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(RESEARCH ARTICLE)

Performance analysis of UPQC for total harmonic distortion

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Abstract

In order to mitigate power quality (PQ) issues in electrical power systems, the Unified Power Quality Conditioner (UPQC) is the main topic of this research study. Power Quality problems, such as voltage sag, voltage swell, harmonics, and flicker, are brought on by the increase in nonlinear loads and the integration of renewable energy sources into traditional systems. Employing a variety of control algorithms and switching techniques, including as the SRF theory, hysteresis controllers, d-q theory of current, and traditional PI controllers, to balance the system, control voltage, and reduce harmonic distortions. For the reduced harmonic distortion, a FFT analysis is done so that the quick response and stability is ensured. UPQC has shown to be a successful method for fully resolving these power quality issues.

Keywords: Unified Power Quality Conditioner (UPQC); FFT Analysis; Shunt Active Power Filter; Series Active Power Filter; Hysteresis Current Controller; SRF Technique; FACTS; DVR.

1. Introduction

The field of power quality enhancement has received a lot of attention due to the growing demand for consistent, high-quality electrical energy. Power distribution networks are facing a number of power quality issues as a result of the widespread use of industrial machinery, renewable energy sources, and sensitive electronic gadgets. Voltage sags, swells, harmonics, and uneven loading are common power quality problems that can cause equipment damage and inefficiencies. Creating practical solutions to reduce these issues and ensure the continuous operation of power systems is therefore essential. UPQC is designed to address challenges of this nature[6]. It improves system balance, reduces harmonics, and regulates voltage to efficiently alleviate power quality issues. The series and shunt APF devices are combined into one unit by the UPQC. Due to this integration, the UPQC can concurrently control and make up for various PQ issues in the distribution system. It improves the quality of power delivered by the electrical system and guarantees the dependable operation of customer equipment[2]. Deviations in voltage, current, or frequency can result in problems with PQ and cause customer-used equipment to malfunction or break down. The electrical power system aims to provide high-quality power so that different electrical devices can operate as intended[1]. On the other hand, the existence of nonlinear loads has prompted issues about the permissible harmonic distortion levels introduced into the power supply system. Problems with PQ have increased frequently as non-linear loads are used more often [4].

This study provides an overview of the fundamentals of UPQC, including its fundamental setup, operational guidelines, and control measures. The development of accurate mathematical models for simulation is the main emphasis of the paper's analysis of modelling and simulation techniques for UPQC systems. Possible solutions for reducing voltage sags, voltage swells, and harmonics that arise inside the power system are discussed, among other PQ problems[3].

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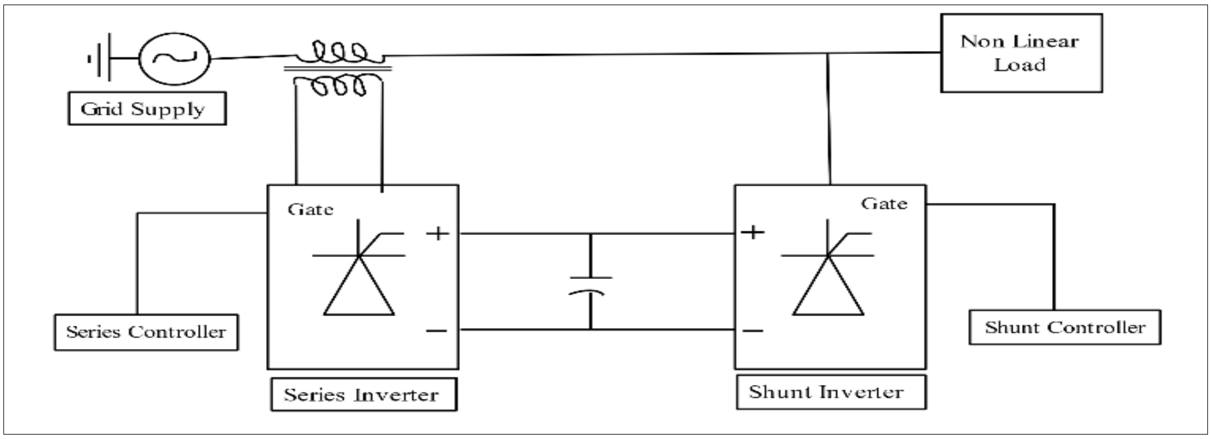

Figure 1 Block diagram for UPQC

1.1. UPQC

Figure 1 illustrates the block diagram for UPQC. It is made up of several essential parts and how they are connected, all of which improve power quality in power distribution systems. The following is an overview of the structure:

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2. Simulation structure of UPQC

