

<sup>1</sup>Manku Priya  
<sup>2</sup>Chada Prathyusha\*

# Adaptive Control of Three-Level UPQC via ANFIS for Enhanced Power Quality: A MATLAB/Simulink-Based Evaluation



**Abstract:** - This paper presents a comprehensive study of a three-level Unified Power Quality Conditioner (UPQC) controlled by Adaptive Neuro-Fuzzy Inference System (ANFIS) and its simulation in MATLAB/Simulink. The UPQC is designed to enhance power quality by simultaneously mitigating voltage sags, swells, and harmonic distortions while providing voltage regulation. The proposed ANFIS controller leverages the advantages of both fuzzy logic and neural networks, allowing for adaptive learning and improved performance in dynamic environments. Simulation results demonstrate the effectiveness of the ANFIS controller in comparison to traditional Proportional-Integral (PI) and fuzzy controllers. Key performance metrics, including response time, settling time, and steady-state error, are evaluated across various operating conditions. The findings indicate that the ANFIS-controlled UPQC outperforms both the PI and fuzzy controllers in terms of rapid response and robustness, making it a promising solution for advanced power quality management in modern electrical systems. This research contributes to the growing body of knowledge on intelligent control strategies for power quality enhancement, emphasizing the potential of ANFIS in improving the performance of UPQC systems.

**Keywords:** Three-level UPQC, ANFIS controller, Power quality enhancement, MATLAB/Simulink simulation, PI controller comparison, Fuzzy control.

## I. INTRODUCTION

The growing reliance on electrical energy and the integration of renewable energy sources into modern power grids have intensified the need for maintaining high power quality. In this context, power quality issues such as voltage sags, swells, unbalance, and harmonic distortions have become significant concerns [1]. These disturbances can negatively impact the performance and longevity of electrical equipment, leading to increased energy losses, reduced system efficiency, and potential damage to sensitive devices. Ensuring stable and clean power delivery is, therefore, critical to the overall performance of power systems, especially in grids with renewable energy integration. One of the most effective solutions to address power quality issues is the Unified Power Quality Conditioner (UPQC). UPQC is a multifunctional device capable of simultaneously mitigating voltage- and current-related disturbances, thereby improving the overall power quality of the grid. Traditional UPQC systems typically operate using a two-level inverter, which, although effective, may not offer the best performance in handling complex power quality issues under dynamic grid conditions [2-3].

The foundational work on UPQC introduced a system for simultaneous mitigation of voltage and current disturbances in power systems in [4-5]. The UPQC employed a series and parallel inverter configuration to address power quality issues. The proposed system was based on traditional two-level inverters, which struggled with harmonic suppression in high-power applications. In [6] authors improved the original UPQC by introducing an advanced control technique for better compensation of harmonics and reactive power in nonlinear loads. The control technique was complex and required precise tuning, making it difficult to implement in real-time under dynamic grid conditions. In [7] authors proposed a three-phase four-wire UPQC system designed to mitigate both current and voltage imbalances in distributed generation systems. The system faced issues with increased losses in the four-wire configuration, reducing overall system efficiency. In [8] The authors developed a new control algorithm for UPQC aimed at reducing voltage sags and swells. The control method effectively addressed short-duration disturbances. The method was less effective in dealing with long-duration voltage fluctuations and harmonics simultaneously.

In [9] author implemented a UPQC using a synchronous reference frame (SRF) control strategy for better harmonic mitigation and reactive power compensation. The SRF-based control had a slow dynamic response during sudden voltage changes, limiting its performance in fast-changing grid environments. In [10] author proposed a UPQC with a real-time control system designed to address voltage sags, swells, and load imbalances in a grid-connected environment. The real-time control system required significant computational resources,

<sup>1</sup>Research Scholar, Chaitanya Deemed to be University, Assistant professor, Sumathi Reddy institute of technology for Women, Warangal, Telangana, India

<sup>2</sup>\*Corresponding author: Associate Professor, Chaitanya Deemed to be University, Warangal, Telangana, India  
[chada.prathyusha@gmail.com](mailto:chada.prathyusha@gmail.com)

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making it unsuitable for low-cost implementations. In [11] author introduced a dual-inverter-based UPQC configuration to improve harmonic mitigation in both high-voltage and high-power applications. The dual-inverter system was expensive to implement and maintain due to the increased number of power components. In [12] The authors presented a novel hysteresis-based control strategy for UPQC to achieve better dynamic performance in harmonic suppression and voltage stabilization. The hysteresis control led to higher switching losses, which decreased the overall efficiency of the UPQC system. In [13] this author focused on improving power quality using a UPQC with a simplified control algorithm for real-time applications. The simplified algorithm compromised on precision, leading to lower accuracy in compensating for harmonic distortion. The study proposed a comprehensive design of a UPQC for power quality improvement in distributed generation systems with varying load conditions in [14]. The system was not capable of efficiently handling unbalanced loads, leading to reduced performance under such conditions.

In [15] author enhanced the performance of a UPQC by incorporating a fuzzy logic controller to handle non-linear loads and improve harmonic compensation. The fuzzy logic controller required extensive tuning and was highly dependent on membership function design, making it less flexible. In [16] authors introduced a UPQC with fault ride-through capability, designed to enhance system stability during grid faults. The added fault ride-through functionality increased the complexity of the system, leading to higher implementation costs. In [17] author proposed a voltage-controlled UPQC for power quality improvement in renewable energy systems, particularly focusing on reducing voltage fluctuations. The voltage-controlled approach was less effective in mitigating harmonic distortions, which are common in renewable energy systems. In [18] author introduced a neural network-based control for UPQC to achieve better adaptive performance in dynamic grid conditions. The neural network control required a large training dataset, making it challenging to adapt in real-time grid conditions. In [19] author presented a three-level UPQC for improved harmonic mitigation and better voltage control in high-power applications. While the three-level topology improved performance, it increased the system's complexity and cost, limiting its practical application in smaller-scale systems.

From the literature review, it is evident that UPQC technology has evolved significantly over the years, with various control strategies and inverter topologies being proposed to address power quality issues. While two-level inverters and conventional control techniques have been widely used, their limitations in harmonic suppression, dynamic response, and system efficiency under complex grid conditions are apparent [20]. More advanced approaches, such as three-level inverters and intelligent control algorithms like ANFIS, offer promising solutions to overcome these limitations, making them suitable for enhancing the performance of grid-connected PV systems [21-22]. The proposed ANFIS-controlled three-level UPQC in this study builds upon the advancements from previous research, addressing drawbacks such as system complexity, efficiency, and real-time adaptability, thereby offering a more efficient and stable solution for power quality enhancement. This paper focuses on the design and implementation of an ANFIS-controlled three-level UPQC, aiming to provide an advanced solution for enhanced power quality in grid-connected systems [22]. The proposed system is designed to handle a wide range of power quality issues, including voltage sags, swells, unbalance, harmonic distortion, and DC offsets, thereby ensuring a more stable and efficient power supply. To enhance the performance of conventional UPQC systems, this paper proposes a novel Adaptive Neuro-Fuzzy Inference System (ANFIS)-controlled three-level UPQC. The three-level inverter topology provides better harmonic mitigation and improved voltage control compared to two-level inverters, making it ideal for high-power applications. By incorporating ANFIS control, the system can dynamically adapt to varying grid conditions, optimizing its response to disturbances and ensuring superior power quality.

## II. PROPOSED CUSTOMIZED UPQC DEVICE FOR POWER QUALITY IMPROVEMENT

The block diagram of the UPQC device for power quality (PQ) enhancement is shown in Fig. 1. In this configuration, the three-phase utility grid delivers power to a nonlinear diode-bridge rectifier (DBR) load via a three-phase distribution network. The system includes a supply voltage  $V_{sabc}$ , a supply current  $I_{sabc}$ , and a rated impedance  $Z_{sabc}$ . The balanced nonlinear DBR load is powered by a load voltage  $V_{Labc}$  and a load current  $I_{NLabc}$ , respectively. The nonlinear DBR load introduces significant harmonic distortions into the supply current, impacting the voltage at the point of common coupling (PCC). This leads to an increased reactive power demand and rapidly degrades the overall power quality of the distribution network. Additionally, the network faces various voltage-related issues such as voltage harmonics, sags, swells, flickers, and other disturbances. These voltage issues disrupt the continuous power flow to loads connected at the PCC of the distribution system network. Voltage and current quality are the primary concerns in the distribution network,

which are addressed by active customized compensation methods. Among the various custom compensation techniques, UPQC is the optimal choice for mitigating power quality issues related to source and/or load currents. The UPQC consists of dual voltage source inverters (VSIs) configured in a shunt-series arrangement. The dual VSIs in the UPQC are powered by a DC-link capacitor ( $C_{dc}$ ), which is regulated using sensor-based reference extraction control schemes in conjunction with gate-drive circuitry. The DC-link capacitor,  $C_{dc}$ , is responsible for maintaining stable voltages at the point of common coupling (PCC) for the dual parallel VSIs in the DSTATCOM. The proposed combined DC-link-fed parallel VSI topology requires only a single DC-link capacitor, providing advantages such as fewer sensing elements, improved reliability, and lower-cost compensation compared to the isolated DC-link-fed parallel VSI topology. An active DC-link regulator is employed to minimize circulating currents between the DC-link capacitor and the VSIs, while also maintaining a constant voltage,  $V_{dc}$ , across common points.

