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Control of a Single-Phase Unified Power Conditionner for Power Quality Enhancement : Experimental Validation

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***Abstract*—**This paper presents the experimental validation of a single-phase Unified Power Quality Conditioner (UPQC) designed to mitigate common power quality issues in low-voltage distribution networks. The system integrates series and shunt active filters to simultaneously compensate for voltage disturbances, suppress harmonic currents, and provide reactive power compensation. A detailed system model is developed to support the control design, enabling effective performance in both transient and steady-state conditions. The implemented control method prioritizes robustness against grid perturbations and nonlinear load variations. Experimental tests, conducted on a hardware prototype under various load and grid conditions, confirm the UPQC's capability to restore voltage profiles, significantly reduce total harmonic distortion (THD), and maintain stable reactive power compensation. The results validate the practical feasibility and efficiency of the proposed single-phase UPQC solution for enhancing power quality in single-phase distribution systems.

Keywords*— *UPQC; Power Quality; Voltage Sag & Swell; Single-Phase Systems; Experimental Validation; Active Power Filters; Nonlinear Loads.

I. INTRODUCTION

The growing use of nonlinear loads and delicate electrical devices in contemporary power systems has intensified issues related to power quality, including voltage dips, surges, harmonic distortions, and flickering voltages. Voltage dips, characterized by brief reductions in voltage amplitude typically ranging from 10% to 90% of the nominal level and lasting from a few milliseconds up to several cycles, can cause malfunctions or shutdowns in sensitive equipment. These events can interrupt industrial operations by causing motor stalls or triggering protection mechanisms, resulting in significant production losses. Moreover, frequent occurrence of voltage dips accelerates the degradation of electrical machinery, reduces equipment lifespan, and undermines the overall reliability and stability of the power system, highlighting the critical need for effective mitigation strategies[1], [2].

Voltage swells refer to brief rises in voltage levels exceeding the nominal value, usually persisting for several electrical cycles. Though less frequent than sags, they can be more harmful, causing insulation breakdown, component overheating, and premature aging of electronics. In industrial settings, swells may trigger equipment malfunctions, signal distortions, and operational interruptions, posing serious risks to network stability and potentially leading to costly downtime [3].

Nonlinear loads draw non-sinusoidal currents that generate harmonics, distorting voltage waveforms and degrading power quality. Harmonic distortions contribute to increased losses and excessive heating in transformers, motors, and cables, which can lead to premature aging of equipment, disrupt sensitive electronic devices, and degrade the overall efficiency of the power system. In three-phase systems, these harmonics may also cause neutral conductor overloading and provoke resonance phenomena, further compromising system stability. Implementing effective solutions such as harmonic filters and active power quality conditioners like the UPQC is crucial for maintaining dependable and efficient performance in electrical networks subjected to nonlinear loads[4].

These disturbances degrade the reliability and operational efficiency of electrical networks, causing equipment malfunctions and economic losses. To mitigate these power quality issues, the UPQC has emerged as an effective compensating device, integrating series and shunt active power filters to simultaneously address voltage and current-related disturbances[5]. Particularly, the single-phase UPQC configuration is widely employed in distribution networks supplying residential and small commercial loads due to its simplicity and effectiveness. The UPQC's series active filter compensates for voltage disturbances including sags, swells, and unbalance, while the shunt active filter mitigates current harmonics and performs reactive power compensation, thereby improving the overall power factor and reducing transmission losses[6]. Recent advances have focused on improving UPQC control strategies to enhance dynamic performance, robustness against nonlinearities, and minimize control challenges such as chattering. Moreover, experimental validations have become essential for demonstrating real-world feasibility and guiding practical implementation of UPQC systems[7].Despite significant progress in simulation tests, challenges related to precise analysis, system modeling, and hardware implementation remain active research areas, as cited in many references [8], [9].

This paper's primary contribution lies in the experimental validation of a single-phase UPQC system. A detailed system model is first developed to support the control design, after which appropriate methods are implemented to enhance both transient and steady-state compensation. The proposed approach is validated using a hardware prototype, with results confirming the UPQC's effectiveness in mitigating voltage disturbances, suppressing harmonic currents, and compensating reactive power under various load and grid conditions.The paper is organized as follows: Section 2 provides the detailed explanation of the single-phase UPQC system. Section 3 describes the control of the system. Section 4 presents the experimental setup and validation methodology, and discusses also the obtained results and performance analysis. Finally, Section 5 concludes the paper and outlines future research directions.

