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Development of Unified Power Quality Conditioner for Power Quality Improvement in Distribution System using SRF and P-Q Theory-Based Control Strategies

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Abstract

A Unified Power Quality Conditioner (UPQC) functions as an integrated compensation system capable of addressing both voltage-based and current-based power quality disturbances in electrical distribution networks. The device operates through coordinated action of two converters: a series-connected unit that corrects abnormalities in the supply voltage, such as waveform distortion and magnitude variations, and a shunt-connected unit that stabilizes the DC-link voltage while suppressing unwanted current components and reactive power demand. In this work, control of the series and shunt converters is achieved using synchronous reference frame techniques and instantaneous power–based control principles, respectively. The effectiveness of the proposed control framework is examined through detailed modeling and simulation of a three-phase distribution network implemented in MATLAB/Simulink. Simulation outcomes confirm the capability of the proposed approach to enhance overall power quality performance under different operating conditions.

Keywords: *Power quality, unified power quality control, distribution system.*

1. Introduction

In recent years, the mitigation of electric power quality (PQ) disturbances has received increasing attention from utility companies, equipment manufacturers, and end users alike. This is due to the proliferation of highly sensitive electronic devices and microprocessor-based equipment, which are easily affected by PQ disturbances such as harmonics, transients, unbalanced system, voltage sag, voltage swell, flickers and momentary interruptions [1]. The adverse effects of PQ problems include overheating, life expectancy reduction of equipment, motor failures, inaccurate metering, power losses, Electromagnetic Interference (EMI), and maloperation of sensitive equipment [2]. PQ disturbances are prevalent in distribution networks due to the increasing use of power electronic converters in many applications with the attendant problem of power supply degradation [3]. With the increasing penetration of renewable energy into the global energy mix, modern power generation has witnessed a paradigm shift from the centralized generation to decentralized and dispersed distributed generation (DG) [4]. The power generated by converter-based DG is non-sinusoidal, which result into degradation of power quality on the grid. Furthermore, the widespread use of nonlinear loads such as adjustable speed drive (ASD), electric arc furnaces, refrigerators, and electric vehicles in distribution network also degrade power quality. Nonlinear loads draw non-sinusoidal current from utility grid thereby causing various undesirable power quality problems [4]. The economic cost of damaged equipment, interrupted manufacturing processes and computer network downtime that are caused by these disturbances, significantly affects many industries, which necessitates stringent demands for prompt detection and mitigation of PQ problems [5].

Advancements in high-speed power electronic controllers have made it possible to develop effective solutions for power quality (PQ) issues at the distribution level through the use of compensating devices commonly referred to as custom power devices (CPDs). These devices serve as the distribution-system counterparts of flexible AC transmission system (FACTS) controllers used in transmission networks [6]. The concept of custom power, originally introduced by Hingorani [7], focuses on enhancing power quality and system reliability in distribution networks through the application of active power filters (APFs). CPDs include shunt-connected devices such as the distribution static synchronous compensator (D-STATCOM), series-connected devices such as the dynamic voltage restorer (DVR), and combined shunt–series devices such as the unified power quality controller (UPQC). Series-connected CPDs are primarily employed to mitigate voltage-related PQ disturbances, whereas shunt-connected CPDs are used to address current-related issues, including harmonics produced by nonlinear loads [8]. The UPQC integrates both series and shunt APFs connected through a common DC-link capacitor, enabling coordinated operation. In this configuration, the series APF regulates the load voltage by compensating voltage disturbances, while the shunt APF suppresses current-related distortions. Consequently, the UPQC combines the functionalities of both DVR and D-STATCOM, providing simultaneous compensation of voltage and current disturbances to protect sensitive loads from PQ degradation.

This work enhances power quality in distribution systems by employing two complementary control approaches within a unified power quality conditioner (UPQC). Control of the series compensation unit is achieved using a synchronously rotating reference framework, while the shunt compensation unit is governed by an instantaneous power–based control method. Through this coordinated control structure, the UPQC is able to simultaneously suppress voltage abnormalities, eliminate current distortions, and reduce harmonic effects arising from nonlinear loads connected to the utility network.

2. Mathematical Modeling of UPQC

A unified power quality conditioner (UPQC) located at the point of common coupling (PCC) between a distribution system's supply source and a sensitive load is shown in Figure 1 as a single-line diagram. The UPQC is capable of simultaneously mitigating multiple power quality disturbances through coordinated operation of its series and shunt active power filters, which are interconnected via a common DC link. The series-connected APF is designated for voltage compensation, while the shunt-connected APF facilitates current injection and mitigation of current related problems [8].

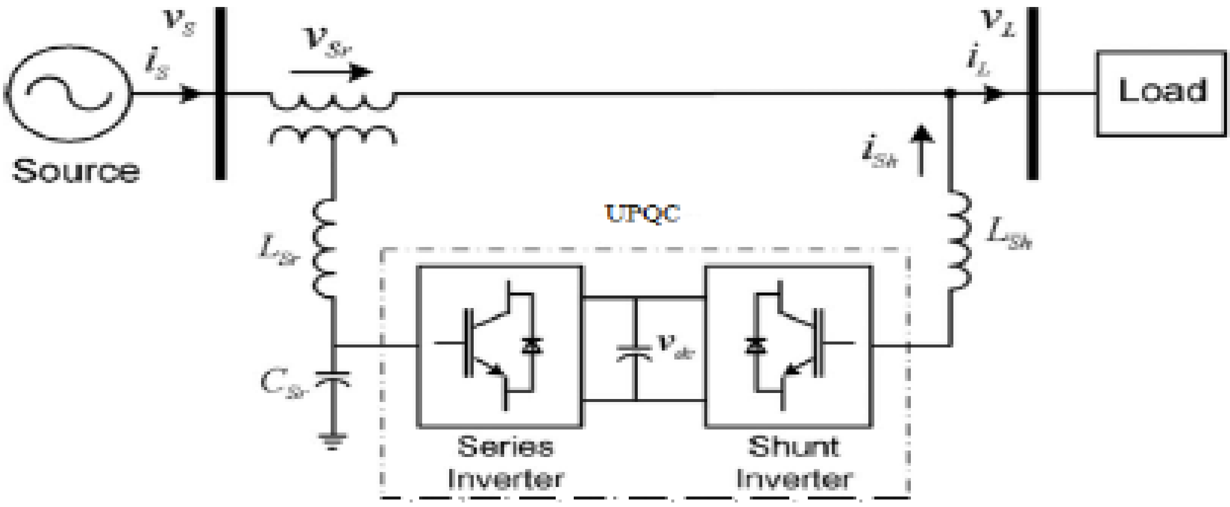

Fig. 1: Single line diagram of UPQC installed in a distribution system

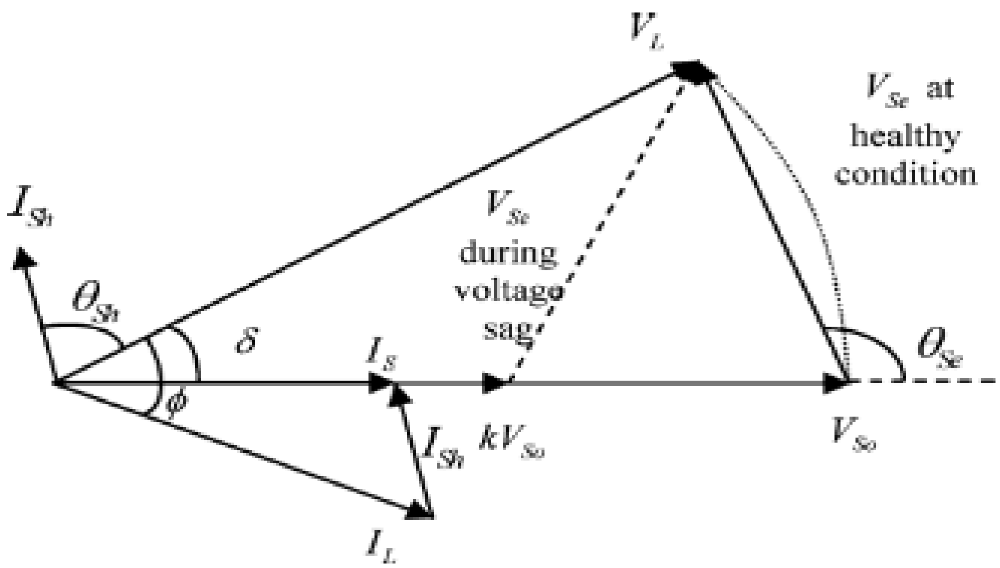

Fig. 2. UPQC phasor representation for shunt and series compensation

Within the distribution system, three voltage quantities are considered: the voltage at the point of common coupling (V_{CC}), the supply voltage (V_S), and the load-side voltage (V_L). During voltage disturbances such as sag or swell, the series active power filter (APF) restores voltage quality by injecting a compensating voltage (V_{SS}) into the system. The apparent power capacity required for the series APF is determined by the magnitude of the injected compensating voltage and the corresponding source current (I_S), which together define the power handling requirement of the compensator [9].

$$S_{Se} = V_{Se} I_s \quad (1)$$

The compensating voltage supplied by the series active power filter is expressed as [10]:

$$V_{se} = V_L - V_{cc} = -KV_L \quad (2)$$

Where K denotes the variations in the source voltage and is expressed as:

$$K = \frac{(V_{cc} - V_L)}{V_L} \quad (3)$$

Consequently,

$$V_{cc} = V_L(1 + K) \quad (4)$$

Figure 2 depicts the phasor representation of the voltage injected by the series active power filter and the current injected by the shunt active power filter during compensation. Under the assumption that the unified power quality conditioner (UPQC) operates without losses, the active power demanded by the load is exactly balanced by the active power drawn from the supply source [11], leading to the following relationship:

$$kV_S I_s = V_L I_L \cos\phi \quad (5)$$

The input real power at the point of common coupling is therefore stated as follows for a given load state:

$$P_{cc} = P_L = V_L I_L \cos\phi \quad (6)$$

Since load voltage and source voltage are equal, the source current is then expressed as shown in (7).