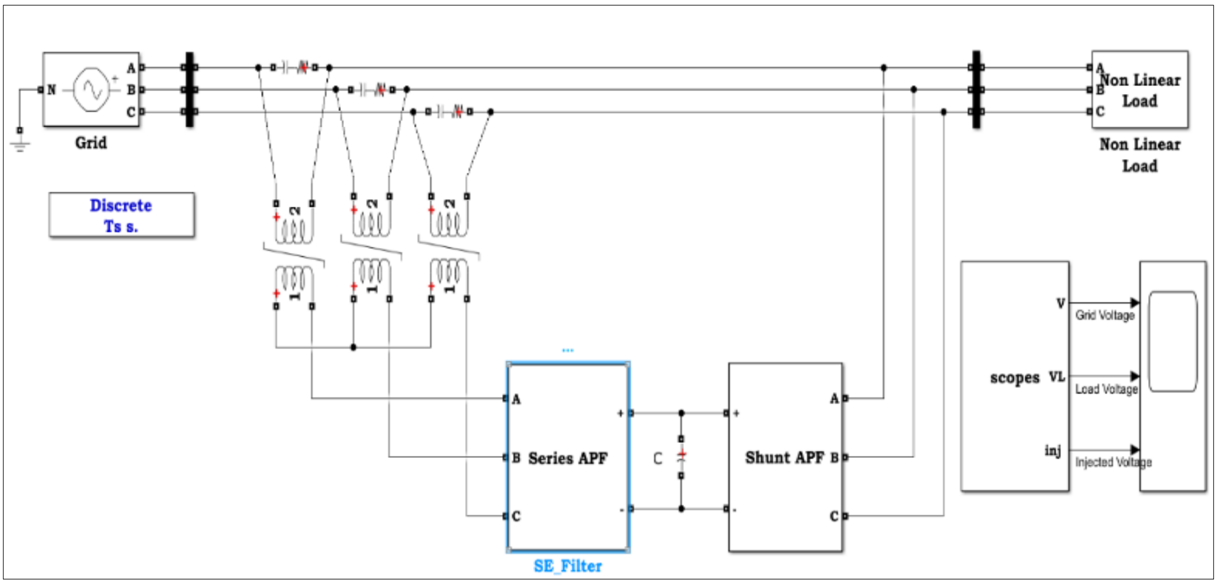

Figure 2 Simulation structure of UPQC in Grid

2.1. Series Active Power Filter (SAPF)

The UPQC's series component is an electrical device that directly interfaces with the load in a series configuration. It incorporates a VSC which utilizes high-frequency switching components, GTOs or IGBTs. The primary function of the VSC is to generate a compensating voltage waveform that is injected into the line in series with the load. To counterbalance different voltage disturbances, such as voltage sags, swells, and harmonic components, this compensatory voltage waveform is carefully managed. To provide a steady and controlled supply voltage and best possible power quality for the connected load, the series active power filter dynamically modifies the compensatory voltage waveform while continuously monitoring the voltage at the load terminals[7].

2.1.1. *Simulation structure of series APF*

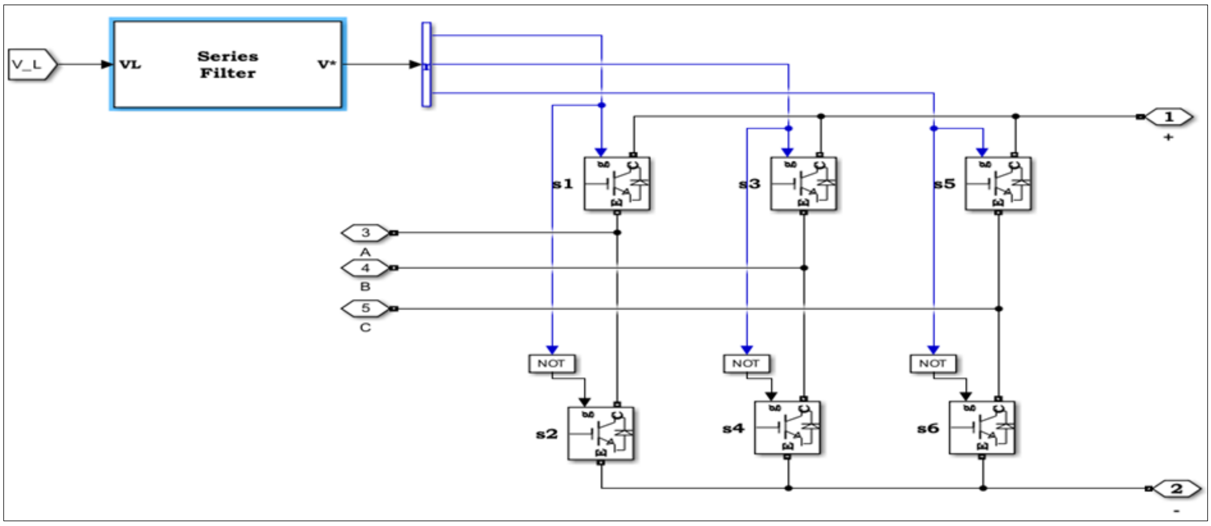

Figure 3 Simulation structure of SAPF

2.2. Shunt Active Power Filter (ShAPF)

A power electronic device known as the shunt component of the UPQC is connected to the electrical system in parallel with the supply. It has high-frequency switching components that produce a waveform of compensatory current that is injected into the line parallel to the source. To solve current-related power quality problems like harmonic distortion, voltage variations (flicker), and load imbalances, this compensating current waveform is carefully controlled. In order to guarantee a clean, balanced, and undistorted current flow from the source and maintain ideal power quality conditions, the shunt APF continuously monitors the current drawn from the supply and dynamically injects the required compensating current[9].

2.2.1. Simulation structure of shunt APF

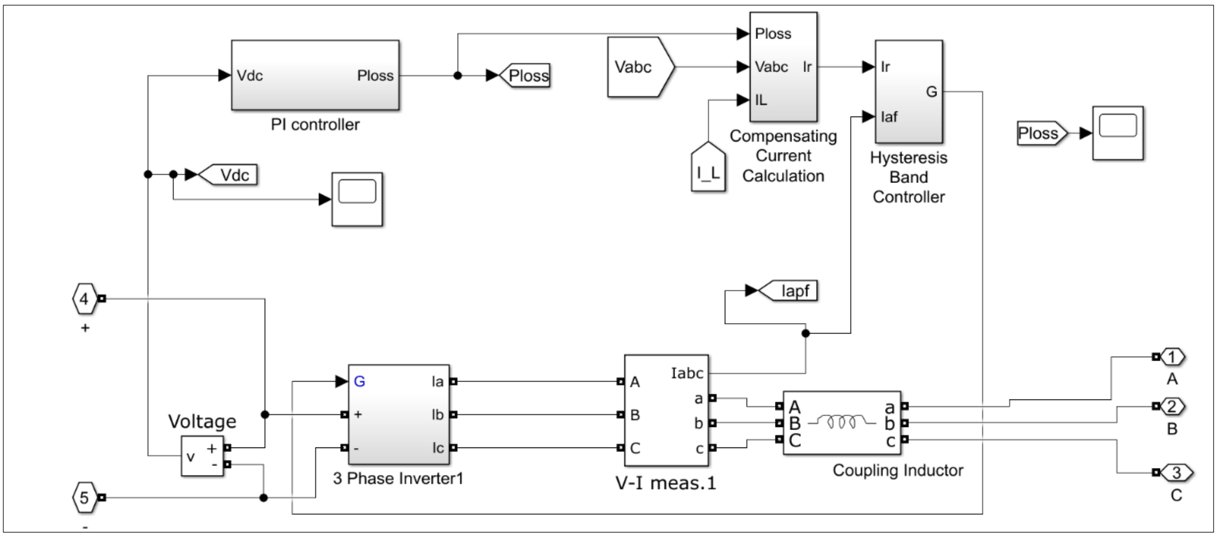

Figure 4 Simulation structure of ShAPF

2.3. Energy Storage Elements:

To improve its functionality and performance, the Unified Power Quality Conditioner can be combined with energy storage components such as capacitors or batteries. These energy storage devices provide a critical source of instantaneous power during compensating periods, allowing the UPQC to maintain a consistent and uninterrupted power supply even in the face of fast fluctuations in load or supply circumstances. The capacitors or batteries serve as a buffer, storing and discharging energy as needed by the series and shunt active power filters. This seamless energy exchange mechanism significantly improves the response time and overall effectiveness of the UPQC, allowing it to respond swiftly and accurately to various power quality disturbances, ensuring optimal power quality conditions for the connected loads[5].

