Modelling and Simulation of UPQC for Mitigating Power Quality Issues

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Abstract— **This research paper focuses on Unified Power Quality Conditioner (UPQC) for mitigating power quality (PQ) problems in electrical power systems. PQ issues, like voltage sag, voltage swell, harmonics, & flicker, due to the proliferation of nonlinear loads and renewable energy sources integrated with conventional systems. Using various control algorithms and switching strategies necessary including the conventional PI controller, hysteresis controllers, d-q theory of current, and the SRF theory to regulate voltage, mitigate harmonic distortions, and balance the system. UPQC has emerged as an effective solution to address these power quality problems comprehensively.**

Keywords— *Power Quality, UPQC, Shunt APF, Series APF, Hysteresis Current Controller, SRF technique.*

I. INTRODUCTION

The increasing demand for reliable and high-quality electrical power has brought significant attention to the field of PQ improvement. With proliferation of sensitive electronic devices, industrial machinery, and renewable energy sources, power distribution systems are encountering various PQ issues. Common PQ problems consist of voltage sags, swells, harmonics, and unbalanced loading, which can lead to equipment damage and inefficiencies. Consequently, its crucial to find effective solutions to mitigate these issues and ensure the uninterrupted operation of power systems. To address these issues, the UPQC acts as a solution. It effectively mitigates power quality problems by regulating voltage, suppressing harmonics, and improving system balance. The UPQC combines two power electronic devices, the series & shunt APF into a single unit. This integration allows the UPQC to simultaneously regulate and compensate for a wide range of PQ disturbances occurring in distribution system. It ensures the reliable operation of customer equipment and enhances the quality of power supplied by the electrical system.

Power quality problems arise when there are variations in voltage, current, or frequency, leading to the breakdown or malfunctioning of equipment used by customers [8]. The

electrical power system is designed to deliver high-quality power to ensure the satisfactory operation of various electrical devices. However, the presence of nonlinear loads has raised concerns regarding the acceptable levels of harmonic distortion injected into the power supply system [3]. As the utilization of nonlinear loads continues to grow, power quality problems have become inevitable.

This paper provides an overview on the fundamentals of UPQC, including its basic configuration, operation principles, and control strategies. Subsequently, the paper delves into the modeling and simulation techniques for UPQC systems, emphasizing the development of accurate mathematical models for simulation. A wide range of power quality problems, including voltage sags, voltage swells, and harmonics occurring within the power system, are discussed along with potential solutions for their mitigation.
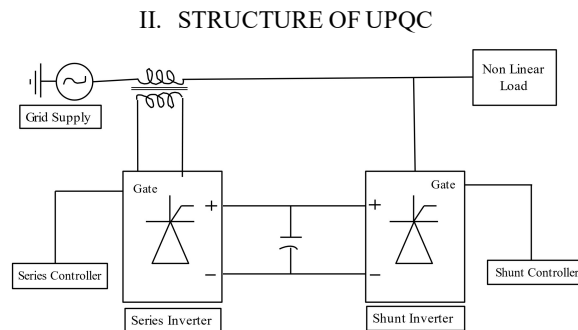
II. STRUCTURE OF UPQC

Figure 1:- Structure of UPQC

Figure 1 shows the structure of UPQC. It consists of several key components and their interconnections, which work together to enhance power quality in power distribution systems. The structure can be described as follows:

A. Series Active Power Filter (SAPF):

It is an electrical device that is connected with the load in series. It comprises a voltage source converter (VSC) that incorporates high-frequency switching components like IGBTs or GTOs. The VSC is responsible for generating a compensating voltage waveform that is injected in series with the load. The compensating voltage waveform is

controlled in such a way that it cancels out voltage disturbances, like voltage sag, swell and harmonics. The SAPF continuously monitors the load voltage and adjusts the compensating voltage to maintain a stable and regulated supply voltage.[7]

B. Shunt Active Power Filter (ShAPF):

It is a power electronic device connected in parallel with the supply. It consists of high-frequency switching devices which generate a compensating current waveform that is injected in parallel with the supply. The compensating current waveform is controlled to mitigate current-related issues, including harmonics, flicker, and unbalance. The ShAPF monitors the supply current and injects the compensating current to ensure a clean and balanced current flow from the source. [9]