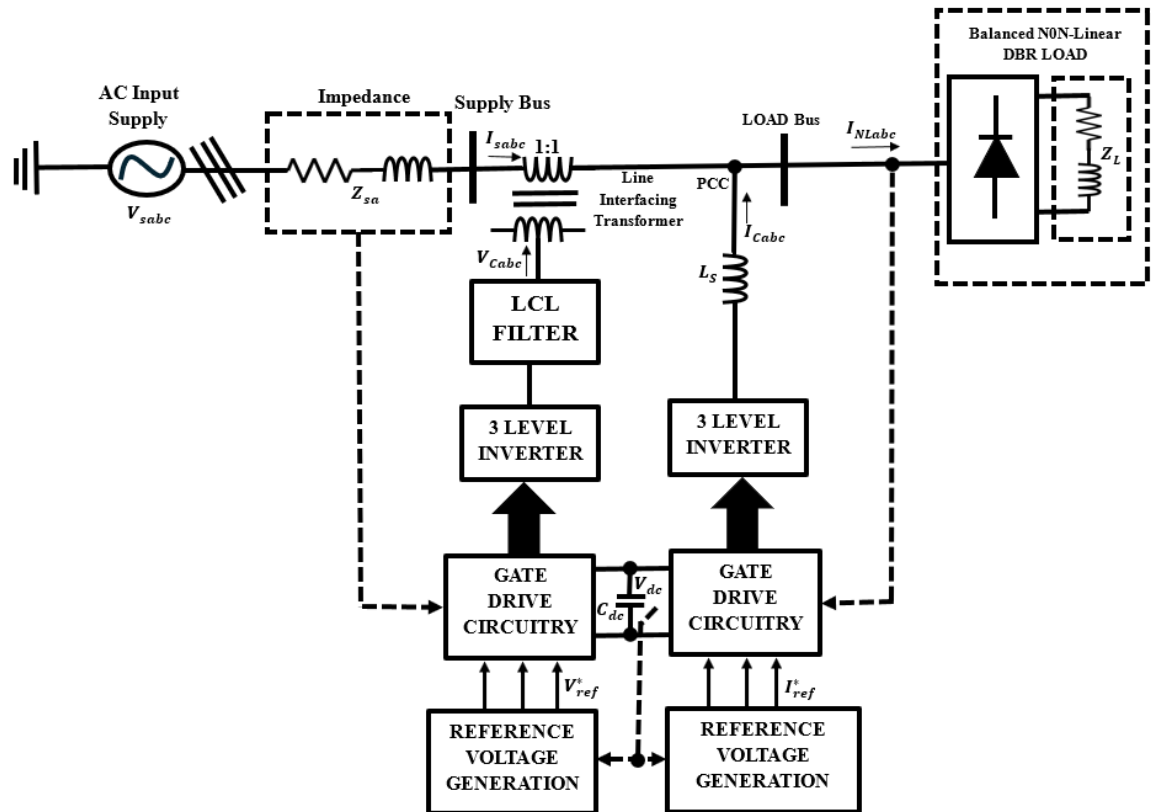


Fig. 1 Schematic of the proposed UPQC device for improving PQ

Additionally, line-interfacing filters are implemented after the VSI modules to eliminate notching and uneven effects that may occur during the injection of compensation currents from the VSI modules. The shunt VSI of the UPQC acts as an active power compensator, mitigating harmonic distortion in the supply current by injecting a shunt compensation current based on the in-phase current compensation principle. The shunt VSI of the UPQC controls the supply current to achieve a harmonic-free response, reactive power exchange, load balancing, and power factor regulation. It addresses current-related issues while keeping the supply voltage constant at the PCC by injecting variable currents that are in-phase with the quadrature of the supply voltage through line-interfaced RL filters. This approach enables the regulation of reactive power and helps maintain a unity power factor on the supply side. The series VSI of the UPQC operates as a series active compensator, addressing voltage harmonics and mitigating issues such as voltage sags, swells, and interruptions in the load voltage. It achieves this by injecting a series compensation voltage according to the direct-phase voltage injection principle. The series VSI of the UPQC is utilized to regulate the load voltage, ensuring a harmonic-free response and maintaining a stable, continuous voltage at the load terminals or the PCC side. It addresses voltage-related issues while keeping the load voltage constant by injecting compensation voltages that are in-phase with the quadrature of the PCC voltage through line-interfacing filters, resulting in an oscillating,

fundamental, and balanced load voltage. The UPQC enhances the distribution network's PCC while complying with IEEE-519/2014 standards through an effective control technique.

### III. UPQC CONTROL SCHEMES

The control scheme for the UPQC series VSI employs a synchronous reference frame (SRF) to tackle voltage-related power quality issues at the PCC of the distribution system. To generate a suitable reference voltage signal, the series VSI of the UPQC utilizes an SRF control scheme with an adequate supply voltage value. The precise supply voltage in the abc-frame ( $V_{Labc}$ ) is converted into a rotating dq-frame ( $V_{dq0.act}$ ) using Park's transformation method, which operates in the direct and quadrature axes.

$$\begin{bmatrix} V_{d.act} \\ V_{q.act} \\ V_{0.act} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix}$$

$$\theta = \int \omega . dt$$

A PI controller's transfer function is expressed as follows:

$$U_{err}(s) = k_{pa} + \frac{k_{ia}}{s} + E_{err}(s)$$

Figure 2 illustrates the block diagram of the SRF control scheme for the series VSI in the UPQC. The PI controller is employed to minimize the resultant error sequences, producing the final reference voltage signal  $V_{dq.ref}^*$ . The obtained reference voltage in the dq-frame is then converted back into the accurate abc-frame using the inverse Park's transformation technique, as shown in Eq. (4).

$$\begin{bmatrix} V_{a.ref} \\ V_{b.ref} \\ V_{c.ref} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_{dq.ref}^* \\ V_{dq.ref}^* \\ V_{dq.ref}^* \end{bmatrix}$$

Finally, the reference voltage extracted from the SRF control scheme is compared with the measured voltage value to generate switching pulses for the series VSI of the UPQC using the sinusoidal pulse-width modulation (SPWM) technique.

### IV. SERIES VSI POWER CONTROL SCHEME FOR UPQC DEVICES WITH INSTANTANEOUS REAL-REACTIVE POWER

In most cases, the IRP controller utilizes Clarke's transformation technique, which converts the standard abc coordinates into symmetric  $\alpha\beta$  coordinates in a stationary frame. The supply voltage  $V_{st.abc}$  and the nonlinear distorted load currents  $I_{NLabc}$  are transformed into symmetric frames for managing both real and reactive powers as ( $V_{st.\alpha\beta}$ ,  $I_{NL.\alpha\beta}$ ). The conversion process of Clarke's transformation is represented by Eqs.

$$\begin{bmatrix} V_{st.\alpha} \\ V_{st.\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_{st.a} \\ V_{st.b} \\ V_{st.c} \end{bmatrix}$$

$$\begin{bmatrix} i_{NL.\alpha} \\ i_{NL.\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_{NL.a} \\ i_{NL.b} \\ i_{NL.c} \end{bmatrix}$$

$$p = V_{st.\alpha} i_{NL.\alpha} + V_{st.\beta} i_{NL.\beta}$$

$$q = -V_{st.\beta} i_{NL.\alpha} + V_{st.\alpha} i_{NL.\beta}$$

Matrix-form representation of the attained power components is as follows:

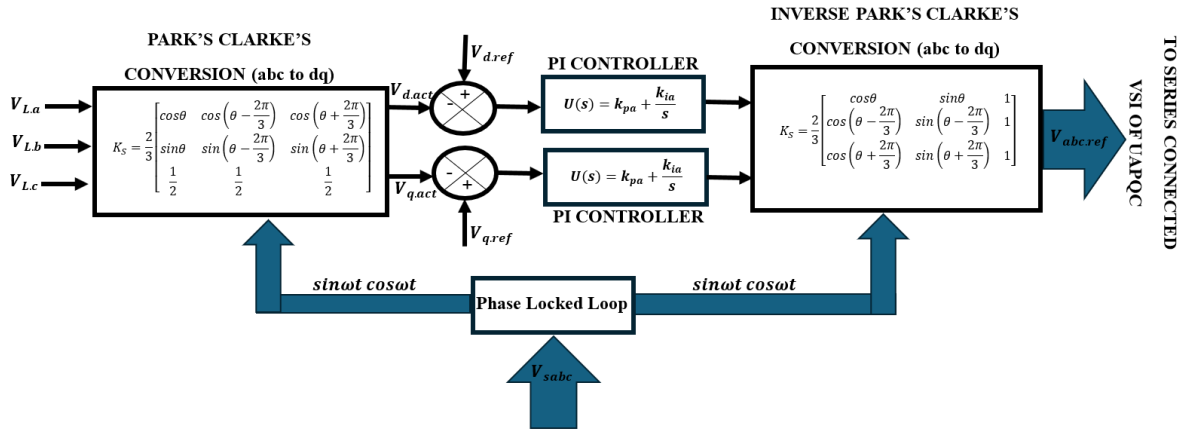


Fig. 2 Schematic of the SRF control scheme for the series VSI of UPQC

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_{st,\alpha} & V_{st,\beta} \\ -V_{st,\beta} & V_{st,\alpha} \end{bmatrix} \begin{bmatrix} i_{NL,\alpha} \\ i_{NL,\beta} \end{bmatrix}$$