$$I_s = \frac{I_L \cos\emptyset}{k} \quad (7)$$

Where $\cos\phi$ is the lagging power factor of the load [10]. From (1) and (2), the real power (P_{Se}) and the reactive power (Q_{Se}) are expressed as

$$P_{Se} = S_{Se}\cos\theta_{Se} = V_{Se} I_s \cos\theta_{se} = -KV_L I_s \cos\theta_{se} \quad (8)$$

$$Q_{Se} = S_{Se}\sin\theta_{Se} = V_{Se} I_s \sin\theta_{se} = -KV_L I_s \sin\theta_{se} \quad (9)$$

Since a unity power factor is maintained by the UPQC, $\theta_{se} = 0$. Thus,

$$P_{Se} = -KV_L I_s \quad (10)$$

$$Q_{Se} = 0 \quad (11)$$

The operation of the series APF is based on the value of K in (3). Under normal operating condition of the distribution network ($K = 0$, and $V_L = V_{cc}$), the UPQC remains inactive. However, if $V_{cc} < V_l$, K is negative and there is voltage sag. The depth of the sag determines the magnitude of the injected compensating voltage (V_{se}). To compensate the voltage sag, the series APF injects real power to the load. From (7), the value of I_s under this condition is higher than the normal rated value such that the real power that is required for the voltage sag compensation and maintenance of the dc link voltage within the acceptable range is taken from the source. Lastly, if $V_{cc} > V_l$, K is positive and there is voltage swell. The series APF compensates this condition by absorbing real power from the source [10].

Under this condition, real power is supplied to the load by the series APF

Similarly, current-related power quality problems such as harmonic distortion caused by nonlinear loads as well as unwanted reactive component of the loads are mitigated with the injection of a shunt current (I_{Sh}) by the shunt APF. By Kirchhoff's current law, the algebraic sum of the compensating shunt current (i_{Sh}) injected by the shunt APF of the UPQC, source current (i_s), and the load current (i_L) at the PCC is zero [6]. Thus,

$$i_L = i_S + i_{Sh} \quad (12)$$

The apparent power rating of the shunt APF is dependent on load voltage (V_L) and the injected shunt current (I_{Sh}) [11].

$$S_{Sh} = V_L I_{Sh} = V_S I_{Sh} \quad (13)$$

The VA rating of the shunt inverter in (13) can be resolved into real power (P_{Sh}) and the reactive power (Q_{Sh}) as

$$P_{Sh} = S_{Sh}\cos\theta_{Sh} \quad (14)$$

$$Q_{Sh} = S_{Sh}\sin\theta_{Sh} \quad (15)$$

2.2 Control Strategy of UPQC

Compensation of power quality problems entails detection, classification and measurement of the power quality events. The control strategies used for generating the compensation commands in UPQC are either implemented in the time domain or frequency domain [12]. Among time-domain control strategies, the synchronous reference frame (d–q) theory and the instantaneous active–reactive power (p–q) theory are the most commonly applied, whereas frequency-domain compensation approaches rely on techniques such as Fast Fourier Transform (FFT) or wavelet analysis to extract distorted voltage or current components and determine the required compensating signals.

2.2.1 Series Active Power Filter Control Strategy

The series active power filter (APF) operates by injecting a controlled voltage into the system to correct voltage-related power quality disturbances such as waveform distortion, phase imbalance, and variations in voltage magnitude including sag and swell. In this work, the dynamic operation of the series APF within the unified power quality conditioner (UPQC) is governed by a synchronous reference frame (SRF)–based control scheme. This control method applies Park's transformation to map the measured three-phase supply voltages from the stationary a–b–c coordinate system into a rotating d–q–0 reference frame [10,13], as formulated in (16). Synchronization of the transformation process is achieved using a phase-locked loop (PLL). In the transformed reference frame, non-fundamental components such as harmonics and negative-sequence voltages manifest as oscillatory signals, while the fundamental positive-sequence component is converted into a steady direct-current quantity.

$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(wt) & \cos\left(wt-\frac{2\pi}{3}\right) & \cos\left(wt+\frac{2\pi}{3}\right) \\ -\sin(wt) & -\sin\left(wt-\frac{2\pi}{3}\right) & -\sin\left(wt+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (16)$$

Where w is the rotation speed of the d-q-0 frame, v_d, v_q, and v_0 are the direct axis supply voltage, quadratic axis supply voltage and zero sequence supply voltage, respectively, while v_{sa}, v_{sb}, and v_{sc} are the instantaneous supply voltages of phase A, phase B and phase C, respectively.

The voltage in d axes (V_d) as given in equation (7) comprises dc component ($\overline{V_d}$) and ac component ($\widetilde{V_d}$).

$$V_d = \overline{V_d} + \widetilde{V_d} \quad (17)$$

The dc voltage component ($\overline{V_d}$) is extracted with a low pass filter (LPF). Reference supply voltages (v^*_{sabc}) are then calculated as given in (9).

$$\begin{bmatrix} v^*_{sa} \\ v^*_{sb} \\ v^*_{sc} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(wt) & -\sin(wt) & 1 \\ \cos\left(wt-\frac{2\pi}{3}\right) & -\sin\left(wt-\frac{2\pi}{3}\right) & 1 \\ \cos\left(wt+\frac{2\pi}{3}\right) & -\sin\left(wt+\frac{2\pi}{3}\right) & 1 \end{bmatrix}\begin{bmatrix} \bar{v}_d \\ v_q \\ v_o \end{bmatrix} \quad (18)$$

Gate pulses for the series active power filter (APF) are produced using a hysteresis band control scheme, where the control error is obtained by comparing the calculated reference supply voltages (V_{sabc}) with the measured load voltages (V_{Labc}) [13].

2.2.2 Shunt Active Filter Control Strategy

The shunt active power filter (APF) functions by supplying a compensating current that suppresses unwanted components of the load current, including reactive, harmonic, and negative-sequence elements. In this study, real-time operation of the shunt APF within the unified power quality conditioner (UPQC) is governed by an instantaneous power–based control approach. This strategy converts the measured three-phase source voltages and currents from the a–b–c coordinate system into a stationary α–β–0 reference frame using the Clarke–Concordia transformation, as formulated in (19) and (20) [13,14]. In the transformed domain, system power is decomposed into three distinct components: instantaneous active power, instantaneous reactive power, and zero-sequence power, as defined in (21), (22), and (25), respectively.

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (19)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\end{bmatrix}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (20)$$

The load side instantaneous real and reactive powers are given in (21) and (22) as

$$p = v_\alpha i_\alpha + v_\beta i_\beta \quad (21)$$

$$q = v_\beta i_\alpha - v_\beta i_\alpha \quad (22)$$

The instantaneous real and reactive powers in (21) and (22) can be resolved into DC components ($\bar{p}$ and $\bar{q}$) and AC components ($\tilde{p}$ and $\tilde{q}$) as given in (23) and (24).

$$p = \bar{p} + \tilde{p} \quad (23)$$

$$q = \bar{q} + \tilde{q} \quad (24)$$

In the instantaneous power framework, the steady (dc) portions of the calculated real and reactive power signals arise from the positive-sequence component of the load current and reflect the fundamental active and reactive power requirements of the load. Conversely, the oscillatory (ac) portions of these power signals are associated with harmonic content and negative-sequence current components. The fundamental dc terms are extracted through the application of a low-pass filtering process. When the load is unbalanced, a neutral current is produced, and the corresponding instantaneous power contribution of the zero-sequence component is described by (25).

$$p_0 = v_0 i_0 \quad (25)$$

To mitigate neutral, harmonic, and reactive current components in the load, the α–β components of the reference source currents for the shunt active power filter (APF) are computed as follows:

$$\begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \overline{-p} + p_0 + p_{loss} \\ -q \end{bmatrix} \quad (26)$$

Where p_{loss} is the switching loss.

The reference source currents in the α-β frame are transformed back to a-b-c frame as

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} \tag{27}$$

The compensating currents to be injected by the shunt active power filter (APF) for the elimination of harmonic, reactive, and neutral current components in the load are determined as follows:

$$i_{Ca} = i_{La} - i_{sa}^* \tag{28}$$

$$i_{Cb} = i_{Lb} - i_{sb}^* \tag{29}$$

$$i_{Cc} = i_{Lc} - i_{sc}^* \tag{30}$$

Using a hysteresis band current controller, the gate pulses that control the switching operations of the shunt APF control algorithm are generated with the error signals obtained by comparing the measured load currents and the estimated reference source currents.

3.0 Simulation Results and Discussion

The proposed unified power quality conditioner (UPQC) integrated into a three-phase distribution network is analyzed through detailed modeling and simulation carried out in MATLAB/Simulink R2023a. The operational control of the UPQC is achieved using two complementary control schemes: a synchronous reference frame–based (d–q–0) approach for the series active power filter and an instantaneous active–reactive power (p–q)–based method for the shunt active power filter. The complete Simulink representation of the UPQC system is shown in Figure 3, and the parameters used for simulation are provided in Table 1.

3.1 Normal Operating Condition

Figure 4 illustrates the supply and load voltages of the distribution system under normal operating conditions without any fault, while Figure 5 presents the corresponding supply and load currents. The total harmonic distortion (THD) of the balanced and undistorted supply voltage is shown in Figure 6. Power quality disturbances—including voltage sag, voltage swell, and harmonic distortion—are introduced into the system as fault conditions, and the unified power quality conditioner (UPQC) is employed to mitigate their effects. Simulation results obtained under these scenarios are used to perform a detailed analysis of system performance, enabling evaluation of system behavior under various operating conditions such as harmonic distortion, voltage sag, and voltage swell.