C. Energy Storage Elements:

The UPQC may incorporate energy storage elements such as capacitors or batteries [5]. These energy storage elements provide instantaneous energy during compensation and help maintain a stable power supply during rapid changes in load or supply conditions. The capacitors or batteries store and release energy as required by the SAPF and ShAPF, enhancing their response time and overall performance.[5]

D. Control Block:

The UPQC utilizes the control block to monitor and control the compensating voltage and current waveforms. The control system employs advanced control algorithms, feedback loops, and reference signals. It continuously measures several electrical parameters i.e. voltage, current, power, harmonics, and other power quality indices. Based on these measurements, the control system calculates the compensation required and generates the appropriate control signals for the SAPF and ShAPF.

III. METHODOLOGY

A. Series APF

The voltage control strategy employed in Series APF relies on the concept of injecting a compensating voltage to control it at the load terminals. By generating a reference voltage as per desired voltage regulation, the series filter is carefully controlled to introduce a compensating voltage that effectively regulates and stabilizes it at the load terminals. This voltage control technique ensures optimal voltage quality and reliability for the connected load, leading to enhanced overall system performance and power delivery. [8]

B. Hysteresis Controller

The hysteresis controller is chosen for its simplicity, quick transient response, improved stability, and high accuracy. It operates by generating a switching signal based on the voltage error within a predetermined tolerance band. The

hysteresis control scheme for DVR typically involves the following steps. The actual voltage is continuously measured using the formula shown below:

$$V_a = V_m \sin(\omega t + \theta)$$

$$V_b = V_m \sin\left(\omega t + \theta - \frac{2\pi}{3}\right)$$

$$V_c = V_m \sin\left(\omega t + \theta + \frac{2\pi}{3}\right)$$

A reference voltage is generated based on the desired output voltage characteristics. The error, which represents the difference between desired and actual voltage, is calculated by subtracting the reference voltage and measured actual voltage.

$$V_{error} = V_{ref} - V_{abc}$$

A hysteresis band is defined around the reference voltage. It determines the range within which the control action remains inactive. Once the error surpasses the hysteresis band, the control action is activated, leading to the introduction of a compensating voltage into the system. This voltage is intended to restore the system's voltage to the desired level.
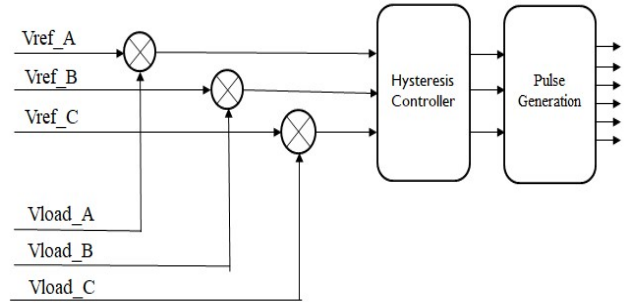

Figure 2:- Hysterisis current controller

B. Shunt APF

It is linked in parallel with the nonlinear load, and it introduces a compensatory current to alleviate the harmonic currents produced by the load[3]. In our modeling of the shunt APF, we implemented a control algorithm known as the Synchronous Reference Frame (SRF) theory. This theory relies on the utilization of a rotating reference frame that is synchronized with the power system's frequency.
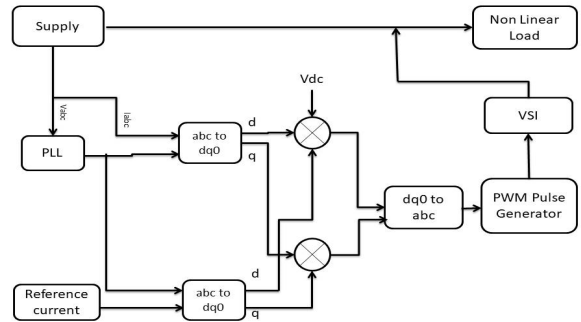

Figure 3:- Synchronous reference frame technique

In SRF theory, the first step is to extract the phase angle of the power system using a Phase-Locked-Loop (PLL)[6]. It is used to generate a synchronized signal that is used in abc to d-q transformation. The 3-phase AC signals are converted into a two-axis reference frame (DQ frame). The D-axis represents the DC component or active power, while the Q-axis represents the reactive power[1].