Distorted load currents in symmetric frames are stated as follows:

$$\begin{bmatrix} i_{NL,\alpha} \\ i_{NL,\beta} \end{bmatrix} = \frac{1}{\Delta_k} \begin{bmatrix} V_{st,\alpha} & V_{st,\beta} \\ -V_{st,\beta} & V_{st,\alpha} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}$$

Where

$$\Delta_k = V_{st,\alpha}^2 + V_{st,\beta}^2$$

The resulting controlling components at the nth point is given as:

$$V_{dc,er} = V_{dc,r}^* - V_{dc,a}$$

$$\Delta_{ia,dc} = K_{p,d} * (V_{dc,er(n)} - V_{dc,er(n-1)}) + K_{i,d} * (V_{dc,er(n)})$$

The performance of a PI controller is heavily influenced by the selection of appropriate gain values, which can be determined through the Ziegler–Nichols method. However, this traditional method does not allow for automatic tuning of gain values during parameter variations or sudden changes, ultimately impacting the overall stability of the system. Various advanced artificial intelligence approaches are employed across a range of domestic and industrial applications, with the adaptive neuro-fuzzy inference system (ANFIS) playing a significant role in control schemes due to its enhanced performance characteristics compared to traditional PI and fuzzy logic control methods. ANFIS control schemes are characterized by their integration of symbolic notation with an expert inference knowledge base. The block diagram of the ANFIS control model is presented in Fig. 3. Although the ANFIS procedure offers greater precision and efficiency, the ANFIS controller assesses layer creation to enhance error reduction and defines the control mechanism that minimizes error values. The structure of the ANFIS control scheme is illustrated in Fig. 4.

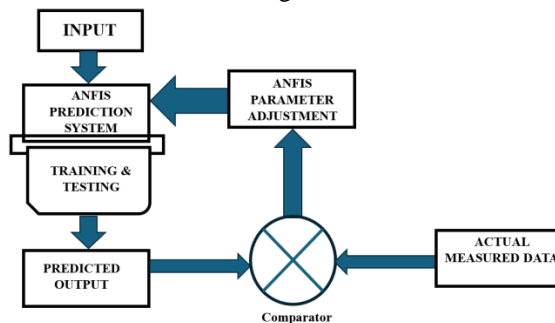


Fig. 3 Block diagram of ANFIS control model

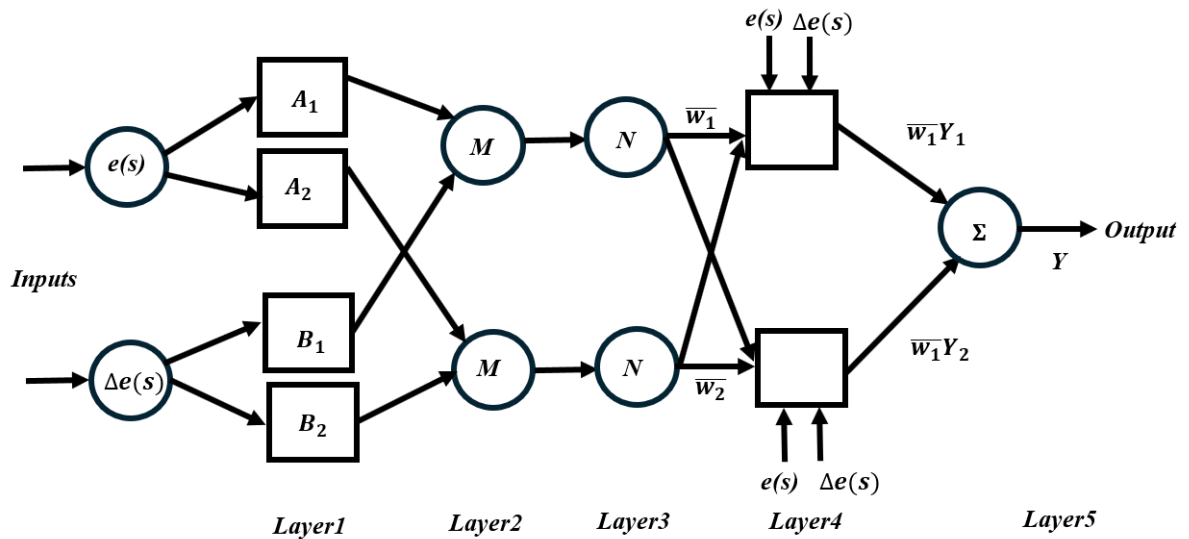


Fig. 4 Structure of ANFIS control scheme

In the current ANFIS control system, a supervised learning approach is employed to train the membership functions, enabling the deduction of the desired output during nominal time periods. The ANFIS controller operates in two phases. In the first phase, the available fuzzy data is validated and transformed into the necessary data by identifying errors, changes in errors, and output requirements. In the second phase, the provided fuzzy data are re-transformed into functional membership functions and a rule base using an advanced training approach linked to the desired output DC-link voltage. The integration of artificial neural networks with fuzzy logic rules establishes clear correspondence rules between input and output, enhancing the overall understanding of the control scheme. While the ANFIS procedure is more precise and efficient, the ANFIS controller assesses layer creation to enhance error reduction and defines the control mechanism that minimizes error values. The structure of the ANFIS control scheme is depicted in Fig. 4. The appropriate membership functions and rule base are trained with the desired output using a hybrid-weighting function algorithm, which combines least squares and backpropagation methods to analyse the various parameters of the membership functions employed in this study. Based on testing and training, the ANFIS control scheme generates new membership functions and a rule base to regulate error sequences in the DC-link voltage of the IRP control scheme. The membership functions for the available ANFIS data, including error  $e(s)$  and change in error  $\Delta e(s)$ , during the first step of the ANFIS controller are illustrated in Fig. 5.

$$e(s) = V_{dc,r}^* - V_{dc,a}$$

$$\Delta e(s) = e(s) - e(s-1)$$

where  $e(s)$  and  $\Delta e(s)$  represent the error and the change in error, respectively. The rules for the ANFIS control scheme are summarized in Table 1. There are two types of instantaneous components: oscillatory DC values and average AC values.

$$p = \bar{p} + \tilde{p}$$

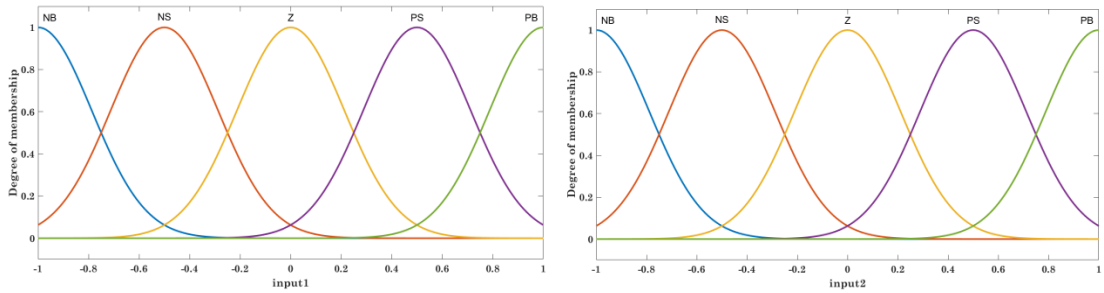
$$q = \bar{q} + \tilde{q}$$

The final reference current signal extracted in the  $\alpha\beta$  symmetric frame, denoted as  $i_{cr,\alpha\beta}^*$  is expressed as:

$$\begin{bmatrix} i_{cr,\alpha}^* \\ i_{cr,\beta}^* \end{bmatrix} = \frac{1}{\Delta_k} \begin{bmatrix} V_{st,\alpha} & -V_{st,\beta} \\ V_{st,\beta} & V_{st,\alpha} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}$$

The block diagram of proposed ANFIS-IRP control scheme as in Fig. 6.