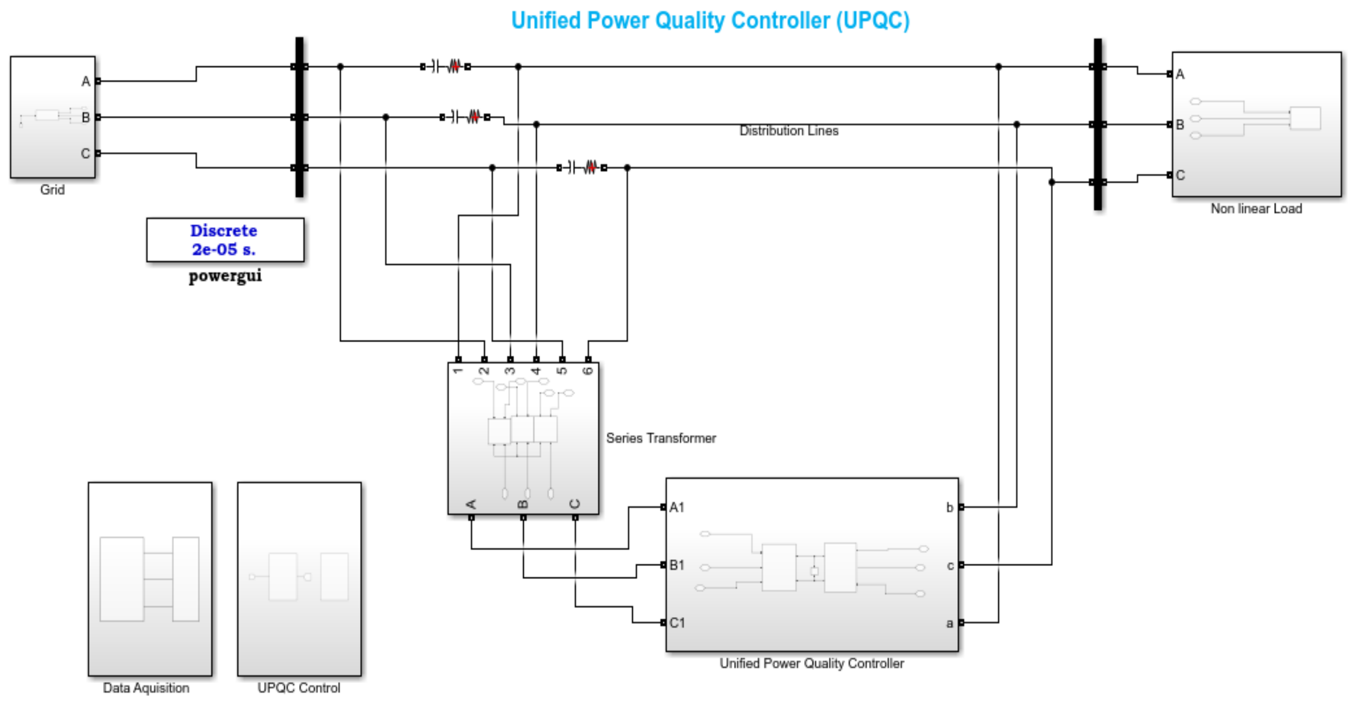

Fig. 3: Simulink model of the entire system with UPQC

Table 1: Simulation Parameter

Parameters	Value
Resistance	1Ω
Coupling Capacitance	100e-6 F
Coupling Inductor	10e-3 H
Source Voltage Amplitude	400 V_{rms}Ph-Ph
Phase angle	0°
Frequency	50 Hz
Proportional gain (K_p)	10
Integral gain (K_i)	0.1
PI Sample time	5e-6 sec
Diode resistance	0.001 Ω
Diode inductance	0 H
Diode forward voltage	0.8 Volt
Diode snubber resistance	500 Ω
Diode snubber capacitance	250e-9 F
IGBT/Diode Internal resistance	1e-3 Ω
IGBT/Diode snubber resistance	1e5 Ω
IGBT/ Diode snubber capacitance	Inf
Load resistance	60 Ω
Load inductance	0.15e-3 H