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The transformation of $\alpha\beta$ stationary reference frame to d-q synchronous frame is given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

$$\theta = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right)$$

The transformation from d-q to abc is given by following equations:

$$i_a = i_d \cos(\theta) - i_q \sin(\theta)$$

$$i_b = i_d \cos\left(\theta - \frac{2\pi}{3}\right) - i_q \sin\left(\theta - \frac{2\pi}{3}\right)$$

$$i_c = i_d \cos\left(\theta + \frac{2\pi}{3}\right) - i_q \sin\left(\theta + \frac{2\pi}{3}\right)$$

The reference current is calculated based on the desired harmonic elimination or reduction in the load current. Reference current is set to zero for the fundamental frequency component, while the harmonics' reference currents are set to the negative of the load's harmonic currents. PI controllers are employed to manage the active and reactive power within the DQ (direct-quadrature) frame. These controllers ensure that the deviation between the reference current and the actual current output of the SAPF is regulated [4]. The current in the DQ frame is subsequently converted back to the three-phase abc frame. The output current of the SAPF is combined with the load current, and the resulting total current is supplied to the system. The PWM generator generates the gate signals for the SAPF's power electronics. The gate signals used in VSI controls the switching of the SAPF's power electronics to produce the desired output current. The system maintains a high level of stability due to the controller primarily managing the d-q quantities, thereby minimizing any potential issues.

IV. RESULT & DISCUSSION

A programmable three-phase voltage source is employed on the distribution side to deliberately induce voltage sag, voltage swell, and voltage harmonics at various intervals within the system. Meanwhile, a non-linear load is present on the load side, which introduces current harmonics into the system. To tackle power quality concerns, the utilization of a Unified Power Quality Conditioner (UPQC) is employed. The UPQC employs a series active power filter to address voltage-related issues like voltage harmonics, voltage sag, and voltage swell. Simultaneously, the shunt active power filter component compensates for the current harmonics generated by the non-linear load by injecting the necessary current into the system. Together, these components of the UPQC work in tandem to improve the overall power quality by effectively mitigating voltage and current disturbances, ensuring a more stable and reliable electrical system.

A. Elimination of Voltage Harmonics

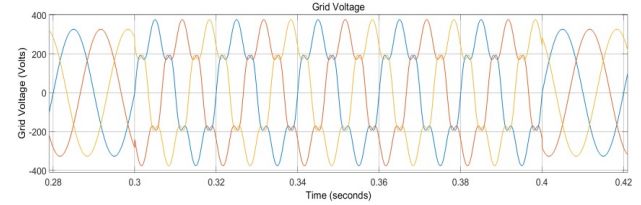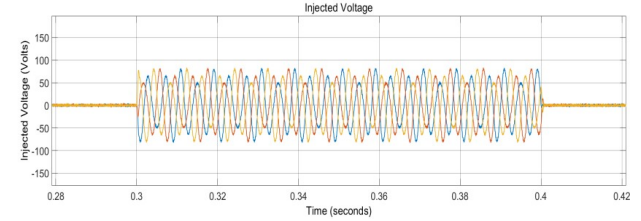
Figure 4:- Grid Voltage during Harmonics

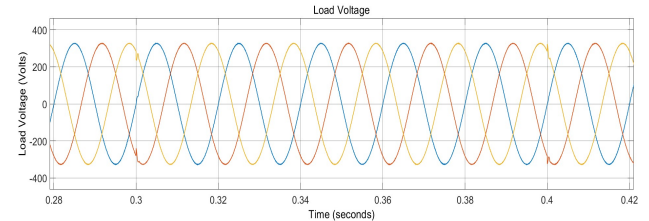Figure 5:-Voltage injected during harmonics by series APF