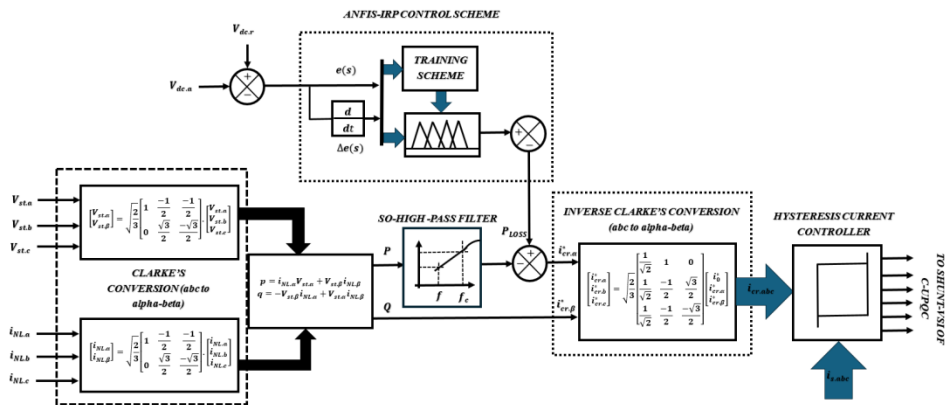
$$\begin{bmatrix} i_{cr,a}^* \\ i_{cr,b}^* \\ i_{cr,c}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_0^* \\ i_{c,\alpha}^* \\ i_{c,\beta}^* \end{bmatrix}$$



(a) Error ( $e(s)$ )(b) Change in error ( $\Delta e(s)$ )  
**Fig. 5** ANFIS control scheme membership functions

**Table 1** ANFIS control scheme rules

$e(s)/\Delta e(s)$	NB	NS	Z	PS	PB
NB	R1	R2	R3	R4	R5
NS	R6	R7	R8	R9	R10
Z	R11	R12	R13	R14	R15
PS	R16	R17	R18	R18	R20
PB	R21	R22	R23	R24	R25



**Fig. 6** Block diagram of ANFIS-IRP control scheme for shunt VSI of UPQC device

The increasing integration of renewable energy sources and the prevalence of nonlinear loads in modern power systems have made power quality issues a critical concern. Problems such as voltage sags, swells, harmonics, and unbalanced loads can significantly affect the performance and reliability of electrical networks. To address these challenges, Unified Power Quality Conditioners (UPQC) have emerged as effective solutions. A UPQC combines series and shunt converters to improve power quality, ensuring stable and high-quality power delivery. The introduction of a three-level architecture enhances the performance of UPQC by providing improved voltage support and reduced harmonic distortion. To optimize the operation of a three-level UPQC, an Adaptive Neuro-Fuzzy Inference System (ANFIS) can be employed as an advanced control strategy. ANFIS is a hybrid intelligent system that integrates the learning capabilities of neural networks with the approximate reasoning capabilities of fuzzy logic. This dual approach allows ANFIS to handle the uncertainties and complexities inherent in power systems effectively. The core of ANFIS consists of a Fuzzy Inference System (FIS) that employs fuzzy sets and rules to process inputs and generate outputs, alongside a neural network architecture that optimizes and adjusts the fuzzy rules and membership functions based on input data. The adaptability of ANFIS makes it particularly suitable for dynamic environments, enabling it to respond effectively to fluctuating loads and varying operational conditions.

In the context of a three-level UPQC, ANFIS plays a crucial role in enhancing power quality by ensuring that both the series and shunt converters operate optimally. The series converter is responsible for compensating voltage-related issues, such as sags and swells, while the shunt converter addresses current quality issues like harmonics and reactive power compensation. The three-level configuration allows for reduced switching losses and improved waveform quality compared to traditional two-level converters. By implementing ANFIS, the control strategy can dynamically adjust to varying conditions, providing better compensation for disturbances and ensuring stable power delivery. The ANFIS architecture used in the control strategy of a three-level UPQC consists of several layers. The input layer receives voltage and current measurements, as well as information on

voltage disturbances and harmonic levels. The fuzzification layer then converts these precise inputs into fuzzy sets, which allows the system to handle uncertainties. In the rule layer, fuzzy rules are applied to the fuzzified inputs to derive control actions for the UPQC. The normalization layer ensures that the outputs from multiple rules sum to one, facilitating the combination of results. The defuzzification layer converts these normalized outputs back into crisp values, which represent the control actions for the converters. Finally, the output layer produces the control signals necessary for the effective operation of the three-level UPQC.

Implementing ANFIS for a three-level UPQC in MATLAB involves several key steps. Initially, data collection is essential to gather various operating conditions, including different types of loads and voltage disturbances. Following data collection, a fuzzy rule base must be created that defines fuzzy sets and rules based on expected scenarios, such as voltage sags or specific harmonic distortions. The next step is to train the ANFIS using the collected data, allowing the system to adjust the membership functions and rules to improve performance. Once trained, the three-level UPQC can be simulated in MATLAB, utilizing the ANFIS controller to generate control signals that ensure effective compensation of voltage and current disturbances. Finally, performance evaluation is conducted by assessing key metrics, such as Total Harmonic Distortion (THD) of output voltage and current, stability during disturbances, and response time to changes in load conditions. The integration of ANFIS into the control strategy of a three-level UPQC offers numerous advantages, including robustness in managing uncertainties and nonlinearities, enhanced learning capabilities through historical data, and adaptive control to respond in real-time to changing conditions. However, challenges such as computational complexity, the risk of overfitting, and dependence on the quality of training data must also be addressed. In conclusion, the Adaptive Neuro-Fuzzy Inference System (ANFIS) represents a powerful control strategy for a three-level Unified Power Quality Conditioner (UPQC) implemented in MATLAB. By leveraging the strengths of both fuzzy logic and neural networks, ANFIS significantly enhances the ability of the UPQC to address a variety of power quality issues, ensuring stable and high-quality power delivery. As the demand for improved power quality continues to grow, the integration of intelligent control strategies like ANFIS in power conditioning devices will be essential for developing efficient and resilient power systems.

## V. MATLAB/SIMULINK RESULTS

The performance of the ANFIS-controlled UPQC device is thoroughly analyzed using MATLAB/SIMULINK to demonstrate its effectiveness in improving power quality. The simulation highlights how the ANFIS-based control strategies enhance power quality under both stable load and source voltage conditions. In Figure 7(a), the voltages at both the source and load sides are shown, illustrating the voltage profiles before and after the compensation by the UPQC. The control system works to maintain the load voltage at the desired levels, despite any disturbances or anomalies present in the source voltage, such as voltage sag, swell, or harmonic distortion. This demonstrates the UPQC's ability to stabilize the voltage and ensure reliable power delivery to the load. Figure 7(b) provides a detailed illustration of the current drawn by the nonlinear load, as well as the currents supplied by the power source and those injected by the shunt active filter. The shunt active filter compensates for the reactive power and harmonics drawn by the nonlinear load. The ANFIS controller adjusts the filter's operation dynamically, ensuring that the source current remains sinusoidal and in phase with the source voltage, effectively mitigating harmonic distortion and improving the overall power factor. The simulation results clearly show how the ANFIS-controlled UPQC enhances power quality by maintaining balanced and clean voltage and current waveforms, even in the presence of nonlinear loads and fluctuating source conditions. This improved performance is achieved through the adaptive and intelligent control provided by the ANFIS system, which optimizes the operation of both the series and shunt active filters.

In cases where the source voltage is free from harmonic distortions and maintains a stable fundamental magnitude, the voltage at the load side can closely match the source voltage. Under these ideal conditions, the Unified Power Quality Conditioner (UPQC) does not need to perform significant voltage compensation, as the source voltage already meets the required power quality standards. Consequently, the voltage reflected at the load side remains clean, with minimal or no deviations from the desired sinusoidal waveform. As the role of the series active filter in the UPQC is to mitigate voltage-related issues such as sags, swells, unbalances, and harmonic distortions, its operation is largely dormant in this scenario. Since the source voltage is stable and free of harmonics, there is no need for the series filter to inject compensating voltage. The voltage that is typically injected by the series active filter across the series transformer becomes negligible or tends toward zero. This indicates that under such ideal conditions, the series filter's contribution to maintaining power quality is

minimal, as the power system is already functioning at optimal voltage conditions. This minimal operation of the series active filter helps reduce unnecessary switching and conduction losses within the system, further improving the efficiency of the UPQC. The system can effectively pass the unaltered source voltage to the load, ensuring that the load receives high-quality power without the need for additional compensation.

Table 1. System Parameters

Parameters	Value
Source	440V, 50Hz
Line Resistance and Inductance	0.2Ω and 0.5mH
Non-Linear Load	10Ω and 20mH
DC Link Capacitance	1200mF
LC Filter of Series Active Filter	15mH and 20μF
LC Filter of Shunt Active Filter	2mH and 300μF

Figure 7(b) illustrates how the shunt active filter effectively mitigates switching harmonics present in the load current, which are typically generated by the AC-to-DC conversion processes in nonlinear loads. Nonlinear loads, such as rectifiers and other power-electronic devices, often introduce substantial harmonic content in the load current, adversely affecting power quality by increasing Total Harmonic Distortion (THD). In the simulated setup, the shunt active filter, operating under the proposed ANFIS control scheme, plays a crucial role in filtering out these unwanted harmonic components from the load current. This is achieved by filter injecting compensating currents that counteract the harmonics, allowing the source current to remain nearly sinusoidal. The control system of the shunt active filter continuously adjusts its operation to maintain high-quality power by dynamically responding to variations in the harmonic content of the load current. As a result, the THD of the source current is significantly reduced, demonstrating the filter's effectiveness in real-time harmonic compensation. In particular, the shunt active filter lowers the THD of the load current from a high level of 30.47% to a substantially low level of 0.98% at the source side. This reduction in THD is achieved by the precise regulation of the DC-link voltage in the shunt active filter, controlled by the proposed ANFIS system. By maintaining an optimal DC voltage, the ANFIS-controlled system ensures that the shunt active filter has sufficient power to generate the necessary compensating currents for harmonic mitigation. Furthermore, Figure 7(b) also shows the voltage profile injected by the shunt active filter, which is connected in parallel with the load. This injected voltage supports the stabilization of the source current and contributes to overall power quality improvement by addressing fluctuations in the load current. The results from the simulation confirm the ANFIS-based system's capability to regulate the shunt active filter's DC-link voltage effectively, leading to an efficient reduction in harmonic distortion and enhanced power quality at the source side.