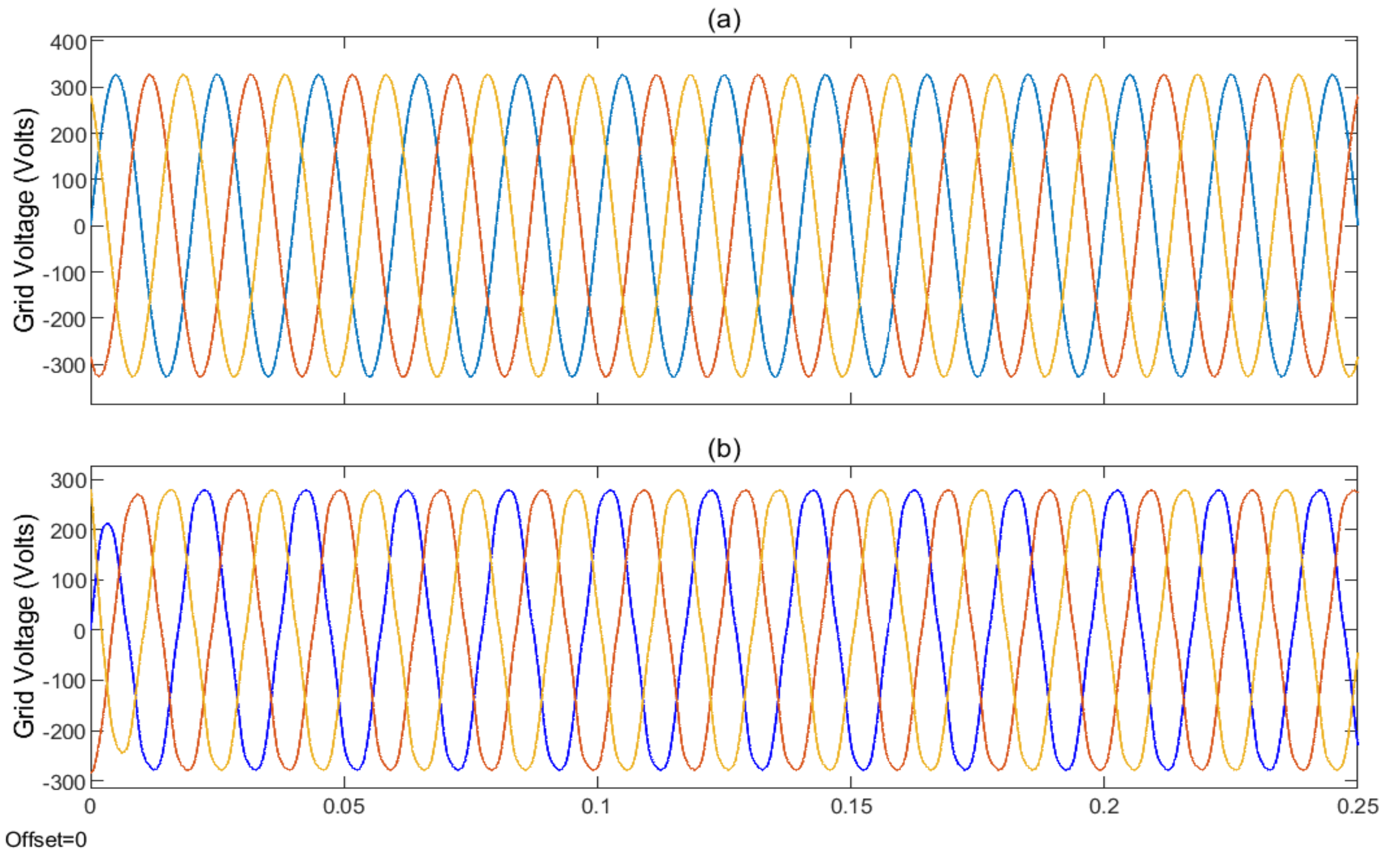

Fig. 4: (a) Input voltage from the distribution system, (b) load voltage

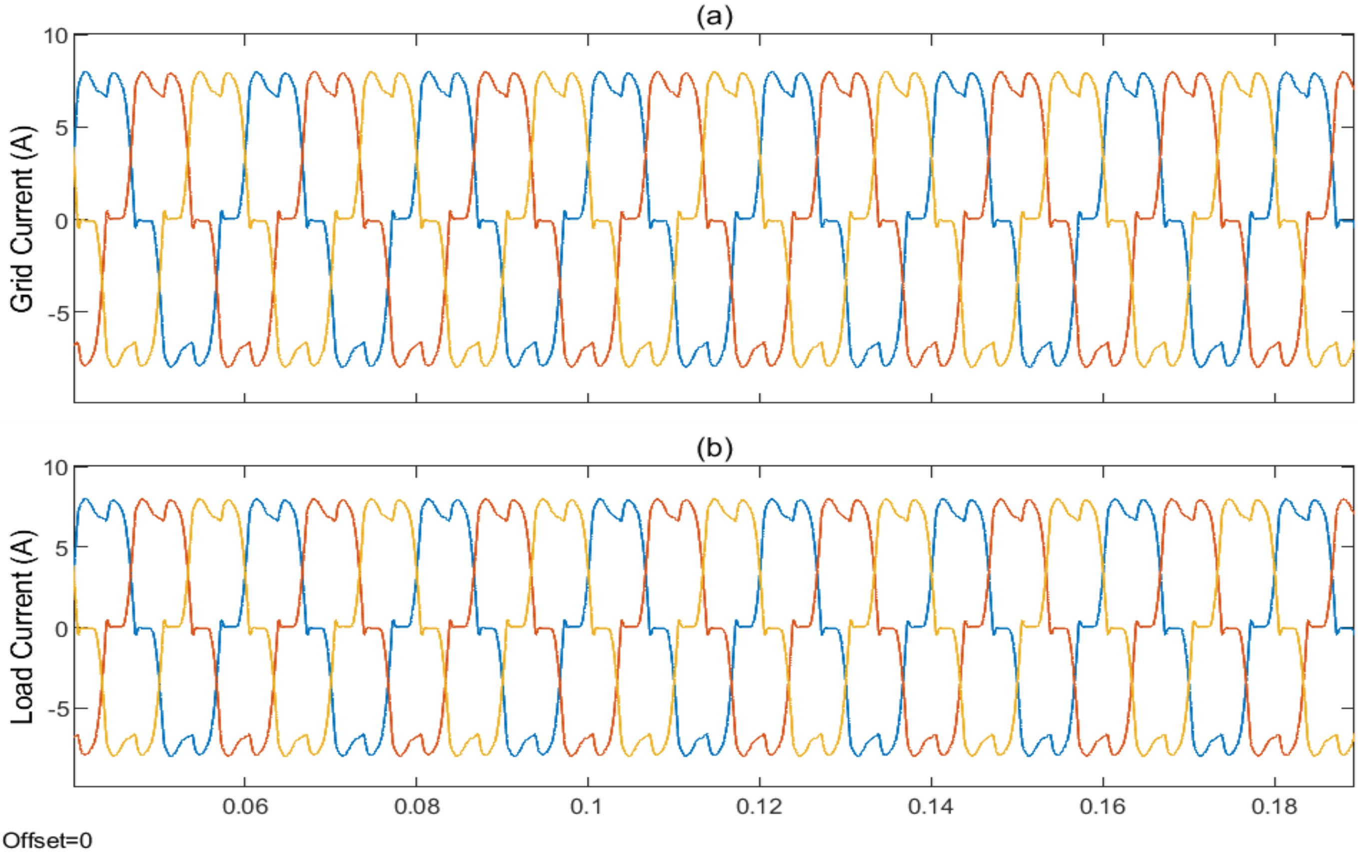

Fig. 5: (a) Input current from the distribution system, (b) load current

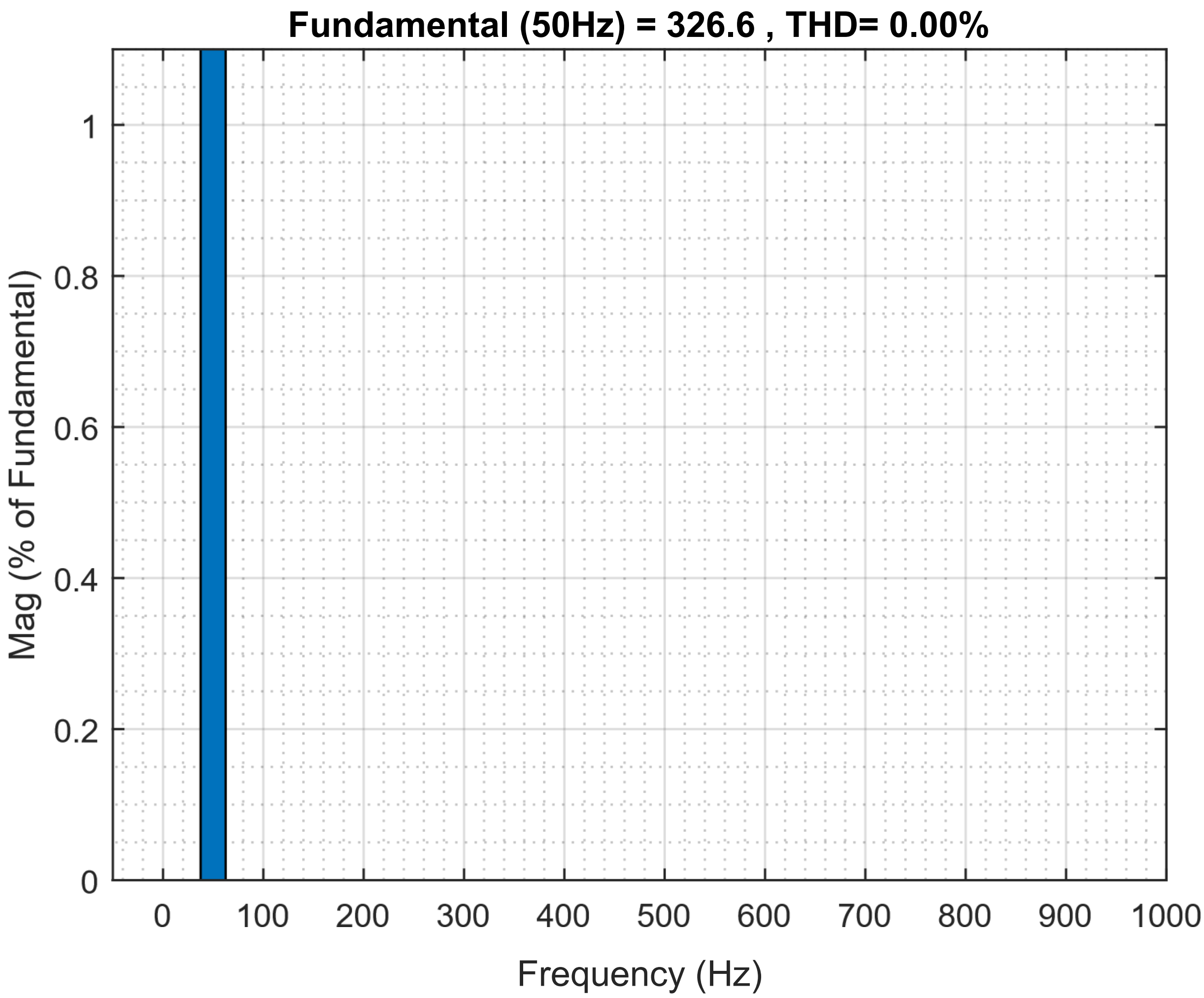

Fig. 6: THD of the balanced and undistorted source voltage.

3.2 Harmonic Compensation

To demonstrate the harmonic compensation capability of the proposed system, 5th and 7th order harmonics with an amplitude of 0.2 p.u. and 0.05p.u., respectively are injected into the system within time t=0.3sec and t=0.4sec.

(a) Voltage Harmonic Compensation

Voltage harmonic compensation is implemented using the Series-APF. Once voltage harmonics are detected by the series APF, it instantly begins compensating for the harmonics by injecting voltage of equal magnitude but opposite phase to the harmonics, thereby eliminating load voltage distortion. The distorted source voltage before UPQC compensation is shown in Fig. 7 (a) while Fig. 7 (b) shows the compensated load voltage waveform that is unaffected by the harmonic. Fig. 7 (c) shows the injected voltage while Fig. 8 shows the THD of the distorted source voltage. As shown in Fig. (9), the load voltage THD improves from 20.62% to 0.74%. This validates the effectiveness of UPQC in load voltage THD reduction.

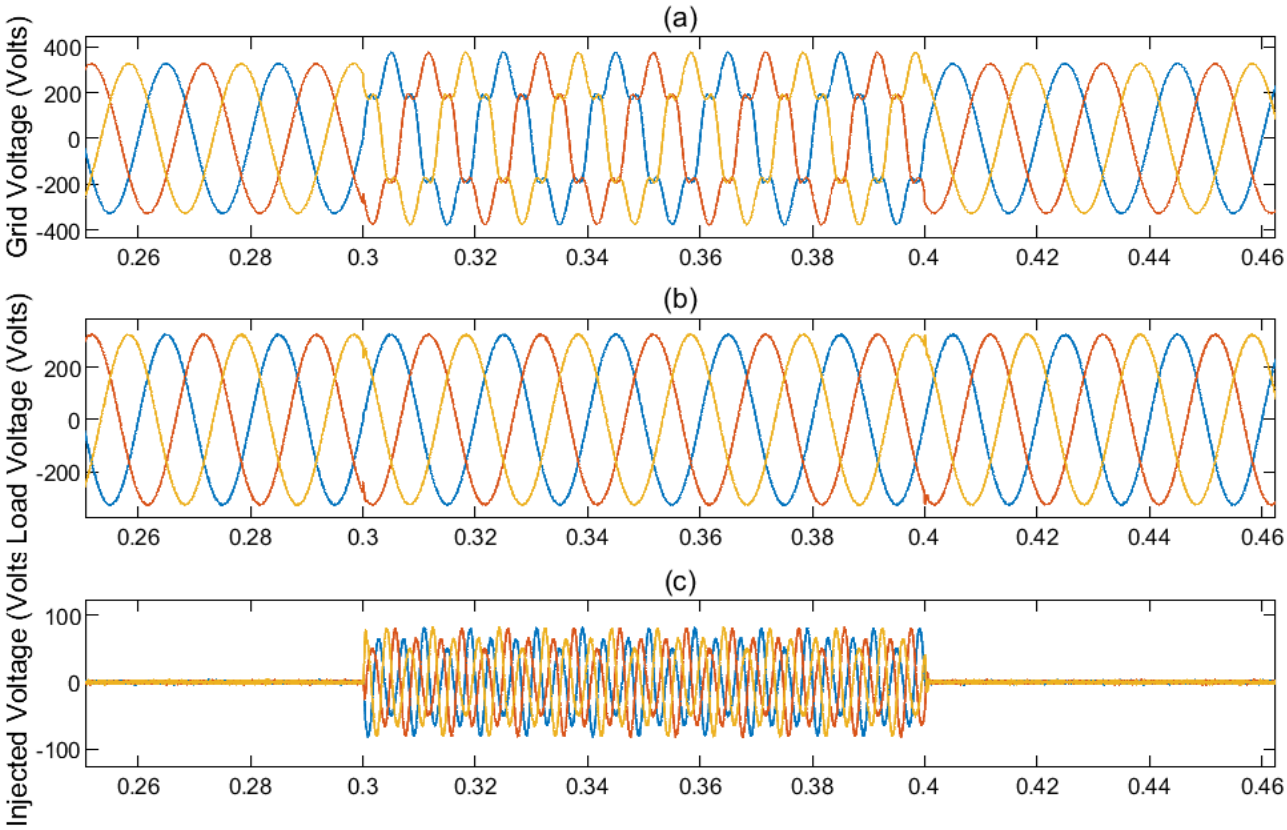

Fig. 7: System response to Voltage harmonic compensation: (a) Distorted source voltage (b) Load voltage and (c) Injected voltage.