Figure 6:- Load voltage during Harmonics

During the time interval between 0.3seconds and 0.4seconds, voltage harmonics are introduced into the system. To counteract the effects of these harmonics, a series APF is employed. It utilizes a linear transformer to inject voltage and compensate for the generated harmonics. Figure 4 represents the grid voltage with the presence of harmonics for duration of 0.1second, specifically from 0.3seconds to 0.4seconds. Figure 5 illustrates the voltage injected by the series APF during the occurrence of the harmonics. The series APF acts as harmonic isolator, preventing harmonics from the grid voltage from reaching the load. Figure 6 depicts the load voltage within the specified timeframe, showing a completely sinusoidal waveform and the elimination of harmonics.
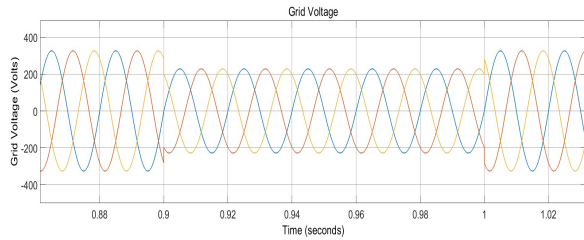
B. Elimination of Voltage Sag

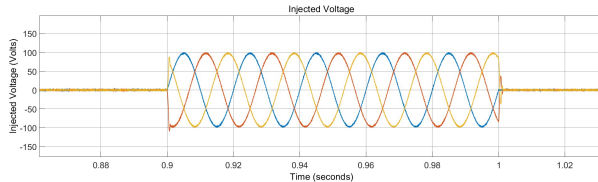Figure 7:- Grid Voltage during Sag

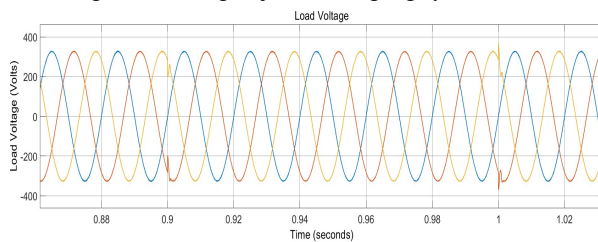Figure 8:- Voltage injected during sag by series APF

Figure :-9 Load Voltage during Sag

Figure 7 displays the grid voltage during a sag, which occurs between 0.9seconds and 1.0second. The sag is a result of voltage unbalance, often caused by faults. In Figure 8 the voltage injected by the series APF is depicted. The injected voltage occurs within the time interval of 0.9seconds to 1.0second. By injecting voltage during this period, the load side voltage is effectively balanced and assumes a completely sinusoidal waveform. Figure 9 represents the load voltage of the series APF, which exhibits perfect balance and a purely sinusoidal shape. Through the implementation of the series APF, the load voltage becomes balanced, successfully eliminating the sag that occurred between 0.9seconds and 1.0second. As a result, the load voltage is now free from any unbalance condition caused by the voltage dip.
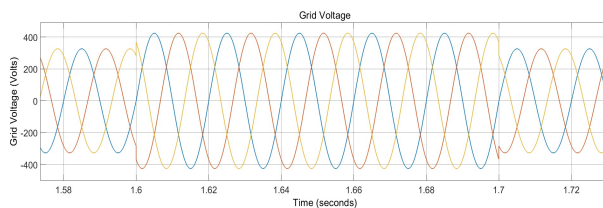
C. Elimination of Voltage Swell
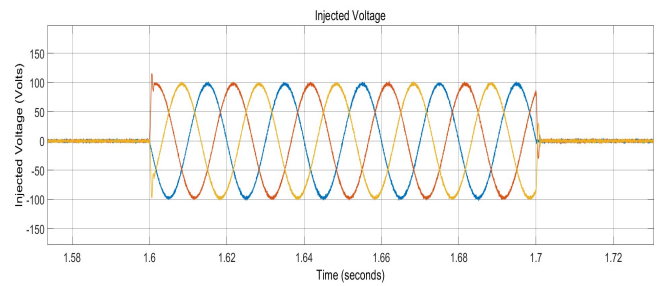