In Figure 9, the UPQC's DC-link capacitor voltage is shown to remain steady at a reference value of 780V, maintained with precision by the ANFIS-based control system. This steady voltage level is crucial for the UPQC's effective operation, as it enables consistent power quality correction and voltage stabilization. The ANFIS controller has been finely tuned to achieve minimal peak overshoot, near-zero steady-state error, and significantly reduced ripple in the DC-link voltage. These attributes indicate a highly stable and efficient control of the DC-link voltage, directly contributing to the enhanced overall performance of the UPQC. Compared to traditional control methods, such as Proportional-Integral (PI) and Fuzzy logic controllers, the ANFIS system demonstrates superior control characteristics. Traditional controllers often struggle with overshoot, steady-state error, and higher ripple in dynamic conditions, leading to less effective power quality management. However, the adaptive capabilities of ANFIS allow it to dynamically adjust and minimize these issues, ensuring a more stable and responsive control over the DC-link voltage. Table 2 provides a detailed comparative analysis, highlighting the distinctions in performance metrics such as current THD, DC-link voltage regulation, and voltage THD between the conventional PI and Fuzzy controllers versus the ANFIS-based controller. The data shows that the ANFIS control strategy significantly outperforms these traditional methods, particularly in reducing current and voltage harmonic distortion and in maintaining a steady DC-link voltage. This comparison confirms the effectiveness of the proposed ANFIS-based control system in improving the UPQC's ability to manage power quality, affirming its superiority over conventional approaches.

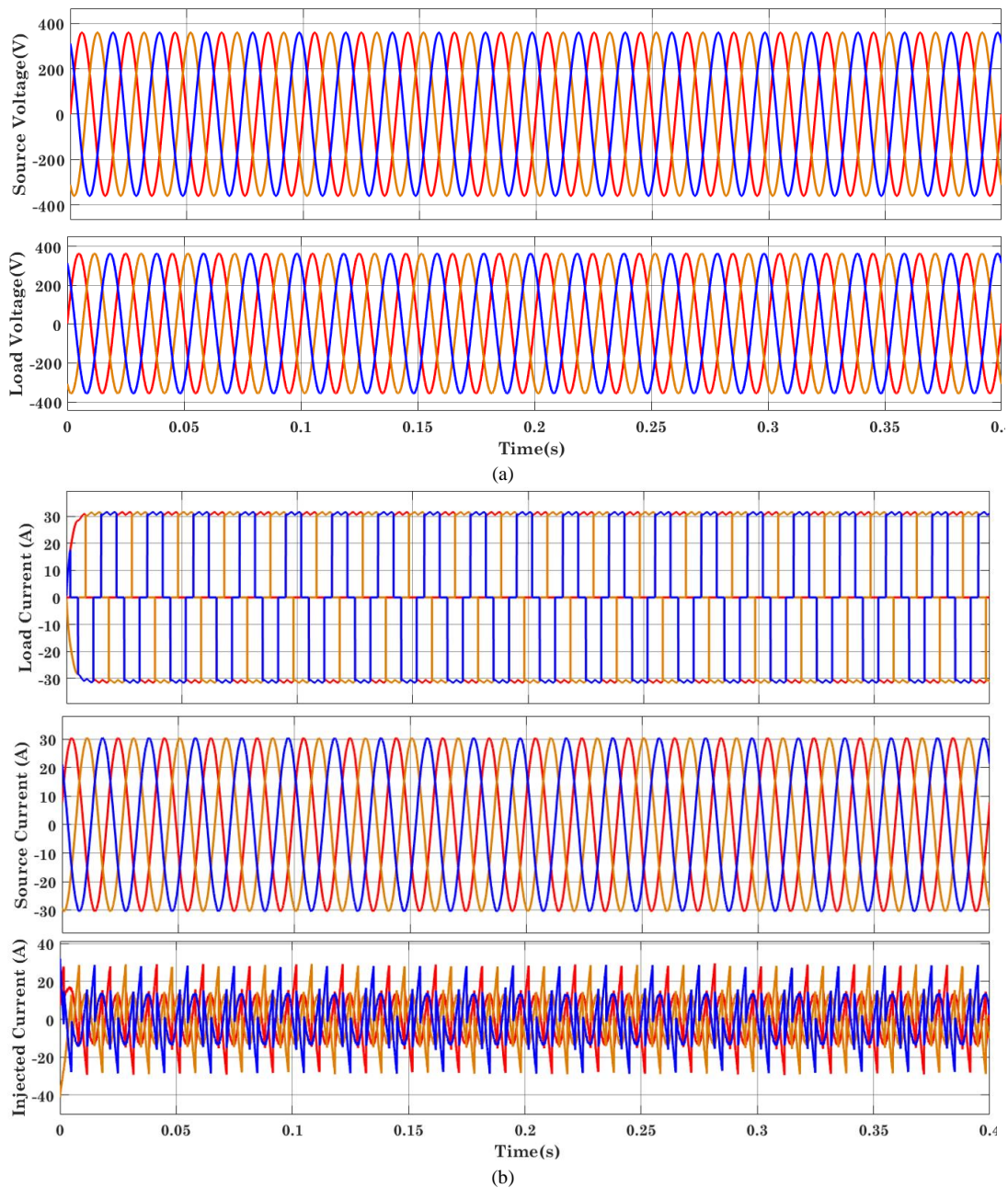


Figure 7. (a) Voltage and (b) Current waveforms of load, source and UPQC

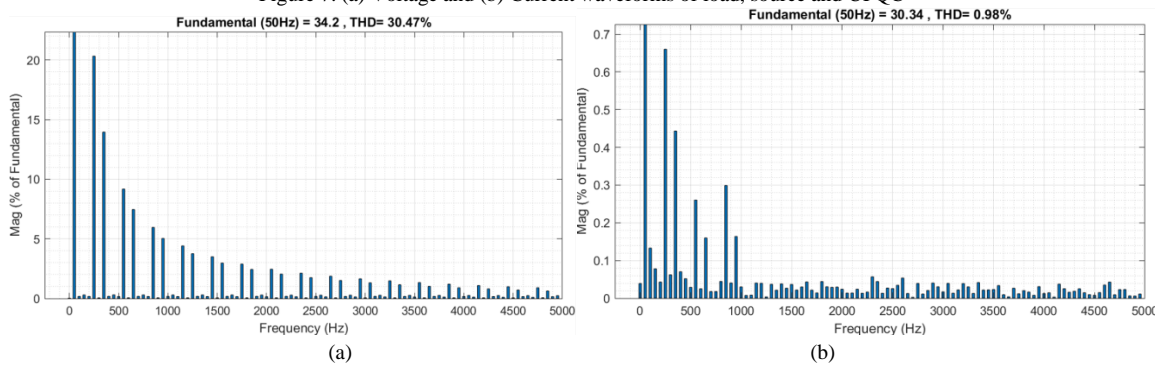


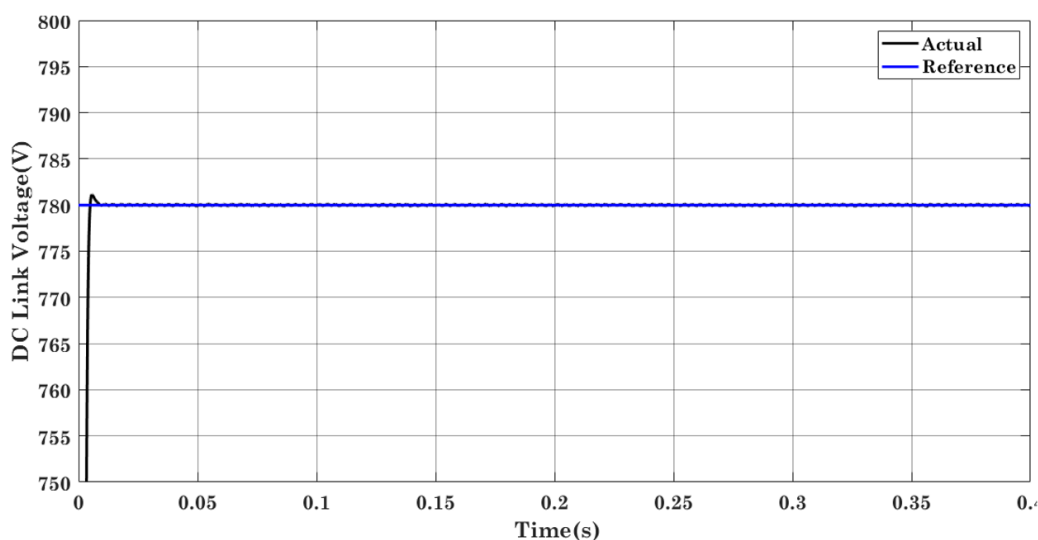
Figure 8. Total Harmonic Distortion of (a) Nonlinear load current and (b) source current