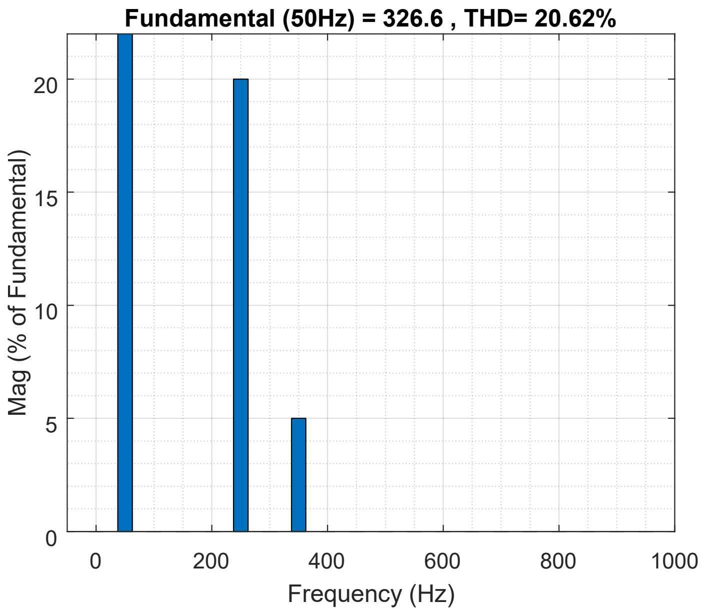

Fig. 8: (a) THD of the unbalanced and distorted source voltage.

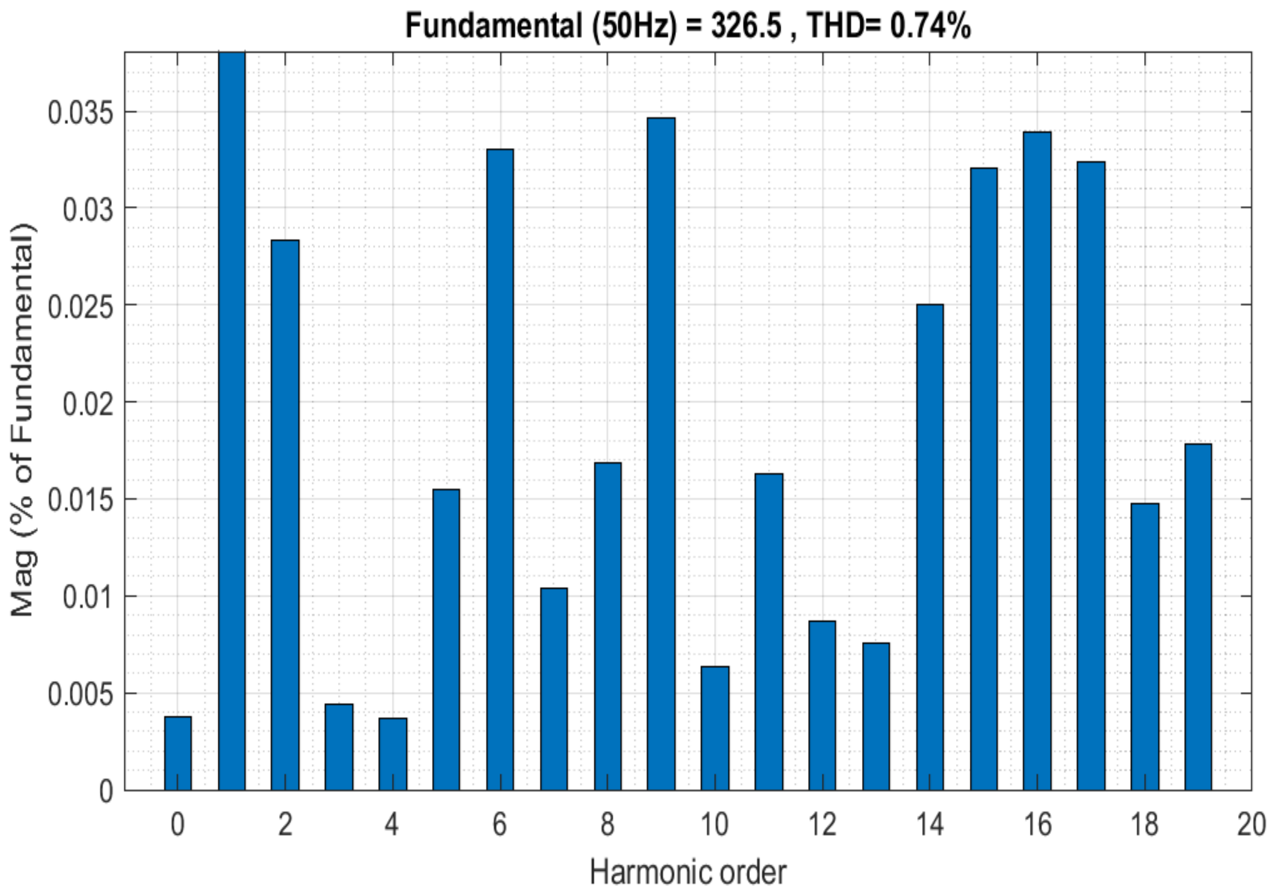

Fig. 9: Load voltage THD after compensation.

(b) Current Harmonic Compensation

During current harmonic compensation, the shunt and series active power filters (APFs) are engaged sequentially, with the shunt APF activated prior to the series unit. Once the DC-link voltage is regulated to its reference value, as illustrated in Fig. 10, the shunt APF begins simultaneous suppression of harmonic components and reactive current generated by the nonlinear load. The distorted source current before compensation and the corrected load current after compensation are presented in Fig. 11(a) and Fig. 11(b), respectively. Following UPQC integration, the load current waveform becomes nearly sinusoidal and aligns in phase with the utility voltage due to the action of the shunt APF, as shown in Fig. 11(b). The compensating current supplied by the shunt APF consists of both harmonic and reactive current components. Prior to UPQC operation, the source current is highly distorted, as depicted in Fig. 12, exhibiting a total harmonic distortion (THD) of 22.95%, while the load current THD reaches 32.41% under nonlinear loading conditions (Fig. 13). After compensation, the load current THD is substantially reduced from 32.41% to 4.63%, as shown in Fig. 14, thereby confirming the effectiveness of the UPQC in mitigating current harmonics.