2.4. Control Block

A complex control module that monitors and adjusts the compensating voltage and current waveforms is at the heart of the Unified Power Quality Conditioner. To accomplish accurate and dynamic control, this control system makes use of reference signals, feedback loops, and state-of-the-art control algorithms. Numerous electrical characteristics, including as voltage, current, power, harmonic distortion, and other power quality indicators, are continuously monitored and analyzed by it. The control system determines the required compensation and creates the right control signals for the series and shunt active power filters by examining these real-time observations. The UPQC can react to power quality disturbances quickly and correctly thanks to this smooth integration of real-time data analysis and innovative control algorithms. This ensures that the connected loads have the best possible power quality conditions.

3. Methodology

3.1. Series APF

The Unified Power Quality Conditioner's series active power filter uses a voltage control technique that is based on the idea of injecting a compensating voltage to manage the voltage at the load terminals. Creating a reference voltage in accordance with the intended voltage regulation specifications is the strategy's main objective. The voltage at the load terminals is then skillfully regulated and stabilized by the series filter through careful management, guaranteeing the best possible voltage quality and consistency. By using this cutting-edge voltage control method, the UPQC improves system performance and power delivery efficiency by ensuring consistent, high-quality voltage supply to the linked loads[8].

3.2. Hysteresis Controller

The hysteresis control strategy for the Dynamic Voltage Restorer (DVR) usually consists of the following steps: first, the actual voltage at the load terminals is continuously monitored and measured using a specific formula that calculates the instantaneous voltage value. This is done because the hysteresis controller is chosen because of its inherent simplicity, rapid transient response characteristics, enhanced stability, and high precision. This controller works by generating a switching signal based on the voltage error falling within a predefined tolerance band.

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

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

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

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

A reference voltage waveform, which depicts the required output voltage characteristics that must be maintained at the load terminals, is generated in parallel. The detected actual voltage is then subtracted from the preset reference voltage by the control system to calculate the voltage error. The difference between the desired voltage level and the voltage that is currently observed at the load terminals is quantified by this voltage error. A specific tolerance band or hysteresis band is incorporated around the reference voltage waveform by the hysteresis controller. This band defines the range in which the control action is inactive. On the other hand, the control action is initiated, and a compensating voltage is introduced into the system when the computed voltage error goes beyond the limits of this hysteresis band. This compensating voltage's major goal is to maintain optimal voltage quality at the load terminals by offsetting the observed voltage deviation and bringing the system's voltage back to the intended reference level.

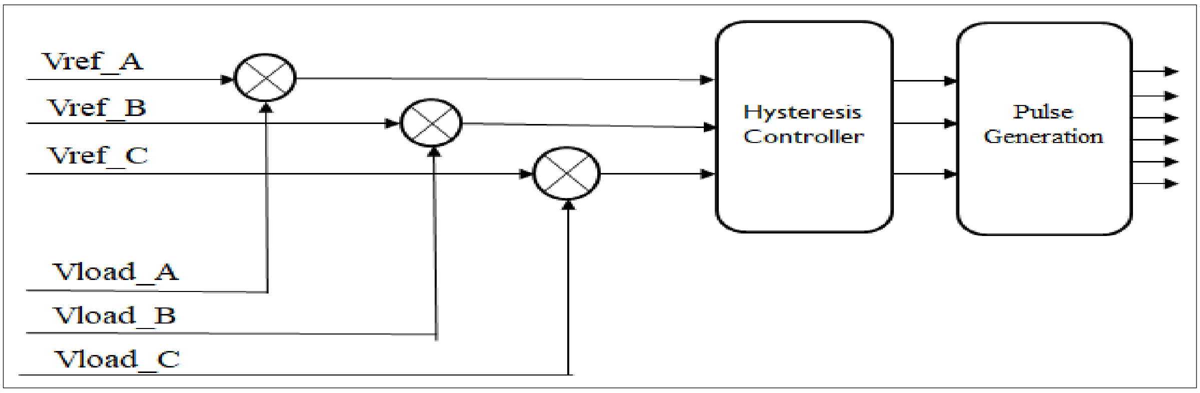

Figure 5 Hysterisis current controller

3.3. Shunt APF

The shunt APF is connected in parallel with the nonlinear load within the system. Its primary function is to introduce a compensating current waveform that effectively mitigates the harmonic currents generated by the nonlinear load. In our modeling approach for the shunt APF, we employed a control algorithm based on the SRF theory. This control strategy revolves around the concept of utilizing a rotating reference frame that is synchronized with the fundamental frequency of the power system.