Figure 10 illustrates the UPQC's robust response to voltage sags and swells in the source, enabled by the ANFIS-controlled system. The figure displays the source voltage, load voltage, and the compensating voltage injected by the series active filter through the series-connected transformer to counteract these fluctuations. In this scenario, a 40% voltage sag is introduced at the source side from 0.1 to 0.2 seconds. During this period, the ANFIS-controlled UPQC detects the drop and promptly injects an additional compensating voltage through the

series active filter. This compensation effectively stabilizes the load voltage, preventing the sag from impacting the load and ensuring consistent power quality. The control system's adaptive nature allows it to respond quickly and with precision, matching the compensating voltage to the sag depth and duration. Following this, a 40% voltage swell is applied at the source side between 0.3 and 0.4 seconds. The UPQC again activates the series active filter to counterbalance the excess voltage, ensuring that the load voltage remains steady and unaffected by the swell. The ANFIS-based control strategy effectively manages the excess voltage by adjusting the compensating voltage output to counteract the swell, demonstrating the UPQC's capacity to maintain stable load voltage during sudden changes in source conditions. The detailed illustration in Figure 10 showcases how the ANFIS-controlled UPQC consistently maintains a steady load voltage by injecting the precise amount of compensating voltage required, regardless of whether a sag or swell occurs. This response underscores the advantage of the ANFIS control system in dynamically adjusting the UPQC's operation to mitigate source voltage anomalies, thereby safeguarding load power quality even under adverse grid conditions. Despite the disturbances in the source voltage, the UPQC's compensating voltage effectively minimizes any impact on the load voltage, keeping it nearly constant with minimal Total Harmonic Distortion (THD). This compensation is crucial for ensuring steady power quality at the load, as it prevents voltage fluctuations from transferring through to sensitive equipment.

Figure 11 illustrates both the source voltage and current waveforms, showing a distinct in-phase relationship. This alignment results from the reactive power compensation provided by the shunt active filter, which adjusts the current to maintain a unity power factor at the source side. By dynamically supplying reactive power, the shunt active filter ensures that the source current is purely active and aligns closely with the source voltage waveform. This coordination not only enhances the efficiency of power delivery but also minimizes power losses, further contributing to overall system stability and optimal power quality. The combination of the series and shunt active filters within the UPQC, guided by the ANFIS control, enables precise control over both voltage and current disturbances. As a result, the load voltage remains consistently regulated, and the source current maintains an in-phase relationship with the source voltage, confirming the UPQC's effective performance in sustaining high power quality despite challenging source voltage conditions.

UPQC, under ANFIS-based control, plays a vital role in providing the reactive power required by the nonlinear load, allowing the source to focus primarily on delivering active power. This selective supply enhances the power factor of the overall grid, demonstrating a clear advantage of the UPQC in improving power quality. The ability of the ANFIS control system to effectively mitigate voltage disturbances further reinforces its superiority over conventional control techniques. Figure 12 illustrates the UPQC system's response when significant distortions are intentionally introduced on the source side. Specifically, harmonic disturbances of various orders—5th, 7th, 11th, and 13th—are injected, with respective magnitudes of 10%, 5%, 3%, and 1%.



**Figure 9** the actual and reference DC link voltage.

These harmonics simulate real-world conditions where source voltage often includes multiple harmonic components, challenging power quality. The UPQC, guided by the ANFIS control, counters these harmonics effectively, ensuring that the load voltage remains largely free of such distortions. Additionally, the system is subjected to unbalanced sag and swell conditions to assess its adaptability under dynamic conditions. A 40% sag is simulated from 0.1 to 0.2 seconds, and a 40% swell from 0.3 to 0.4 seconds. During these events, the UPQC's series active filter actively injects compensating voltages, counterbalancing the sag and swell to maintain a stable and balanced load voltage. The ANFIS-based control responds quickly and accurately, providing the necessary adjustments in real time to address both the harmonics and the voltage variations. Overall, the results in Figure 13 emphasize the efficacy of the ANFIS-controlled UPQC in handling complex voltage disturbances, including harmonics, sag, and swell. This robust performance highlights the ANFIS control's advantages in improving power quality over traditional methods, ensuring a steady and reliable supply of power even under challenging conditions.