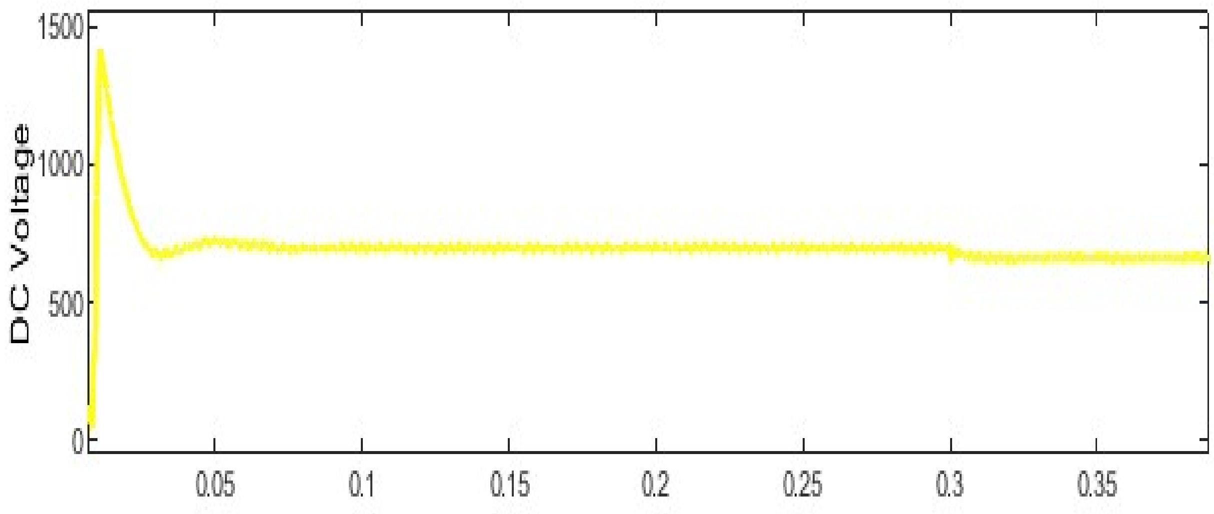

Fig. 10: DC link voltage

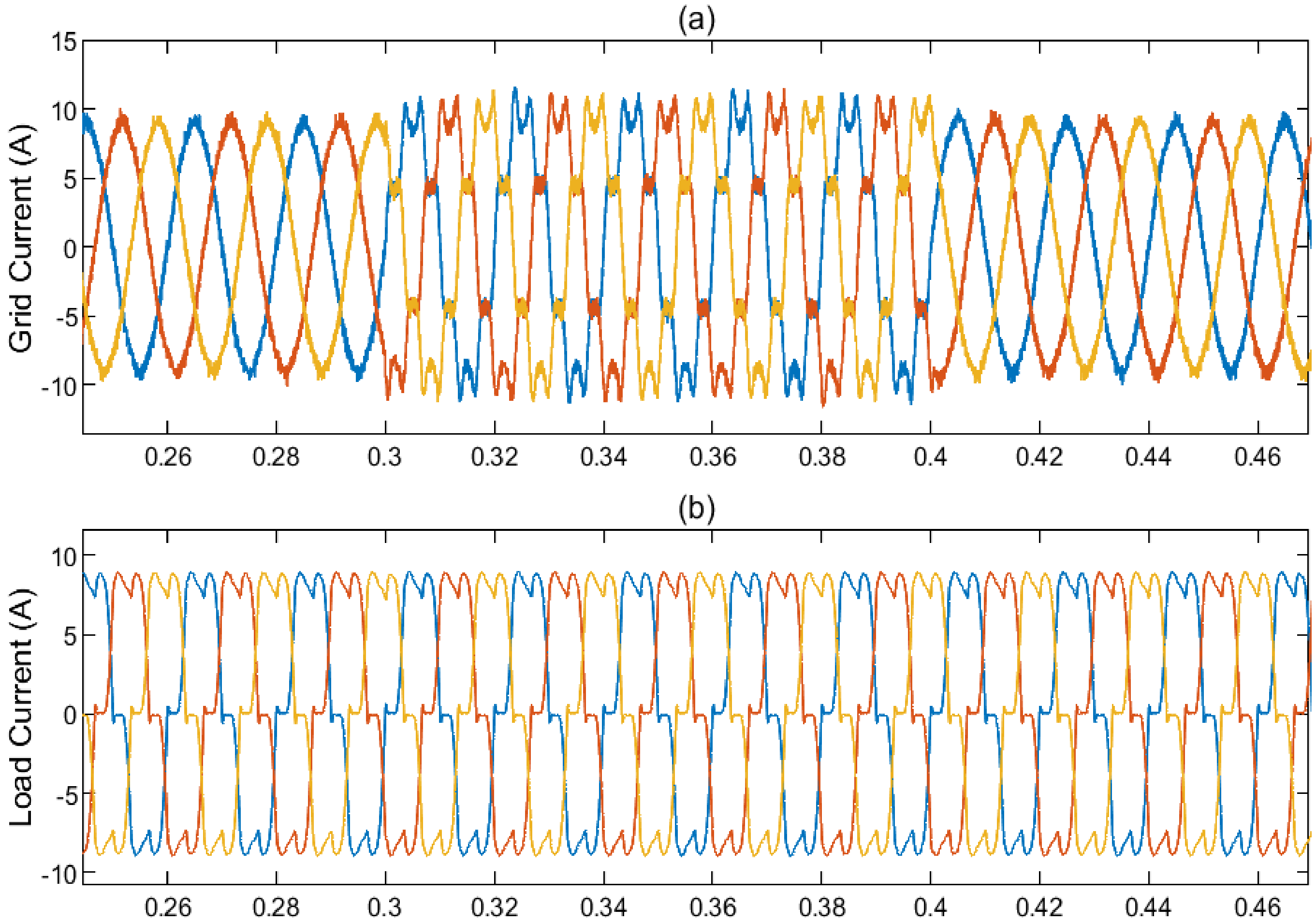

Fig. 11: System response to current harmonic compensation: (a) Source current (b) Load current.

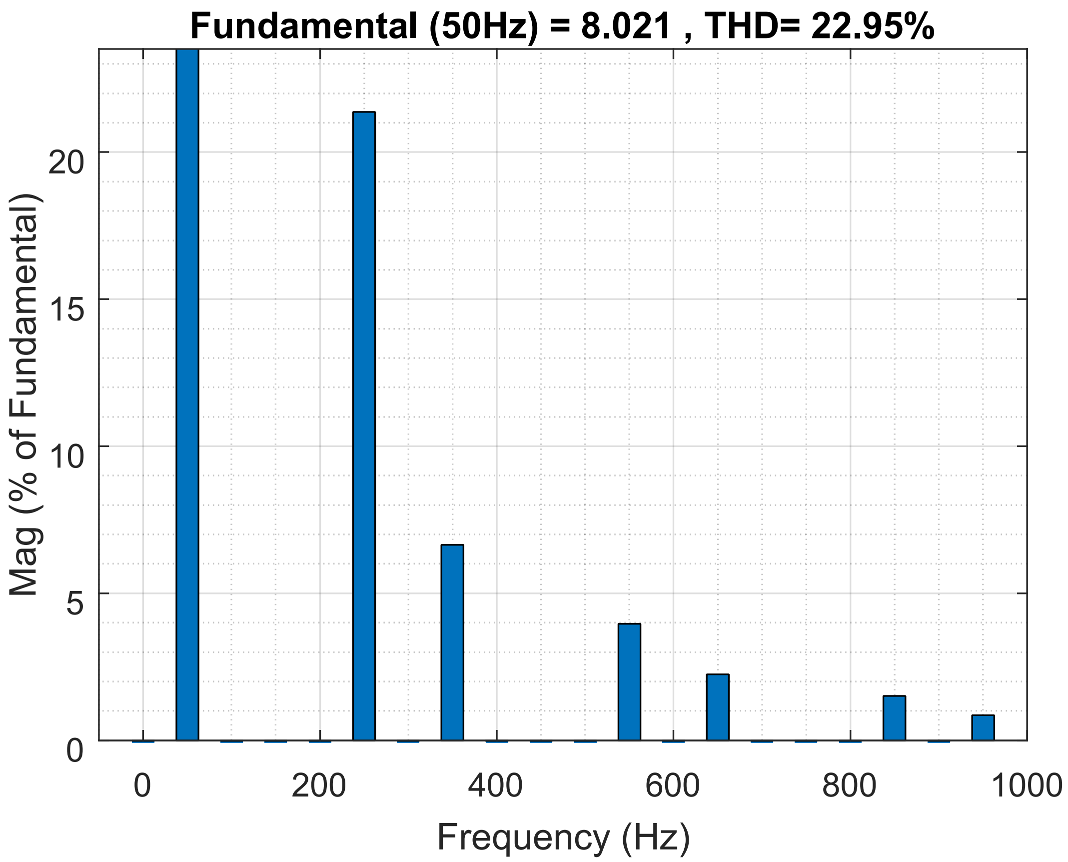

Fig. 12: (a) THD of the load current prior to the 5th and 7th order harmonics injection.

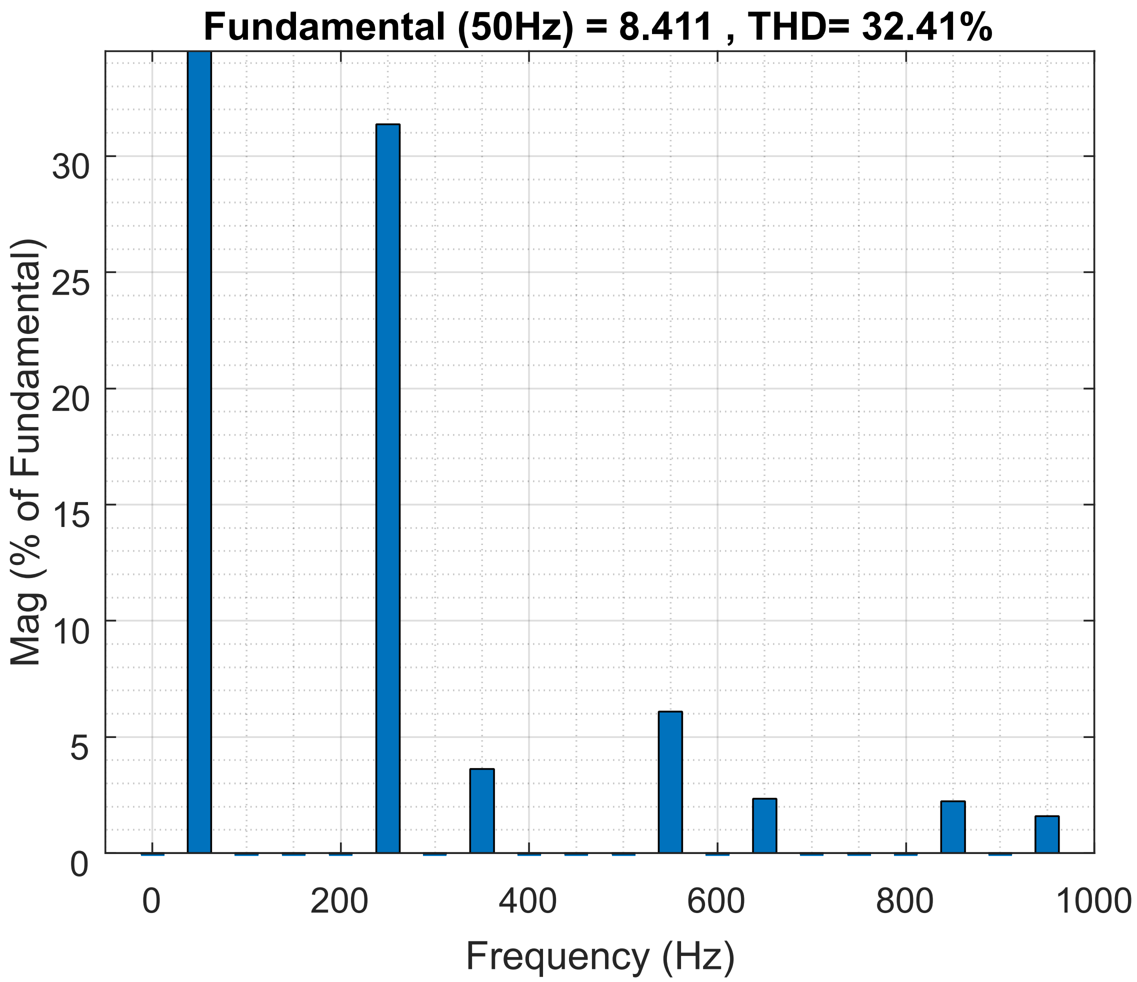

Fig. 13: (b) THD of the load current after the 5th and 7th order harmonics injection.