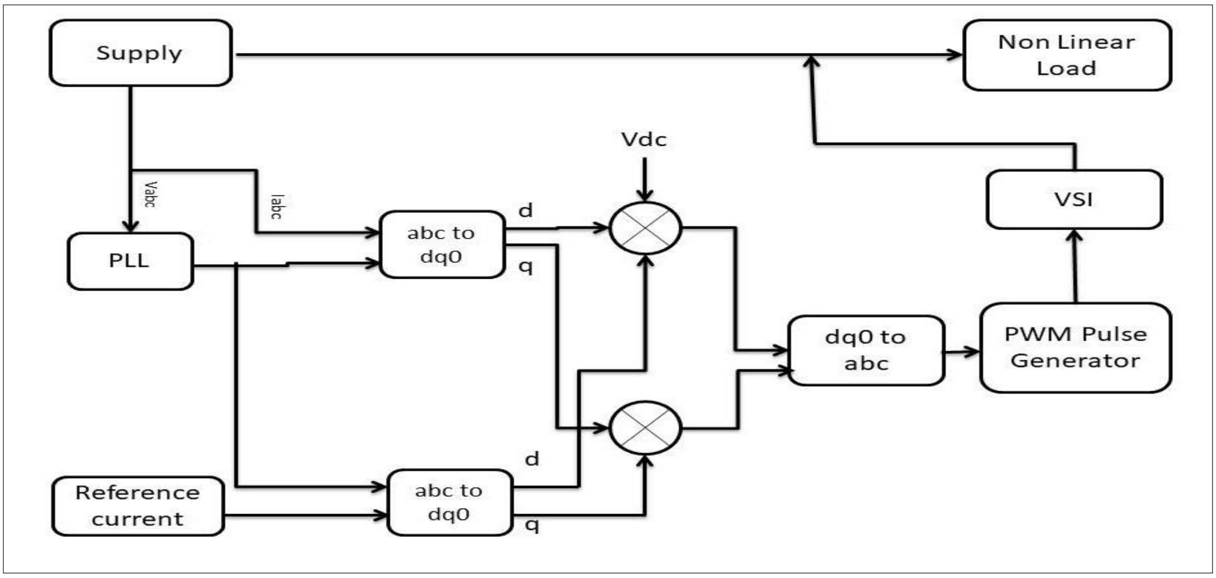

Figure 6 SRF technique

The SRF (Synchronous reference frame) theory commences by extracting the phase angle of the power system through the implementation of a Phase-Locked Loop (PLL) mechanism. This phase angle information is utilized to generate a synchronized signal, which plays a crucial role in the transformation of three-phase alternating current (AC) signals from the abc reference frame to the d-q reference frame. This transformation process converts the three-phase AC signals into a two-axis rotating reference frame, commonly referred to as the DQ frame. Within this d-q frame, the d-axis component represents the direct current (DC) or active power component, while the q-axis component corresponds to the reactive power component.

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

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

The $\alpha\beta$stationary reference frame transformation 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 a-b-c 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 required degree of harmonic elimination or load current reduction is used to calculate the reference current. The reference current for the fundamental frequency component is set to zero, and the reference currents for the harmonic components are set to the load current minus the corresponding harmonic currents. In the direct-quadrature (DQ) rotating reference frame, the active and reactive power components are controlled by proportional-integral (PI) controllers. These controllers make sure that the difference between the shunt active power filter's (SAPF) real output current and reference current is kept to a minimum and within allowable bounds. The original three-phase abc stationary reference frame is then converted back to the regulated current in the DQ frame. The load current and the output current produced by the SAPF are then mixed, and the total current that results is fed into the power system. The SAPF's power electronics components receive their gate signals from a pulse-width modulation (PWM) generator. The gate signals regulate the voltage source inverter's (VSI) switching functions within the SAPF, facilitating the production of the intended output current waveform. By controlling the d-q values, the control approach mainly contributes to the general stability of the system and reduces possible problems that can occur from operating in the stationary reference frame.

3.4. FFT analysis

In UPQC, the mathematical method known as FFT analysis is frequently employed to extract the harmonic components that are present in the voltage and current waveform. This data is essential for the UPQC to function correctly because it enables the control system to produce the right compensating signals. A highly efficient computational method for calculating a signal's Discrete Fourier Transform (DFT) is the FFT. A periodic signal is broken down mathematically into its sinusoidal components, each with a distinct frequency, amplitude, and phase. This process is known as DFT. The mathematical expression for the DFT of a discrete-time signal x(n) of length N is given by:

$$X(k) = \sum_{n=0}^{N-1} x(n) \times e^{\frac{-j2\pi kn}{N}}$$

Where:

X(k) is the DFT coefficient at the kth frequency
x(n) is the sampled signal at time index n
N is the No. of samples in the signal
j is the imaginary unit (sqrt(-1))

With a computational complexity of O(N log N), the FFT is an effective method for calculating the DFT, far less complex than the direct computation of the DFT, which has a complexity of O(N^2). The FFT is used to examine the voltage and current waveforms at the load side and at the point of common coupling (PCC) in the framework of UPQCs. The UPQC control system can extract the fundamental and harmonic components of these waveforms by computing their FFT. These components are then utilized to provide the proper compensation signals for the shunt and series filters. For example, the shunt filter can be adjusted to inject compensatory currents that cancel out these harmonics, ensuring that the source current stays sinusoidal, if the FFT analysis shows that the load current contains harmonic components. Similarly, the series filter can be adjusted to inject compensatory voltages that return the load voltage to a balanced and sinusoidal waveform if the FFT analysis reveals the presence of voltage harmonics or imbalances at the PCC. UPQC usually use digital signal processing (DSP) techniques along with specialized hardware or software implementations to perform FFT analysis in real-time. The control signals for the shunt and series filters are modified based on the constantly updated FFT coefficients, guaranteeing dynamic and efficient correction of power quality problems. It's crucial to remember that in order to increase the precision and effectiveness of the UPQC control system, the FFT analysis is frequently used in conjunction with additional signal processing methods including windowing, synchronization, and filtering.

4. Results and discussion

A programmable three-phase voltage source is used on the supply side of the electrical distribution system under consideration to purposefully introduce voltage disturbances, such as sags, swells, and harmonics, at different intervals. At the same time, there is a non-linear load on the load side, which adds to the system's current harmonic generation. A UPQC is used to solve these PQ issues. A series APF component built within the UPQC is intended to reduce voltage-related problems such as voltage harmonics, sags, and swells. In addition, by introducing the required compensatory current into the system, the shunt active power filter part of the UPQC corrects for the current harmonics caused by the non-linear load. The UPQC efficiently improves overall PQ by reducing voltage and current disturbances through the coordinated operation of these two components, guaranteeing a more stable and dependable electrical system.

4.1. Voltage Harmonics reduction

A voltage harmonics, often brought on by faults , can be seen in Figure 7(a) between 0.3 and 0.4 seconds in the grid voltage. The voltage injected by the series APF at the same time-frame of 0.3 to 0.4 seconds is shown in Figure 7(b). The series APF successfully balances the load side voltage by injecting this compensating voltage, producing the perfectly sinusoidal waveform seen in Figure 7(c). By effectively mitigating the voltage harmonics that transpired between 0.3 and 0.4 seconds, the series APF implementation guarantees that the load voltage stays balanced and free from any unbalanced condition resulting from the voltage harmonics.