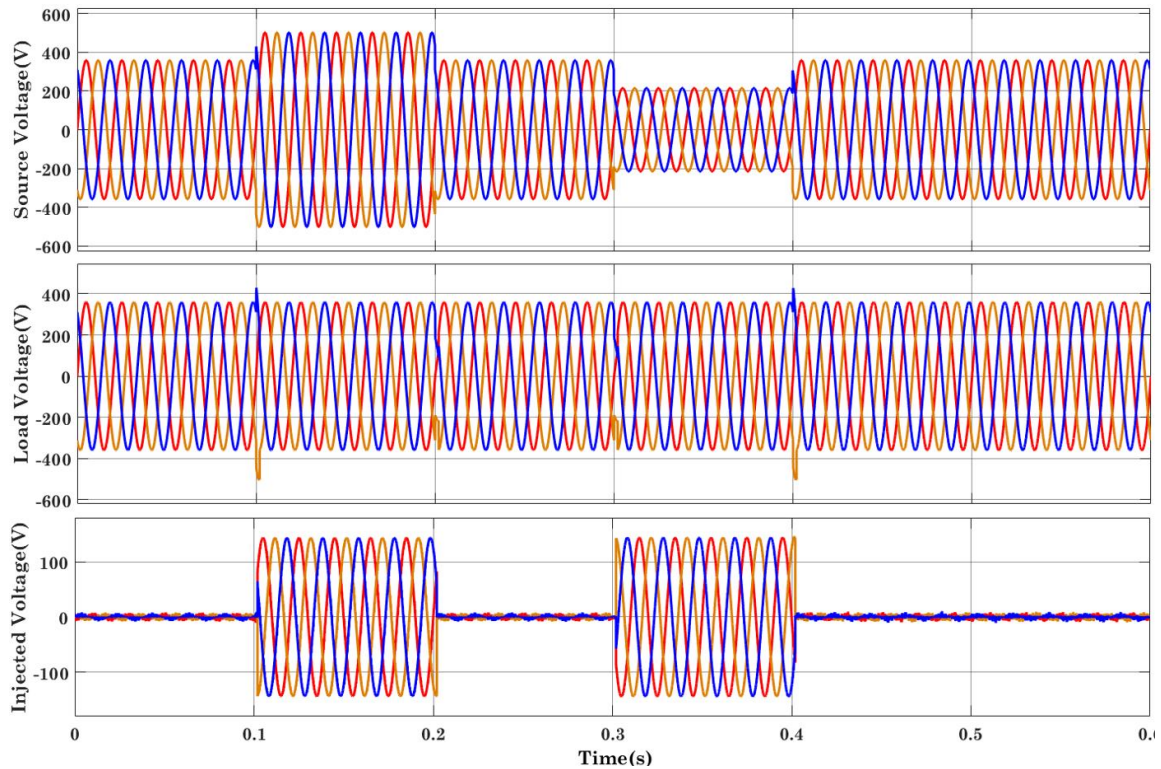


Figure 10 Voltage Waveforms during sag and swell conditions

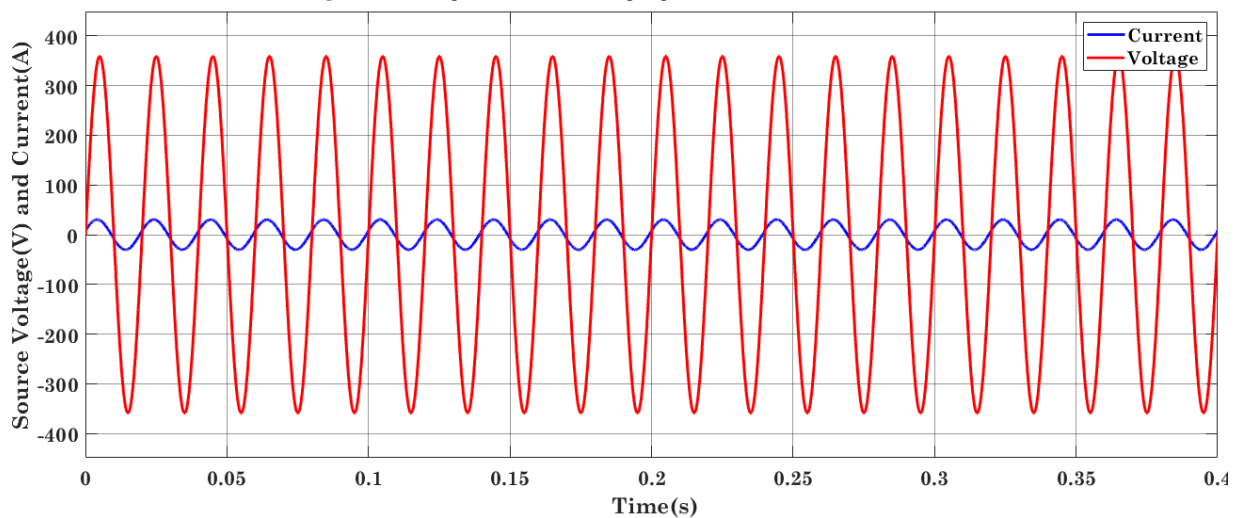
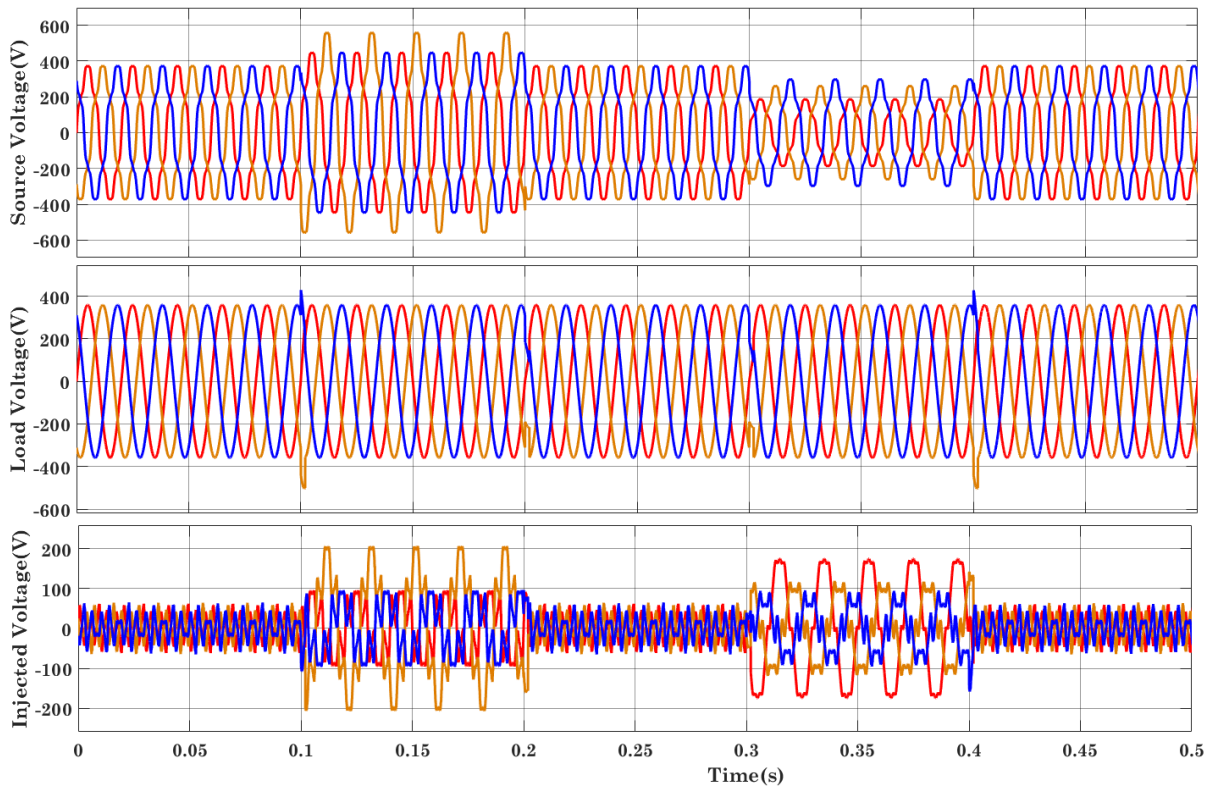


Figure 11. In Phase Source Voltage Source Current



**Figure 12. Source, Load, and Injected voltage when grid voltages are harmonic and unbalanced.**

Despite the presence of disturbances in the source voltage, the series active filter integrated within the UPQC demonstrates remarkable efficacy in compensating for these irregularities. This compensation results in a load voltage characterized by minimal Total Harmonic Distortion (THD) and a stable fundamental magnitude, which are critical for maintaining power quality and protecting sensitive equipment. Initially, the THD of the source voltage is recorded at 11.66%. However, through the intervention of the UPQC, specifically via the injection of compensatory voltages by the series active filter, this THD is dramatically reduced to just 0.53% at the load side. This substantial reduction signifies a highly effective filtering process, demonstrating the UPQC's capability to not only stabilize voltage levels but also purify the waveform, ensuring that the load receives clean, high-quality power. Figure 12 provides a visual representation of the current variations in response to changes in the load conditions. As the load changes, the UPQC's active filtering mechanisms adapt accordingly to ensure that the load voltage remains consistent, despite fluctuations in demand. This adaptability is essential for managing power quality, especially in scenarios where nonlinear loads are present, as these can introduce additional harmonics and instability in the system.

The current waveforms depicted in Figure 13 illustrate how the UPQC modulates the supply current to effectively match the varying load demands. As the load increases or decreases, the series active filter dynamically adjusts its output to maintain the desired load voltage and minimize harmonic content. This responsive behavior underscores UPQC's role as an essential component in modern power systems, enhancing performance while ensuring compliance with stringent power quality standards. In this scenario, a combination of linear and nonlinear loads is examined to evaluate the performance of UPQC. The introduction of nonlinear loads, known for generating significant harmonic currents, can severely affect the overall power quality. However, the simulation results reveal that the Total Harmonic Distortion (THD) significantly decreases due to the effective contribution of the shunt active filter. The shunt active filter operates by dynamically injecting compensating currents to counteract the harmonics produced by the nonlinear loads. As it monitors the load current continuously, the filter identifies the harmonic components and generates corresponding compensation, which helps in aligning the current waveforms closer to a pure sinusoidal shape. This capability is particularly vital in this mixed-load environment, where the presence of nonlinear loads would typically exacerbate distortion levels.

The outcomes of this simulation highlight the robustness and reliability of the UPQC system in effectively mitigating voltage and current distortions, even in the presence of complex harmonic components. The shunt active filter not only addresses the immediate effects of harmonics but also helps manage unbalanced conditions that may arise from the simultaneous operation of linear and nonlinear loads. By stabilizing both voltage and current waveforms, the UPQC enhances the quality of the power supply, leading to improved stability and reliability of the electrical system. This ensures that sensitive equipment connected to the grid operates optimally, free from the adverse effects of voltage sags, swells, and harmonics. Overall, the results affirm the effectiveness of the UPQC in delivering cleaner, more stable power, thereby significantly contributing to enhanced power quality in diverse conditions.