Figure 10:- Grid Voltage during Swell

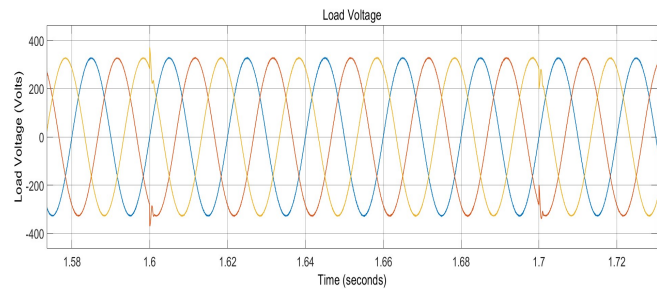Figure 11:- Voltage injected during swell by series APF

Figure 12:- Load voltage during swell

Figure 10 illustrates the grid voltage of the series APF during a swell event, occurring from 1.6seconds to 1.7seconds. During this period, there is an increase in the voltage magnitude. Swells in voltage can be attributed to faults or capacitor switching. Figure 11 gives the voltage injected by the series APF specifically during the swell condition, within the time duration of 1.6seconds to 1.7seconds. The injected voltage ensures that the load voltage across the series-APF is accurately regulated. In Figure 12, the load voltage of the series APF during the swelling condition is presented. As a result the series APF operates and the voltage swells occurring between 1.6seconds and 1.7seconds are eliminated, leading to a completely balanced load voltage. Consequently, the voltage remains balanced throughout the entire time interval.

D. Elimination of Current Harmonics

This refers to the process of reducing or removing undesirable harmonic components from an electrical current waveform. The implementation of a Shunt APF is utilized to address issues caused by current harmonics. Its purpose is to ensure that the current drawn from the grid becomes entirely sinusoidal, effectively mitigating the impact of load current harmonics.
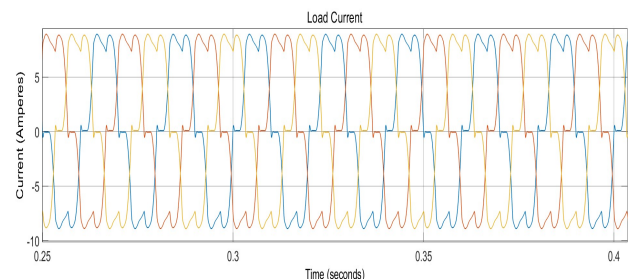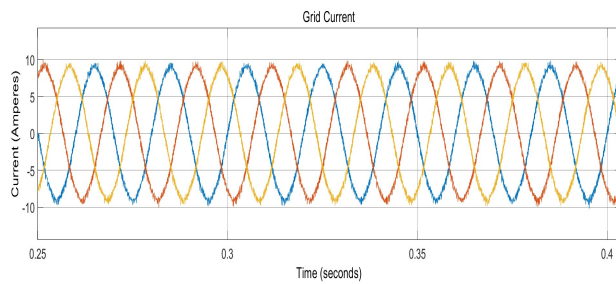