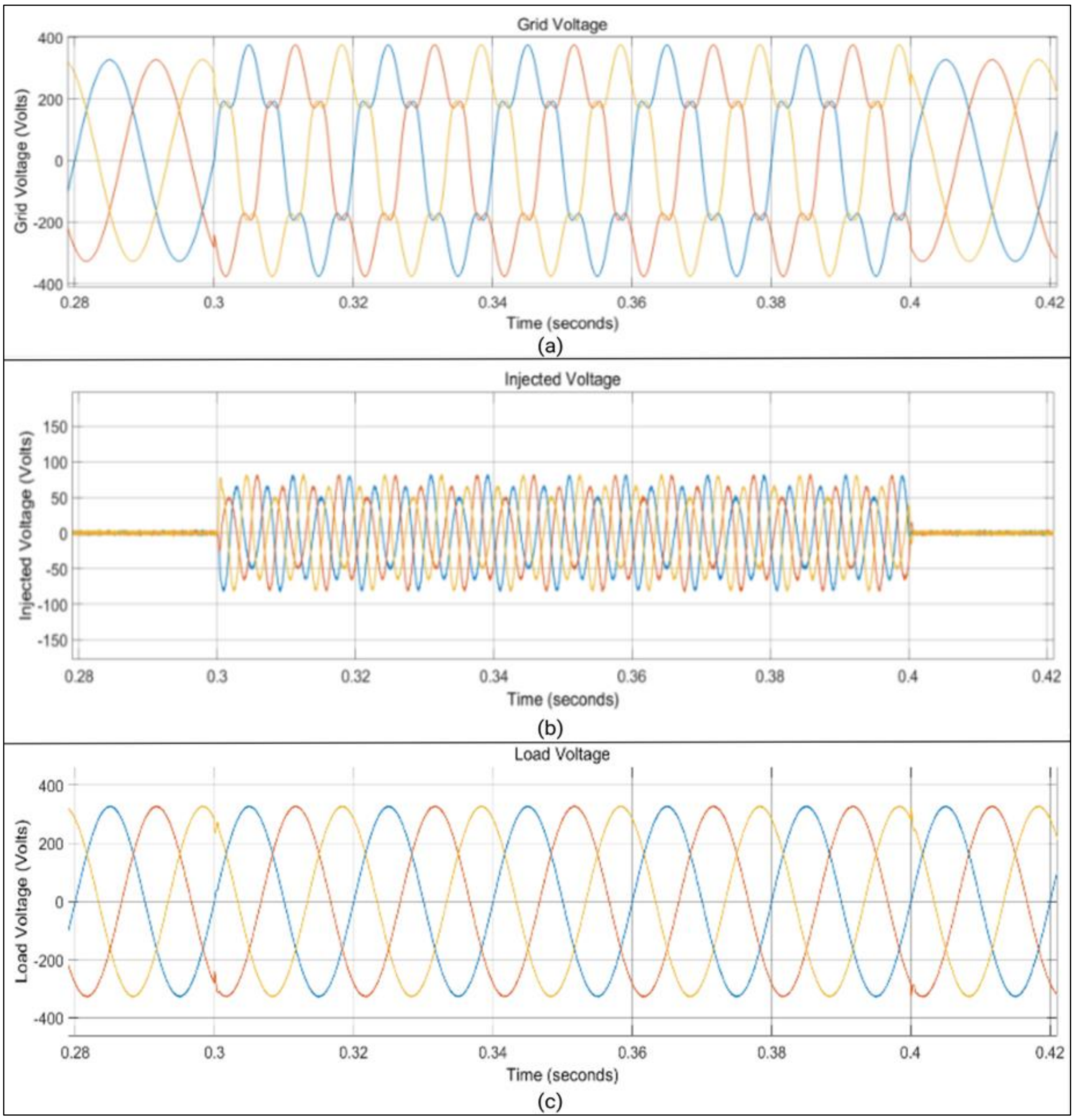

Figure 7 (a) Voltage of Grid during Harmonics, (b) Injected Voltage by series APF during harmonics, (c) Voltage of load during Harmonics

4.2. Voltage Sag Reduction

A voltage sag, often brought on by faults or voltage imbalances, can be seen in Figure 8(a) between 0.9 and 1.0 seconds in the grid voltage. The voltage injected by the series APF at the same time-frame of 0.9 to 1.0 seconds is shown in Figure 8(b). The series APF successfully balances the load side voltage by injecting this compensating voltage, producing the perfectly sinusoidal waveform seen in Figure 8(c). By effectively mitigating the voltage sag that transpired between 0.9 and 1.0 seconds, the series APF implementation guarantees that the load voltage stays balanced and free from any unbalanced condition resulting from the voltage dip.