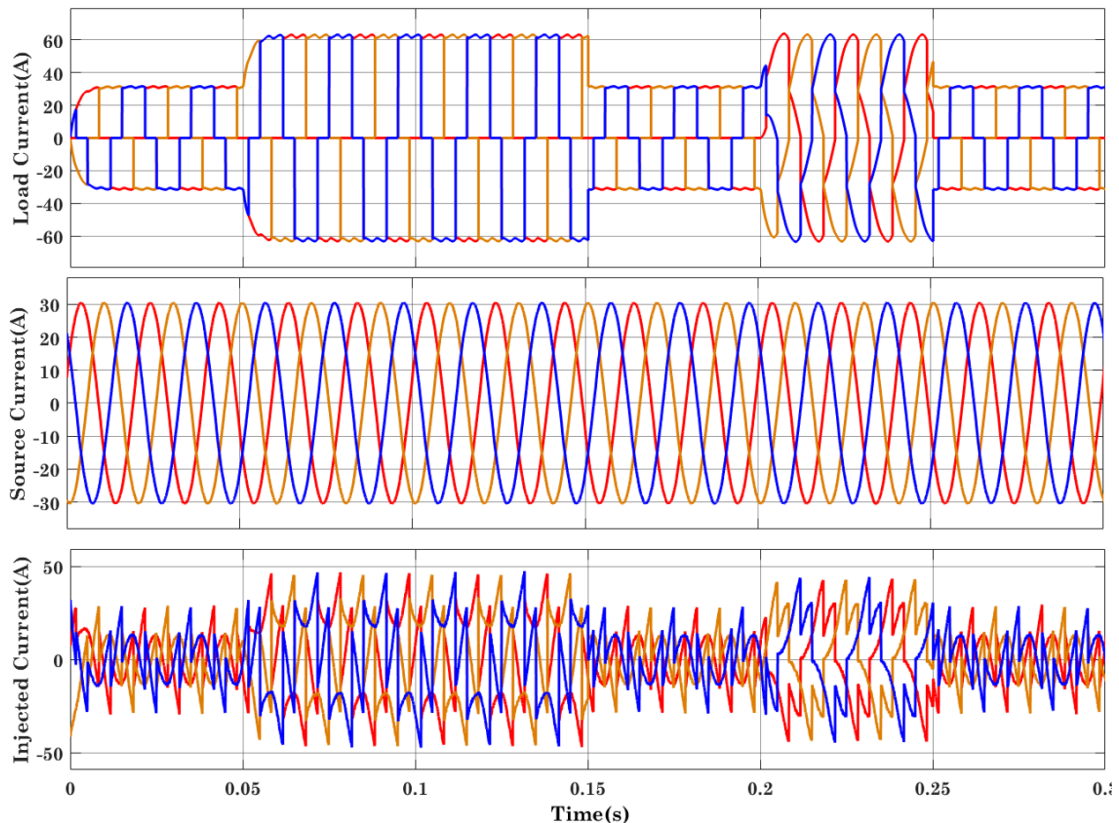


Figure 13. Source, Load, and Injected current with Dynamic load

## VI. CONCLUSION

In conclusion, this study confirms that the three-level UPQC controlled by an Adaptive Neuro-Fuzzy Inference System (ANFIS) offers significant advantages in power quality management over traditional control approaches, namely PI and fuzzy controllers. Through extensive simulations in MATLAB/Simulink, the ANFIS-based UPQC system was shown to be highly effective at mitigating common power quality issues such as voltage sags, swells, and harmonic distortions, while simultaneously providing consistent voltage regulation. This capability is essential in modern electrical networks where sensitive equipment requires stable and clean power to operate efficiently. The comparative analysis highlighted several performance benefits of the ANFIS controller. Unlike the PI controller, which relies on fixed gain parameters, and the fuzzy controller, which depends solely on rule-based inference, the ANFIS controller integrates neural networks and fuzzy logic principles. This integration enables adaptive learning and online parameter tuning, allowing the ANFIS-controlled UPQC to dynamically adjust its response in real time. As a result, the ANFIS controller achieves faster response times, shorter settling times, and reduced steady-state errors, thus ensuring high-quality power output even under varying load and supply conditions. The enhanced adaptability and robustness of the ANFIS-controlled UPQC position as a promising solution for addressing power quality challenges in complex electrical systems. These findings suggest that ANFIS offers a more resilient and efficient control strategy compared to traditional controllers, which are limited by their inability to self-adjust in changing environments. This research paves the way for further exploration of ANFIS-based UPQC systems, with potential applications in industrial, commercial, and residential power distribution networks. Future work may involve optimizing the ANFIS

model to reduce computational requirements, making it feasible for real-time implementation in hardware-based systems. Additionally, experimental validation on physical UPQC setups would provide insights into the practical effectiveness of ANFIS control in real-world scenarios. Overall, this study demonstrates that ANFIS-controlled UPQC systems hold substantial potential for enhancing power quality in the increasingly demanding landscape of modern electrical grids.

#### REFERENCES

- [1] Gonzalez-Abreu, Artvin-Darien, Roque-Alfredo Osornio-Rios, Arturo-Yosimar Jaen-Cuellar, Miguel Delgado-Prieto, Jose-Alfonso Antonino-Daviu, and Athanasios Karlis. "Advances in power quality analysis techniques for electrical machines and drives: A review." *Energies* 15, no. 5 (2022): 1909.
- [2] Jiang, Chang, and Shaohua Zhang. "Power quality compensation strategy of MMC-UPQC based on passive sliding mode control." *IEEE Access* 11 (2022): 3662-3679.
- [3] Benbouhenni, Habib, Zinelaabidine Boudjema, and Abdelkader Belaidi. "DPC based on ANFIS super-twisting sliding mode algorithm of a doubly-fed induction generator for wind energy system." *Journal Européen des Systèmes Automatisés* 53, no. 1 (2020): 69-80.
- [4] Renduchintala, Udaya K., Chengzong Pang, Krishna M. Tatikonda, and Lin Yang. "ANFIS-fuzzy logic based UPQC in interconnected microgrid distribution systems: Modeling, simulation and implementation." *The Journal of Engineering* 2021, no. 1 (2021): 6-18.
- [5] da Silva, Sérgio A. Oliveira, Leonardo Bruno Garcia Campanhol, Guilherme M. Pelz, and Vinícius de Souza. "Comparative performance analysis involving a three-phase UPQC operating with conventional and dual/inverted power-line conditioning strategies." *IEEE Transactions on Power Electronics* 35, no. 11 (2020): 11652-11665.
- [6] Alam, S.J., Arya, S.R. and Jana, R.K., 2021. Biogeography based optimization strategy for UPQC PI tuning on full order adaptive observer based control. *IET Generation, Transmission & Distribution*, 15(2), pp.279-293.
- [7] Zhao, Xiaojun, Xiuhui Chai, Xiaoqiang Guo, Ahmad Waseem, Xiaohuan Wang, and Chunjiang Zhang. "Impedance matching-based power flow analysis for UPQC in three-phase four-wire systems." *Energies* 14, no. 9 (2021): 2702.
- [8] Sztajmec, Elżbieta, and Paweł Szcześniak. "A review on AC voltage variation compensators in low voltage distribution network." *Energies* 16, no. 17 (2023): 6293.
- [9] Patjoshi, Rajesh Kumar, Rakhee Panigrahi, and Venkata Ratnam Kolluru. "Variable nonlinear gain fuzzy with improved synchronous reference frame control strategy for performance enhancement of unified power quality conditioner." *Ain Shams Engineering Journal* 12, no. 1 (2021): 739-753.
- [10] Nkado, Fredrick, Franklin Nkado, Ifedayo Oladeji, and Ramon Zamora. "Optimal design and performance analysis of solar PV integrated UPQC for distribution network." *European Journal of Electrical Engineering and Computer Science* 5, no. 5 (2021): 39-46.
- [11] Choudhury, Subhashree, Mohit Bajaj, Tarapasanna Dash, Salah Kamel, and Francisco Jurado. "Multilevel inverter: A survey on classical and advanced topologies, control schemes, applications to power system and future prospects." *Energies* 14, no. 18 (2021): 5773.
- [12] Rohten, Jaime A., David N. Dewar, Pericle Zanchetta, Andrea Formentini, Javier A. Munoz, Carlos R. Baier, and Jose J. Silva. "Multivariable deadbeat control of power electronics converters with fast dynamic response and fixed switching frequency." *Energies* 14, no. 2 (2021): 313.
- [13] Afonso, J.L., Tanta, M., Pinto, J.G.O., Monteiro, L.F., Machado, L., Sousa, T.J. and Monteiro, V., 2021. A review on power electronics technologies for power quality improvement. *Energies*, 14(24), p.8585.
- [14] Heenkenda, A., Elsanabary, A., Seyedmahmoudian, M., Mekhilef, S., Stojcevski, A. and Ab Aziz, N.F., 2023. Unified power quality conditioners based different structural arrangements: A comprehensive review. *IEEE Access*, 11, pp.43435-43457.
- [15] Lenjo, E., Kenfack, P. and Yome, J.M.N., 2024. Power system stability improvement using fuzzy logic FACTS-UPQC conditioner. *Indonesian Journal of Electrical Engineering and Computer Science*, 36(1), pp.127-136.
- [16] Mosayyebi, S.R., Shahalami, S.H. and Mojallali, H., 2022. Fault ride-through capability improvement in a DFIG-based wind turbine using modified ADRC. *Protection and Control of Modern Power Systems*, 7(4), pp.1-37.
- [17] Fagundes, S. M., F. L. Cardoso, E. V. Stangler, F. A. S. Neves, and M. Mezaroba. "A detailed power flow analysis of the dual unified power quality conditioner (iUPQC) using power angle control (PAC)." *Electric Power Systems Research* 192 (2021): 106933.
- [18] Nicola, M., Nicola, C.I., Sacerdotianu, D. and Vintilă, A., 2023. Comparative performance of UPQC control system based on PI-GWO, fractional order controllers, and reinforcement learning agent. *Electronics*, 12(3), p.494.
- [19] Lumbreras, David, Eduardo Gálvez, Alfonso Collado, and Jordi Zaragoza. "Trends in power quality, harmonic mitigation and standards for light and heavy industries: A review." *Energies* 13, no. 21 (2020): 5792.
- [20] Wu, Mingzhe, Yun Wei Li, and Georgios Konstantinou. "A comprehensive review of capacitor voltage balancing strategies for multilevel converters under selective harmonic elimination PWM." *IEEE Transactions on Power Electronics* 36, no. 3 (2020): 2748-2767.

- [21] Debdouche, N., Deffaf, B., Benbouhenni, H., Laid, Z., & Mosaad, M. I. (2023). Direct power control for three-level multifunctional voltage source inverter of PV systems using a simplified super-twisting algorithm. *Energies*, 16(10), 4103.
- [22] Miron, Anca, Andrei C. Cziker, and Horia G. Beleiu. "Fuzzy Control Systems for Power Quality Improvement—A Systematic Review Exploring Their Efficacy and Efficiency." *Applied Sciences* 14, no. 11 (2024): 4468.