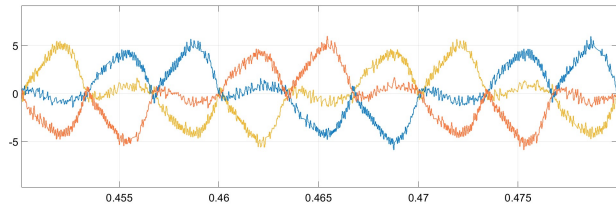Figure 13:- Load Current

Figure 14:- Grid Current
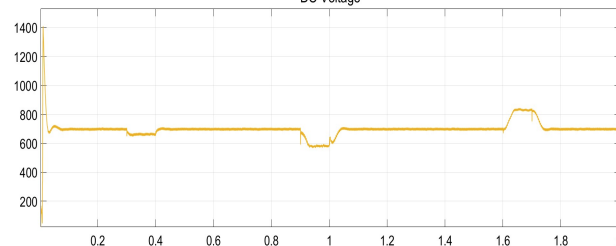

Figure 15:- Current injected by Shunt APF

Figure 16:- DC Capacitor Current

In Figure 13, the load current of a shunt Active Power Filter (APF) is depicted, and it is evident that the waveform is non-sinusoidal. This non-linearity is attributed to the presence of nonlinear loads, like diodes, within the system. These non-linear loads introduce harmonic components into the current waveform, causing deviations from a pure sinusoidal shape. Figure 14 illustrates the grid current of a shunt Active Power Filter (APF). Initially, until 0.01seconds, the grid current contains harmonics because the shunt APF is not yet active. However, once the shunt APF starts operating, the harmonics are eliminated from the grid current. The shunt APF's operation time is controlled by a circuit breaker. Figure 15 displays the current injected by the shunt APF, which commences at 0.01seconds when the shunt APF starts functioning. Consequently, after 0.01seconds, the current supplied by the power source becomes completely sinusoidal. Figure 16 represents the rise in capacitor voltage initially, which stabilizes at a constant level after 0.01seconds. This stabilization occurs because the shunt APF begins operating at that point. The shunt APF regulates and maintains the DC capacitor voltage at a reference value of 700 V.

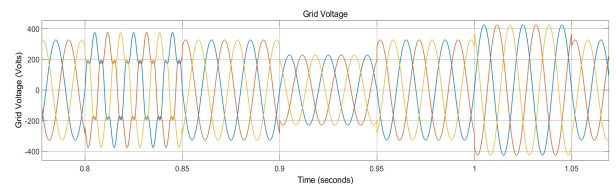*E. Simultaneous elimination of voltage sag, swell and harmonics*
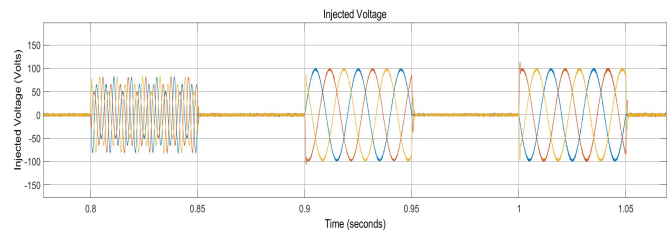

Figure 17:- Source Voltage of UPQC

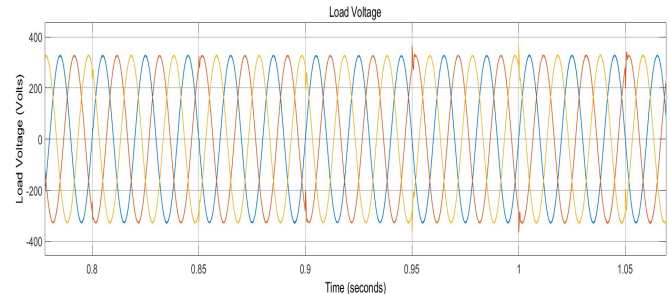Figure 18:- Injected Voltage by UPQC

Figure 19:- Load Voltage-UPQC

Fig 17 depicts the UPQC grid voltage. It contains voltage harmonics, voltage sag and voltage swell at different intervals i.e. harmonics from 0.8seconds to 0.85seconds, sag from 0.9seconds to 0.95seconds and swell from 1.0seconds to 1.05seconds. Figure 18 shows the injected voltage by UPQC for mitigating voltage problems (voltage sag, swell and harmonics) to give a proper sinusoidal waveform at the load side. The load voltage with a perfect sine wave is obtained as shown in Figure 19.

V. CONCLUSION

To mitigate current and voltage problems together, UPQC is a promising solution. The combination of shunt and series APFs provides an effective way to mitigate various power quality issues. The control strategy for UPQC is a critical aspect of the device's operation, as it ensures its effectiveness and grid stability. This paper presents an enhanced control strategy for operating the UPQC system. Various control strategies are examined, including the p-q theory, SRF-based approach, and hysteresis control, specifically for operation of the Active Power Filter (APF). The study shows that the proposed control scheme of UPQC i.e. SRF theory and hysteresis control are control strategies that can be used, as they are fast, and highly reliable and are effective in mitigating power quality issues, and it provides stable power supply to consumers. The shunt component of the UPQC effectively eliminates all current-related harmonic issues within the system. Simultaneously, the Series APF of the UPQC system addresses and eliminates voltage harmonics that arise from the utilization of nonlinear loads.

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