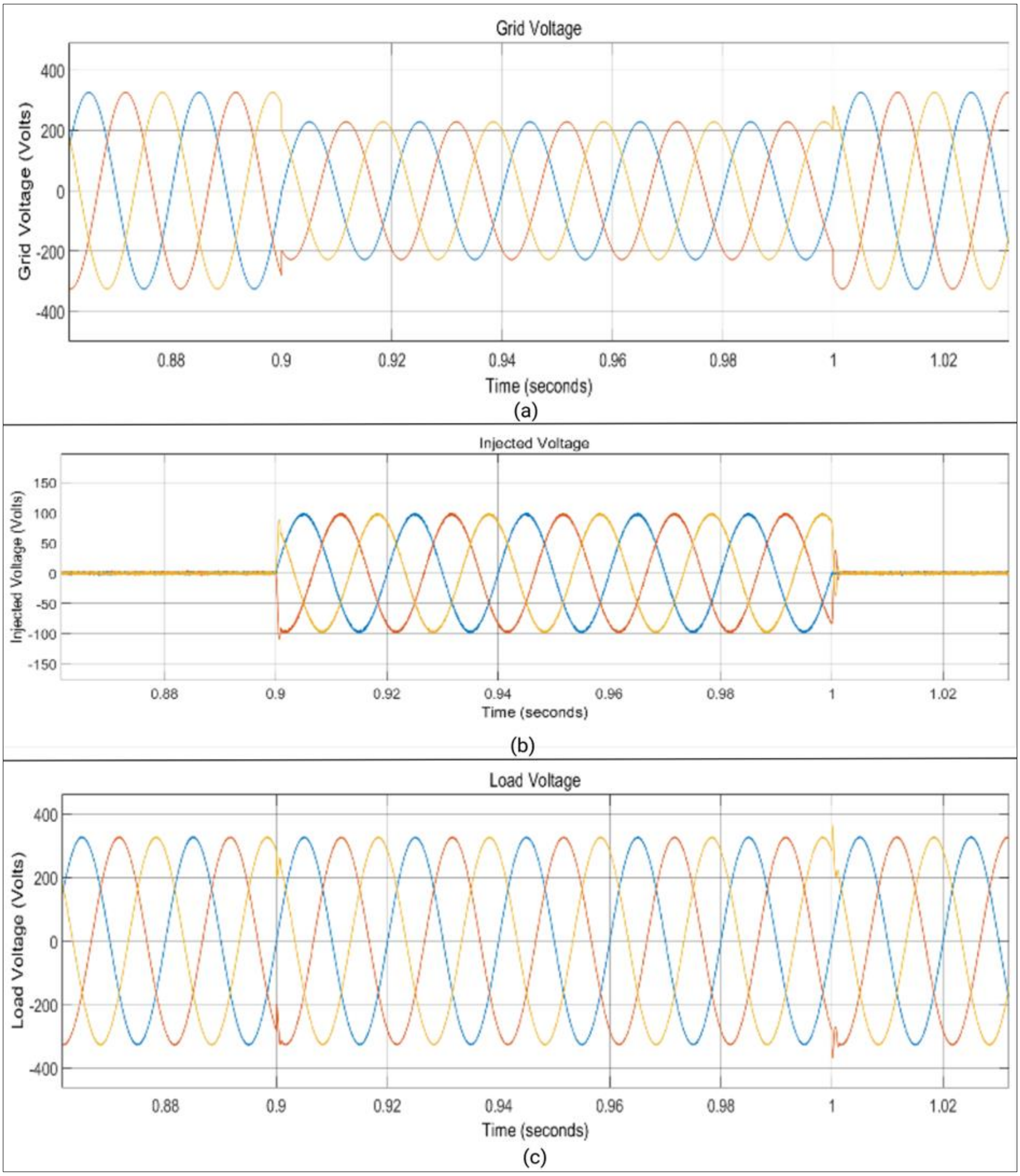

Figure 8 (a) Voltage of Grid during Sag, (b) Injected Voltage by series APF during sag, (c) Voltage of load during Sag

4.3. Voltage Swell Reduction

A voltage swell occurrence is shown by Figure 9(a), which shows an increase in the grid voltage magnitude between 1.6 and 1.7 seconds. Such overvoltage situations may result from power system malfunctions or capacitor swapping. As illustrated in Figure 9(b), the series APF injects a compensatory voltage to counterbalance this within the same 1.6 to 1.7 second interval. The APF is able to precisely control the load-side voltage across its terminals thanks to this injected voltage. Consequently, Figure 9(c) illustrates that throughout the swell occurrence, the load voltage of the series APF stays balanced and free from any overvoltage condition. The series APF effectively reduces the voltage spikes that happen between 1.6 and 1.7 seconds by injecting the right voltage, keeping the load voltage constant over that whole interval.

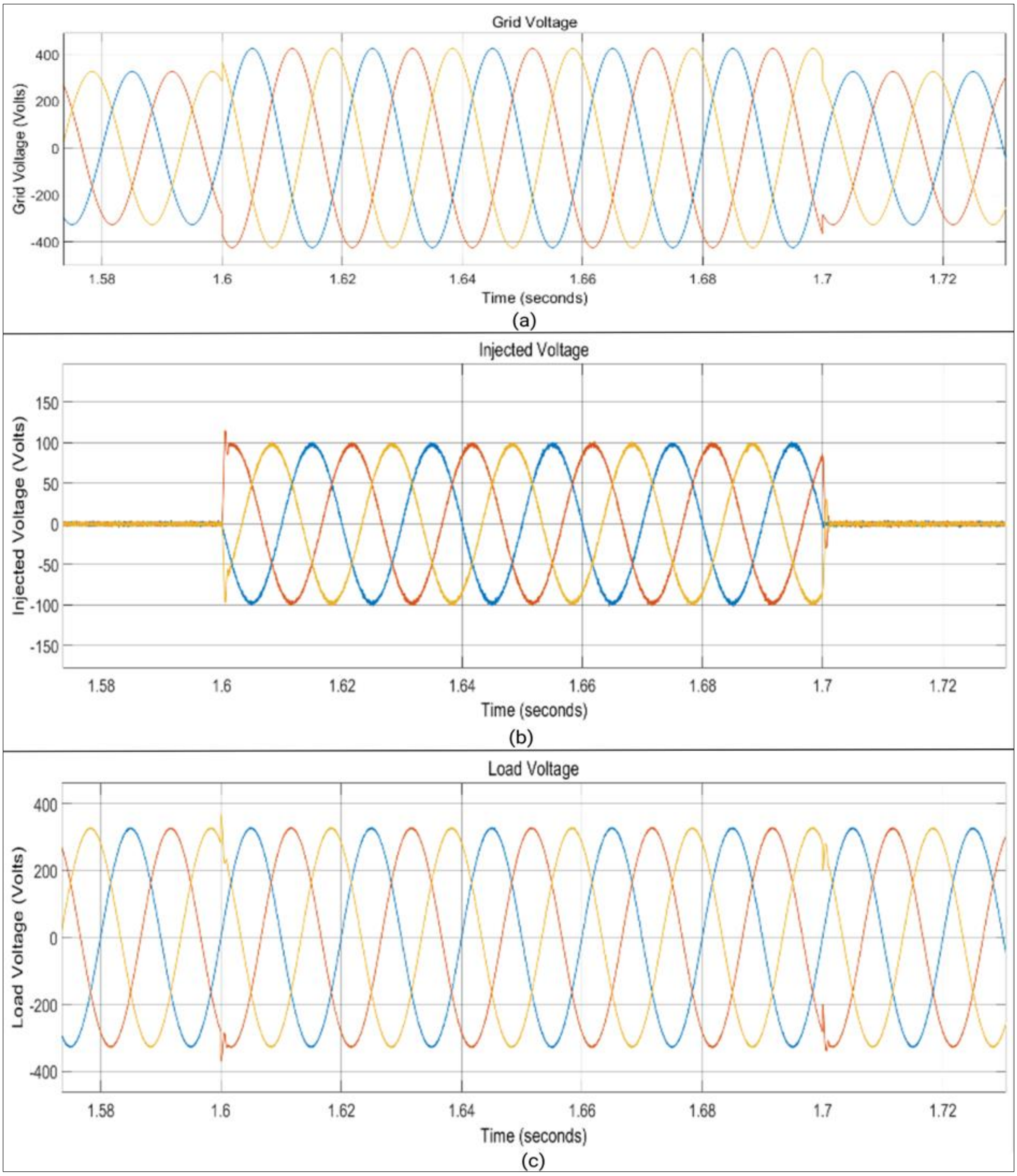

Figure 9 (a) Voltage of Grid during Swell, (b) Injected Voltage by SAPF during swell, (c) Voltage of load during swell