II. SYSTEM UNDER STUDY

The single-phase UPQC analyzed in this study comprises two primary components: a series inverter and a shunt inverter, both designed to address power quality challenges in distribution networks with nonlinear loads. The series inverter, connected through an injecting transformer, actively corrects voltage abnormalities such as sags, swells, and harmonic distortions by injecting a compensating voltage in series with the supply. Meanwhile, the shunt inverter operates in parallel with the load, injecting currents to mitigate harmonics, regulate reactive power, and maintain the grid current as a sinusoidal waveform aligned in phase with the supply voltage. These two inverters are linked by a common DC-link capacitor, enabling coordinated energy transfer between them. This combined arrangement allows the UPQC to effectively enhance power quality by stabilizing the voltage at the load, reducing total harmonic distortion (THD), and managing reactive power, thereby improving the overall reliability and efficiency of the electrical system under various nonlinear load and grid perturbation scenarios. The configuration of the single-phase UPQC system is depicted in Figure (1).

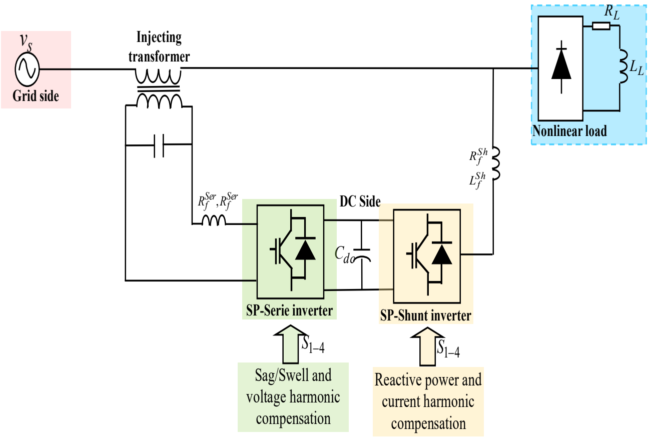


Fig.1. Single-line circuit diagram representation of UPQC

III. CONTROL OF UPQC SYSTEM

The control system of the UPQC is divided into two primary sections: the series active power filter (APF) control and the shunt APF control. Harmonic currents and voltages targeted for cancellation can be considered as reactive power components. The UPQC control strategy must full fill several key objectives: 1) accurately generate reference current signals for the shunt inverter, 2) precisely produce reference voltage signals for the series inverter, 3) maintain the DC-link voltage at a stable setpoint, and 4) properly create switching pulses for both inverter units. This section discusses these aspects of control aimed at mitigating power quality issues in the distribution network.

A. *Shunt APF control strategy*

The shunt APF within the UPQC is responsible for injecting compensating currents and supplying the current necessary to regulate the DC-link voltage, as shown in Figure (2). To create the reference signals for these compensating currents, a dq frame extraction technique is applied. This approach involves converting the two-phase load currents from the imaginary two-phase reference frame ($\alpha\beta$) into the synchronous dq reference frame through Park's transformation (Equation 1). The signals required for this conversion are derived by employing a single-phase PLL on the source voltage ($\omega t = \theta$)[10].

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \tilde{i}_{Ld} + \bar{i}_{Ld} \\ \tilde{i}_{Lq} + \bar{i}_{Lq} \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (1)$$

Where:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} i_L \\ i_L(\omega t - \pi/2) \end{bmatrix} \quad (2)$$

Park's transformation converts the fundamental in-phase components of AC signals into constant DC values, which can be easily isolated using low-pass filtering techniques. Ideally, the source current should deliver this fundamental component in phase with the voltage, forming the basis for generating reference source current signals that are free from power quality distortions. The current necessary to regulate the DC-link voltage is calculated through a proportional-integral (PI) controller and combined with the d-axis load current. This combined d-axis current is subsequently converted back into sinusoidal reference source currents, as described in (3)[10].

$$\begin{bmatrix} i_{L\alpha}^* \\ i_{L\beta}^* \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix}^{-1} \begin{bmatrix} i_{Ld}^* \\ i_{Lq}^* \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_{Ld}^* \\ i_{Lq}^* \end{bmatrix} = \begin{bmatrix} \bar{i}_{Ld} + i_{dc} \\ i_{lq} \end{bmatrix} \quad (4)$$

Where :