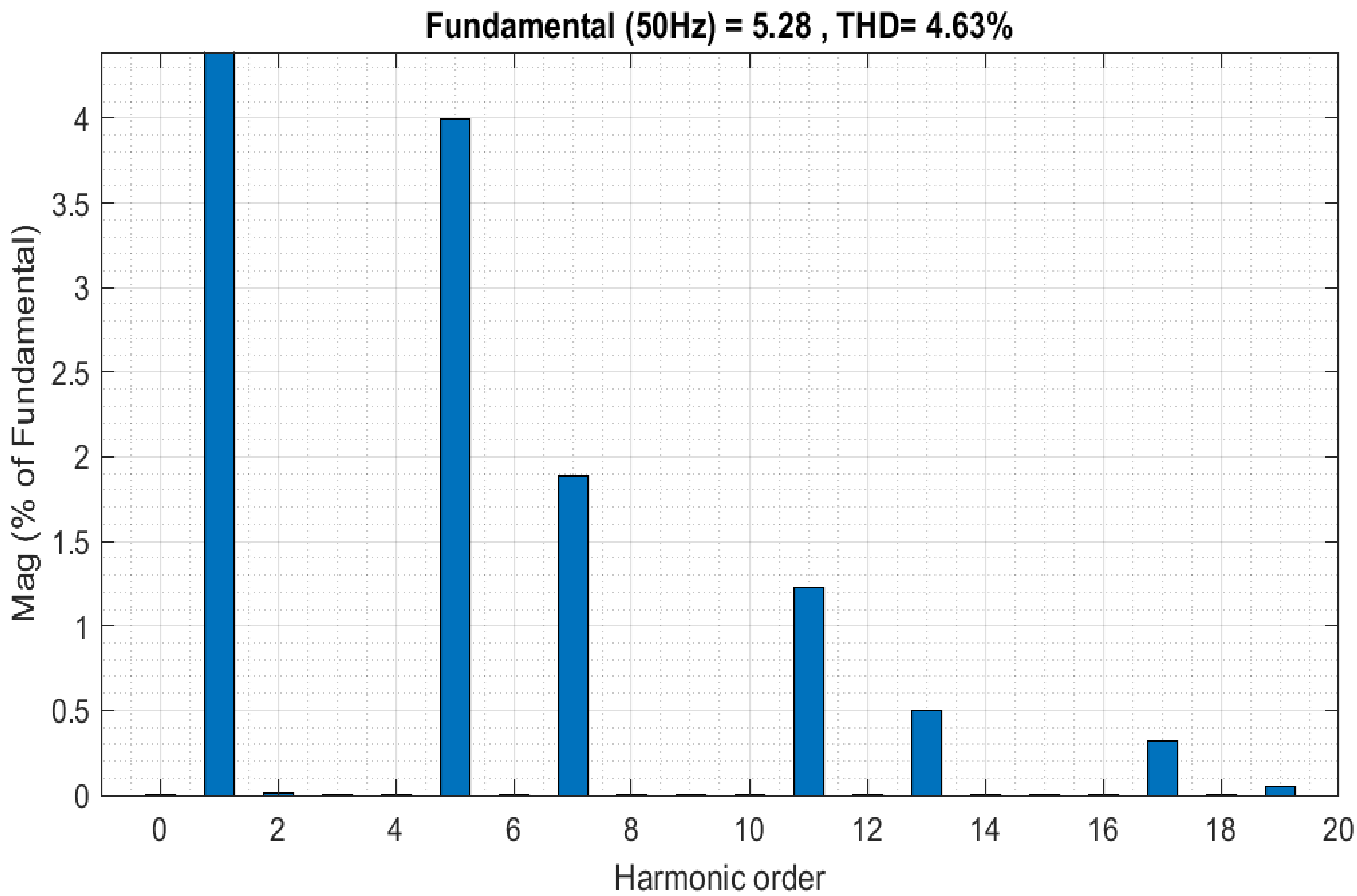

Fig. 14: Load current THD after compensation.

3.3 Voltage sag compensation

A voltage sag of 0.7 per unit (p.u.) is imposed on the system at $t = 0.9$s and remains until $t = 1.0$s, after which normal operating conditions resume. During this disturbance, as depicted in Fig. 15(a), the series active power filter (Series-APF) counteracts the voltage reduction by injecting an in-phase compensating voltage of 0.3 p.u., which represents the mismatch between the reference load voltage and the supply voltage, as illustrated in Fig. 15(c). The regulated load voltage waveform shown in Fig. 15(b) verifies that the unified power quality conditioner (UPQC) successfully maintains the load voltage at its prescribed constant magnitude throughout the sag period. While the Series-APF delivers the necessary real power to sustain the load during the disturbance, the shunt active power filter (Shunt-APF) ensures stability of the DC-link voltage, thereby facilitating uninterrupted power exchange between the filters. The load current response presented in Fig. 16 indicates that the sag condition does not adversely influence load operation. Additionally, the injected compensating voltage produced by the Series-APF and the corresponding DC-link voltage profiles are illustrated in Figs. 17(a) and 17(b), respectively, further confirming the effective performance of the UPQC during voltage sag conditions.

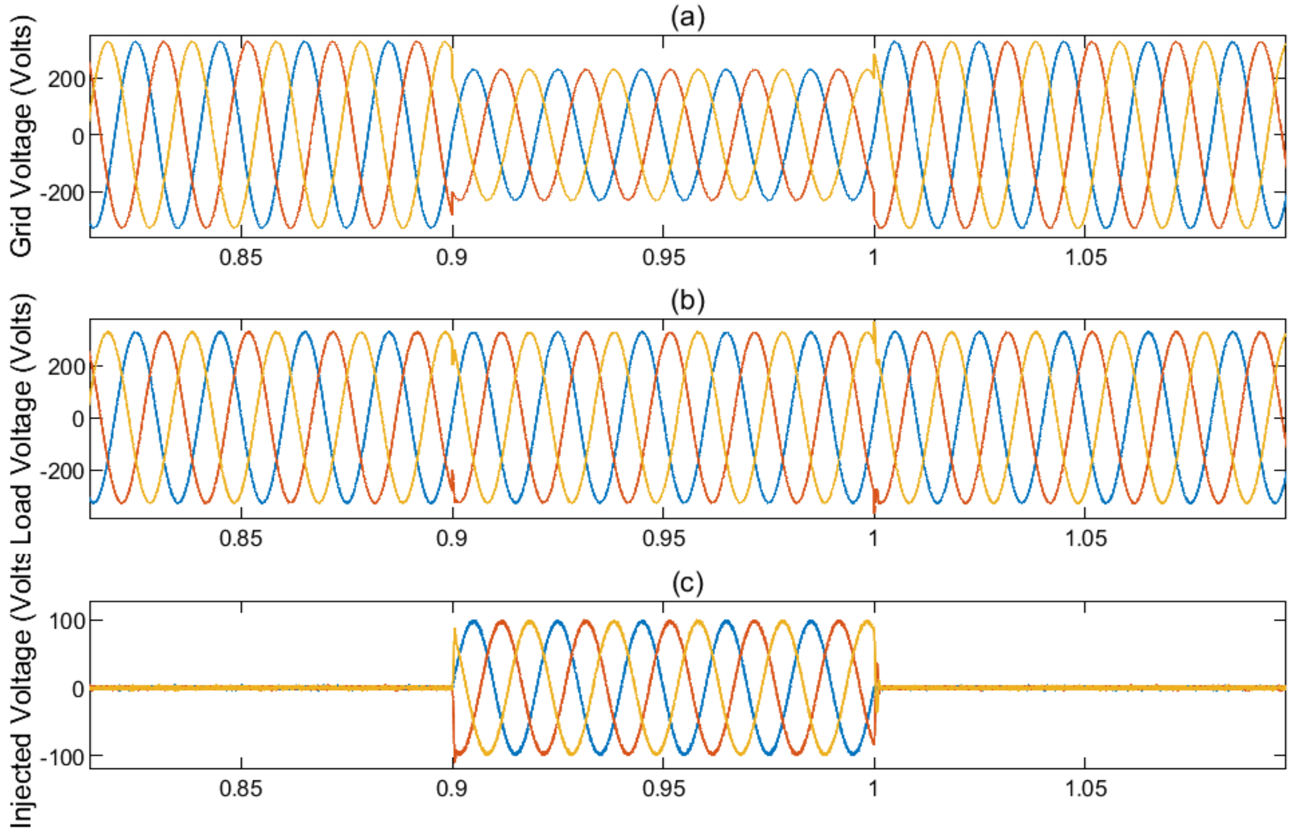

Fig. 15: System response to voltage sag compensation: (a) Source voltage (b) Load voltage and (c) Injected voltage