4.4. Current Harmonics Reduction

The load current of a shunt APF is shown in Figure 10(a), showing a non-sinusoidal waveform. The existence of nonlinear loads in the system, such as diodes, causes this distortion. Due to the introduction of harmonic components by these nonlinear loads, the current waveform no longer has a clean sinusoidal shape. The shunt APF's grid current is depicted in Figure 10(b). Because the shunt APF is not yet functioning, the grid current initially contains harmonics before 0.01 seconds. However, the harmonic components are essentially removed from the grid current once the circuit breaker-controlled shunt APF operates. The compensatory current injected by the shunt APF is displayed in Figure 10(c), starting at the 0.01 second mark when it activates. As a result, the power source's current turns entirely sinusoidal after 0.01 seconds. The first rise in the capacitor voltage is shown in Figure 10(d), and it takes 0.01 seconds for it to stabilise at a constant level, which is when the shunt APF activates. The DC capacitor voltage is controlled and kept constant at 700 V by the shunt APF.

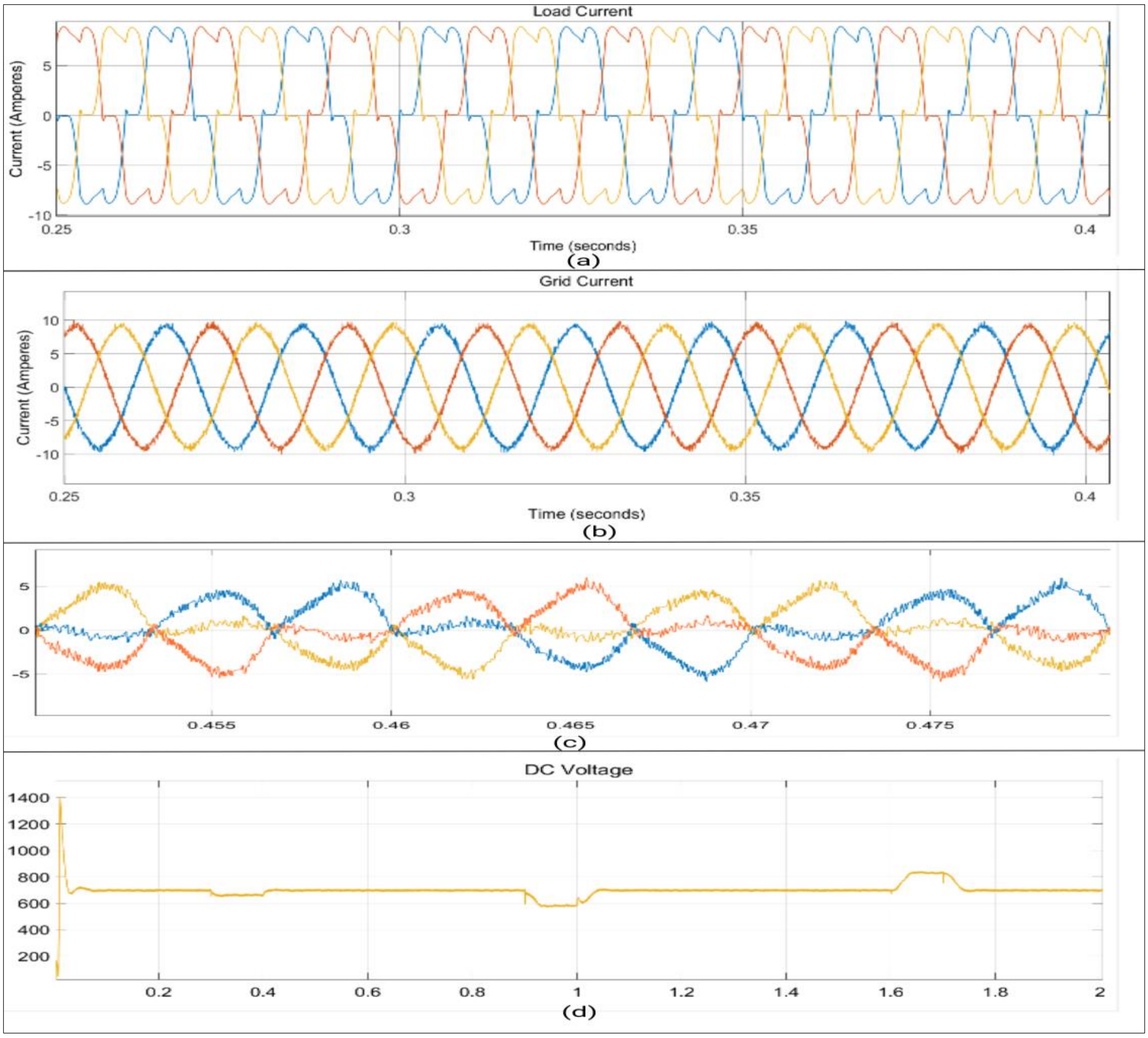

Figure 10 (a) Current in load, (b) Current in Grid, (c) Injected current by ShAPF, (d) DC Capacitor Current

4.5. Simultaneous reduction of voltage sag, swell and harmonics

The UPQC grid voltage is shown in Figure 11(a), where several voltage disturbances occur at various intervals. In particular, there are voltage harmonics between 0.8 and 0.85 seconds, a voltage sag between 0.9 and 0.95 seconds, and a voltage swell between 1.0 and 1.05 seconds. As seen in Figure 11(b), the UPQC injects a compensating voltage to alleviate these voltage problems. The purpose of this injected voltage is to reduce harmonic distortions, voltage swell, and sag while maintaining a normal sinusoidal waveform at the load side. Consequently, the load voltage acquired during the operation of the UPQC is displayed in Figure 11(c), displaying a pure sine wave devoid of any disruptions.

