distribution systems, the suggested approach performed great. Incorporating renewable energy sources into the power grid has never been easier than with the suggested UPQC with ANFIS controller, according to the results. Ultimately, as compared to alternative control systems, the suggested solution provides considerable benefits for the distribution network's voltage stability and power quality. In the context of renewable energy sources, it offers a practical and economical way to enhance power quality, decrease power losses, and guarantee a steady and dependable power supply.

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