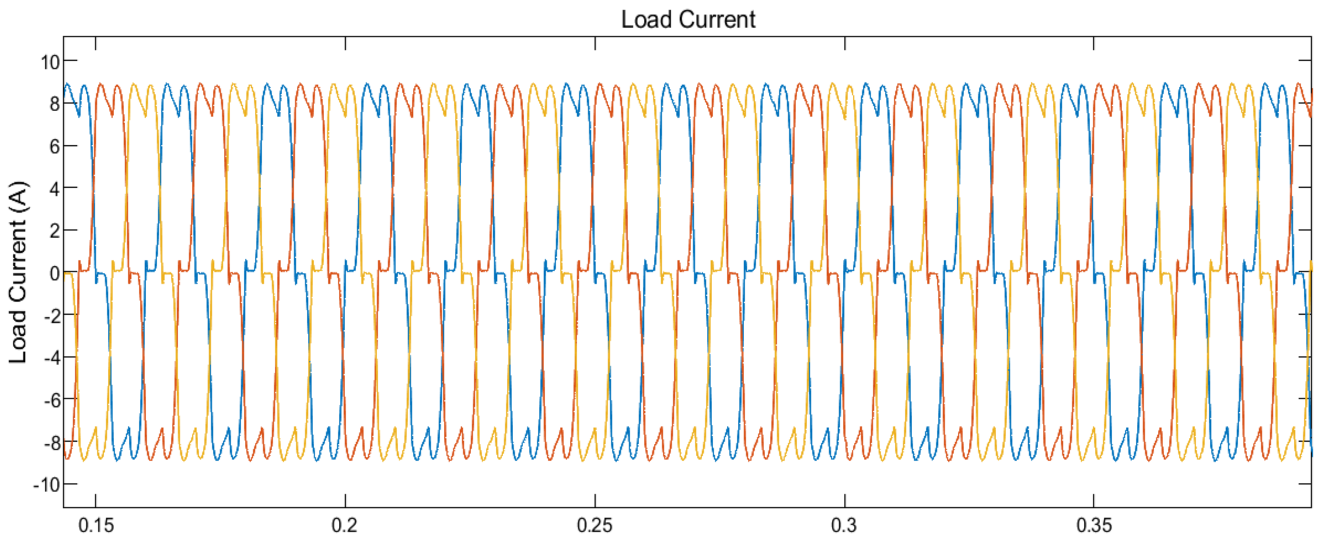

Fig. 16: Load current profile after voltage sag compensation

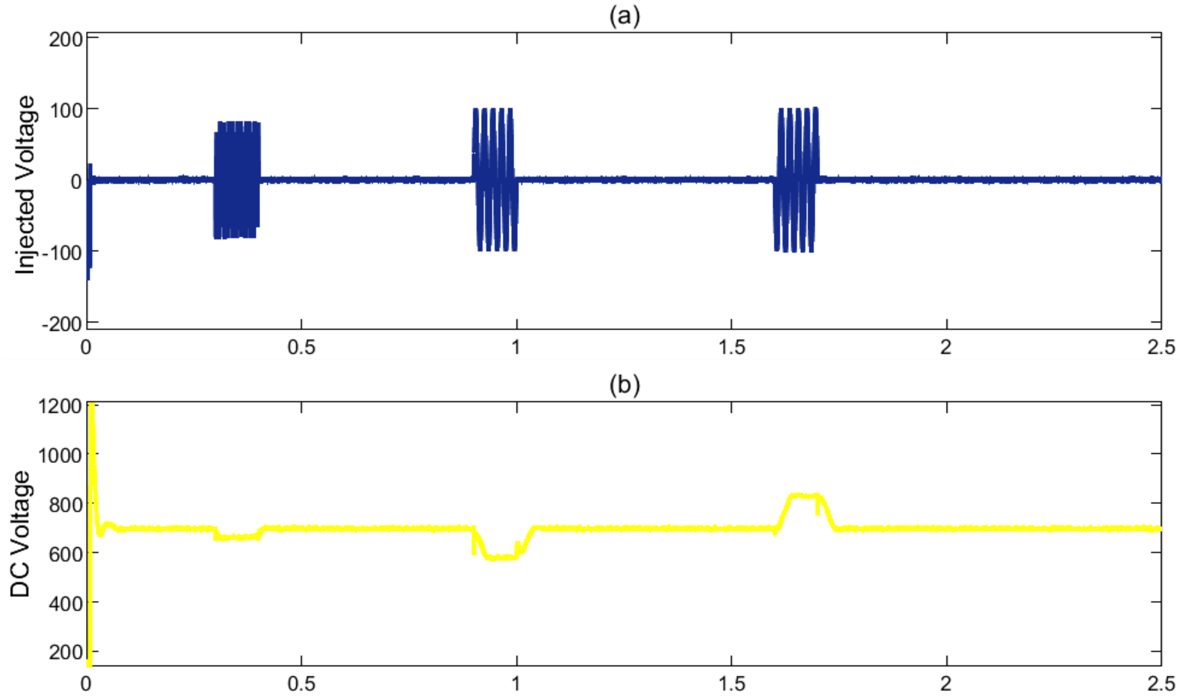

Fig. 17: (a) Injected voltage by series APF, (b) DC voltage

3.4 Voltage swell compensation

A voltage swell of 1.3 per unit (p.u.) is introduced into the system at $t = 1.6$s and persists until $t = 1.7$s, as shown in Fig. 18(a), after which normal operating conditions are restored. When the voltage swell occurs, the series active power filter (Series-APF) counteracts the excess supply voltage by introducing a compensating voltage that is phase-opposed to the source voltage through the series coupling transformers. This injected voltage corresponds to the deviation between the desired reference load voltage and the actual source voltage, as shown in Fig. 18(c). After compensation, the load-side voltage waveform regains a smooth sinusoidal shape, as illustrated in Fig. 18(b), confirming that the unified power quality conditioner (UPQC) successfully regulates the load bus voltage at its specified constant value. Under this condition, the UPQC control strategy ensures that the source supplies a reduced current, while the excess power associated with the voltage swell is returned to the source by lowering the fundamental component of the source current. Figure 19 further confirms that the load current remains unaffected by the voltage swell when the UPQC is employed in the system.

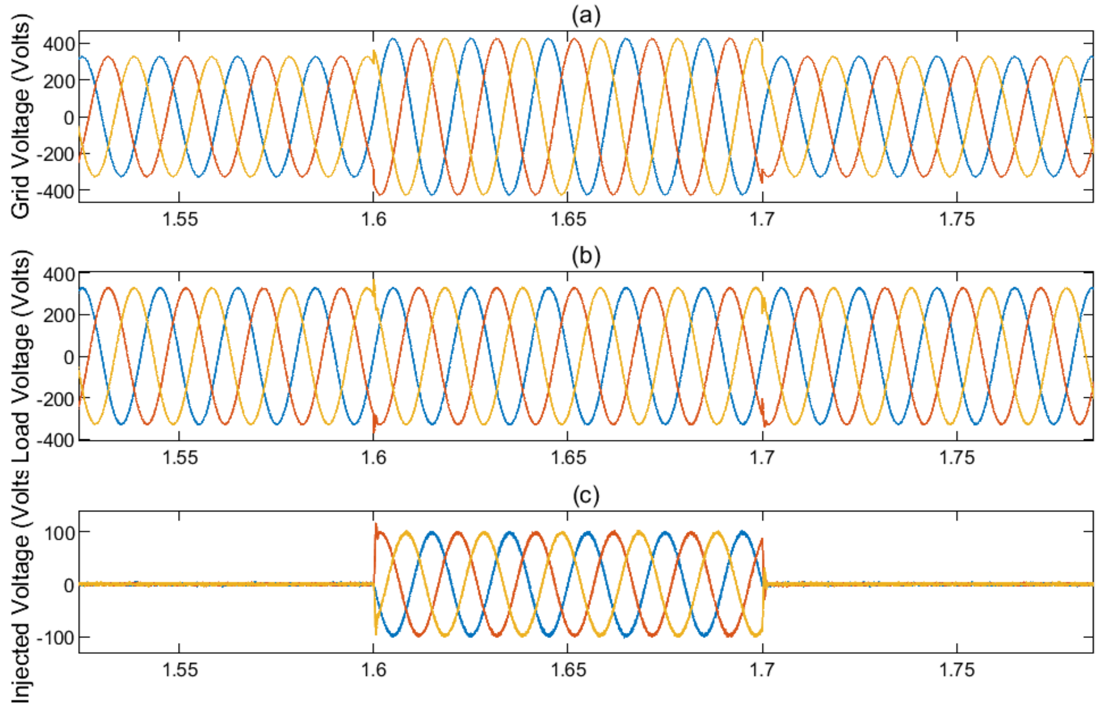

Fig. 18: System responses to voltage swell compensation: (a) Source voltage (b) Load voltage and (c) Injected voltage

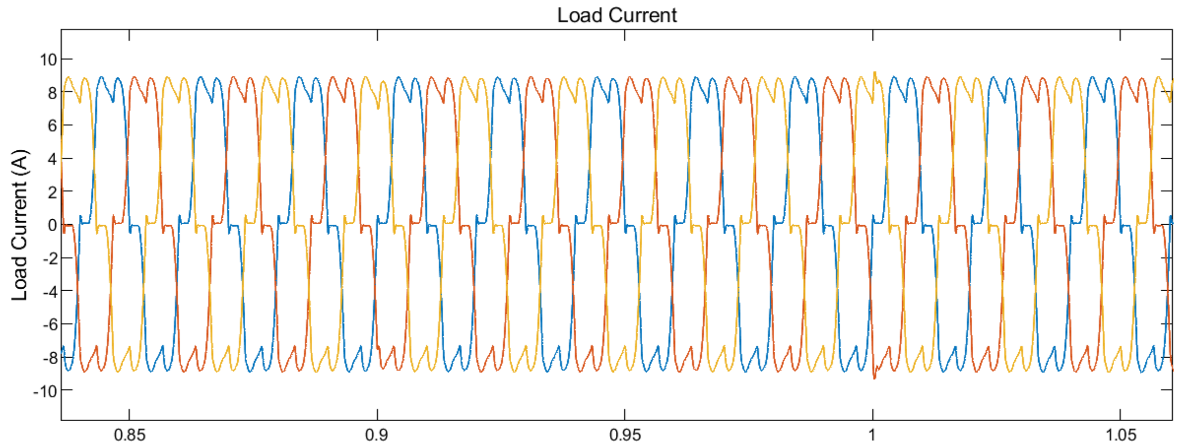

Fig. 19: Load current profile after voltage swell compensation

4. Conclusion

This work presents a power-quality enhancement framework based on a unified power quality conditioner (UPQC) for application in distribution networks. The proposed scheme employs a synchronously rotating reference frame control approach for the series active power filter and an instantaneous power–based control method for the shunt active power filter. A three-phase distribution network supplying both sensitive and nonlinear loads was developed and analyzed through simulation using MATLAB/Simulink R2023a. The effectiveness of the control scheme was examined under multiple disturbance scenarios, including voltage magnitude variations and harmonic distortions affecting both voltage and current waveforms. Simulation outcomes indicate that the UPQC successfully mitigates these disturbances by stabilizing the load voltage and substantially suppressing harmonic content during abnormal operating conditions. The results therefore validate the capability of the proposed control framework to enhance power quality and operational reliability in distribution systems.

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