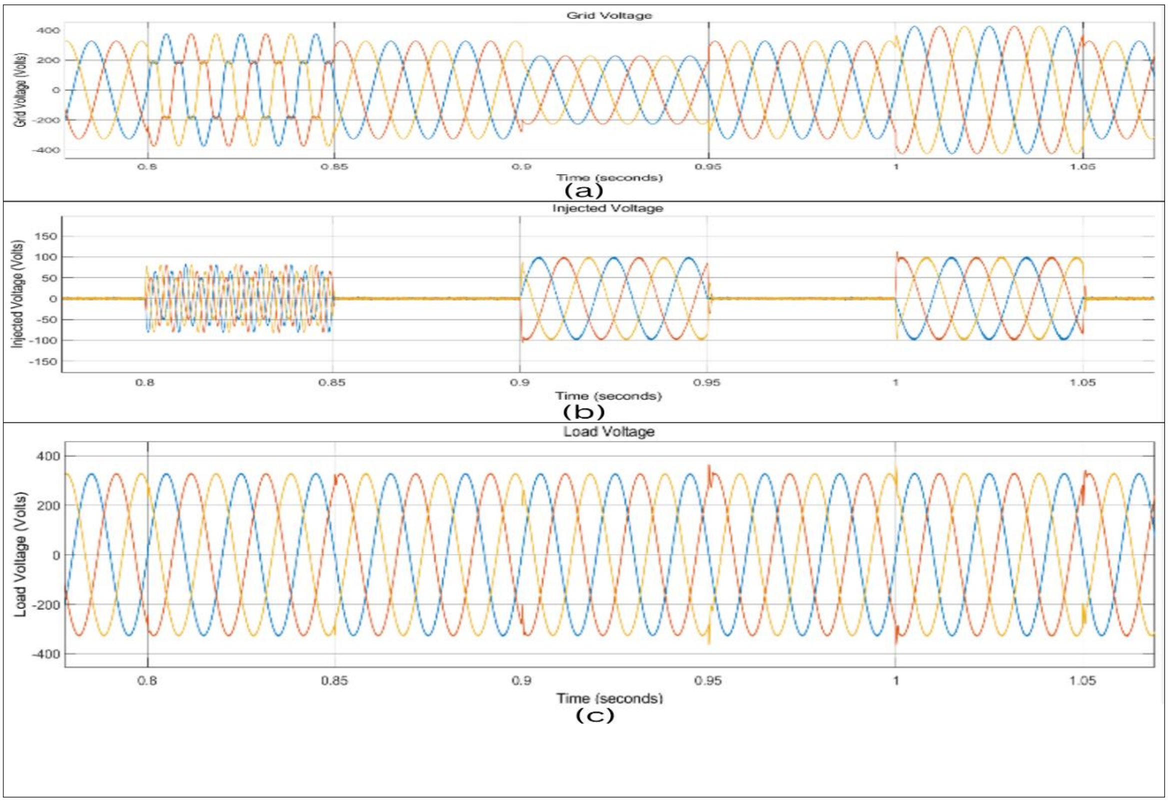

Figure 11 (a) Source Voltage of UPQC, (b) Injected Voltage by UPQC, (c) Load Voltage of UPQC

4.6. FFT Analysis

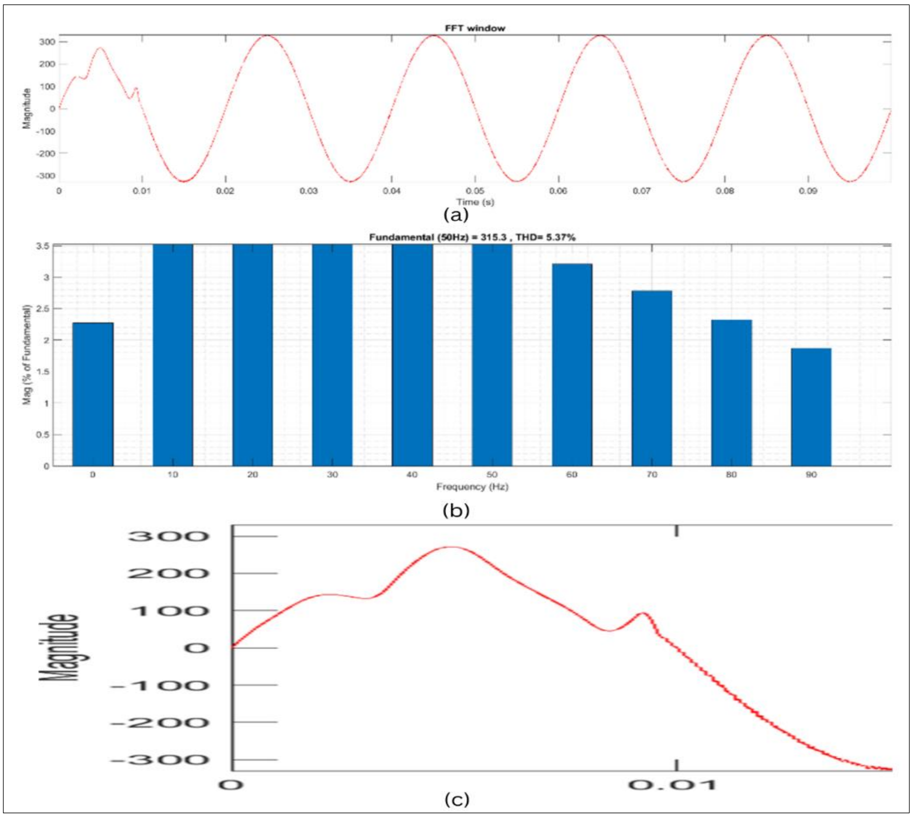

Figure 12 (a) 5 cycle response for FFT analysis, (b) THD for 50Hz, (c) Response time for system stability

From FFT analysis for as shown in Figure 12(a), the total harmonic distortion is almost 5.37% as shown in Figure 12(b) and the system is settling approximately within 0.01 secs. This shows that this UPQC is clearing various power quality issues simultaneously and is also attaining stability quickly.

5. Conclusion

The integration of shunt and series APFs within the UPQC presents a robust solution for tackling diverse PQ challenges simultaneously. Central to the efficacy and grid stability of the UPQC is its control strategy. This study introduces an advanced control methodology tailored for UPQC operation, assessing various techniques including the p-q theory, the SRF approach, and the hysteresis control, with a focus on APF functionality. Through analysis, it is demonstrated that the proposed control strategy, leveraging SRF theory and hysteresis control, stands out for its speed, reliability, and effectiveness in mitigating power quality issues while ensuring a steady power delivery to end-users. All current-related harmonic distortions are removed from the system by the UPQC's shunt component, while voltage harmonics caused by nonlinear loads are addressed and reduced by the series APF. The FFT analysis shows the total harmonic distortion for the stable output is 5.37% and the system gets stable within 0.01 secs. This shows that the system gets stable quickly with lesser response time of the system and hence the power quality of the system is improved.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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