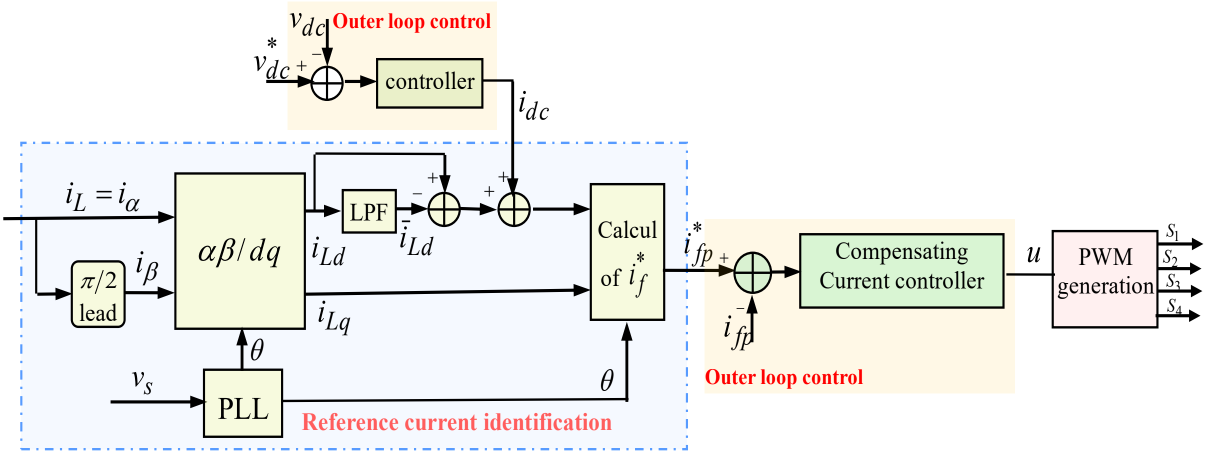


Fig.2. Structure of shunt part control circuit

B. *Series APF control strategy*

The primary role of the Series APF in a UPQC is to ensure that the load bus voltage maintains a pure sine waveform with the rated magnitude. This is particularly crucial for protecting sensitive loads, where two main conditions must be satisfied: 1) the voltage should be a perfect 50 Hz sinusoid, and 2) the load voltage magnitude must remain constant. A straightforward approach to achieve this is to generate a clean sinusoidal waveform at the load bus by designing the series converter to replicate this ideal voltage profile Connected in series with the load, the series APF monitors the load voltage for any power quality anomalies such as harmonics, sags, or swells. Once these disturbances are detected, a control algorithm processes the measured voltage and generates a reference voltage waveform that matches the load voltage frequency but with minimized distortion. The filter then injects this compensating voltage into the load circuit, with a phase and harmonic composition designed to counteract the voltage distortions effectively. Besides cancelling voltage harmonics, the series active filter also compensates for voltage sags and swells[11].

Figure (3) illustrates the control architecture of the series compensator. The fundamental component of the Point of Common Coupling (PCC) voltage is extracted using a phase-locked loop (PLL), which is utilized to generate the reference load voltage. This reference voltage can be mathematically represented as shown in equation (5).

$$v_L^* = V_{LM} \times \sin\omega t \quad (5)$$

Where : V_{LM} denotes the peak amplitude of load voltage.

The reference voltage to be injected by the series inverter is obtained by calculating the difference between the load reference voltage and the actual Point of PCC voltage. This voltage error is then fed into a PI controller, which outputs the desired reference current for the series APF i_{fs}^*. The reference current is compared with the measured series filter current, and the resulting error is processed by a current regulator to produce accurate reference signals. These signals drive a pulse-width modulation (PWM) voltage controller that generates the necessary gating signals to operate the series APF effectively[12].

The complete control scheme for the UPQC system is illustrated in Figure (4). The switching signals that govern the inverter operation for both the shunt and series components of the UPQC are generated based on the evaluated reference signals.

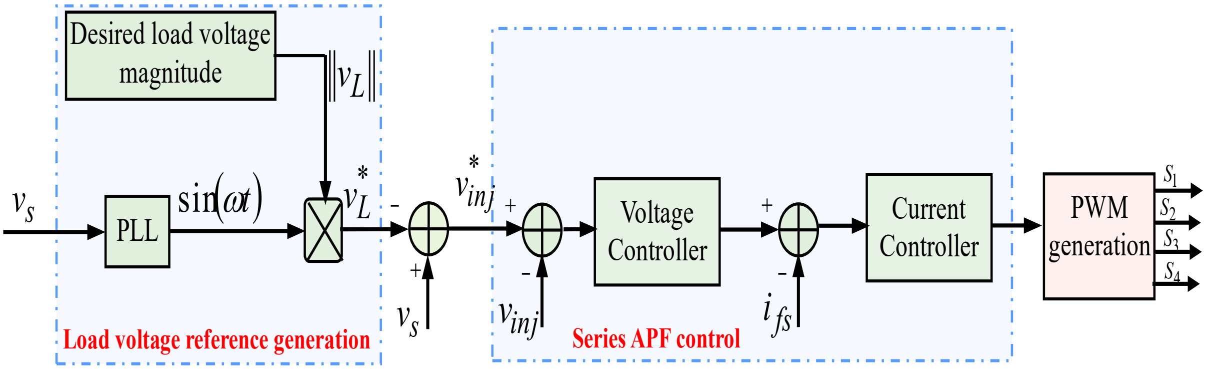


Fig.3. Structure of series part control circuit

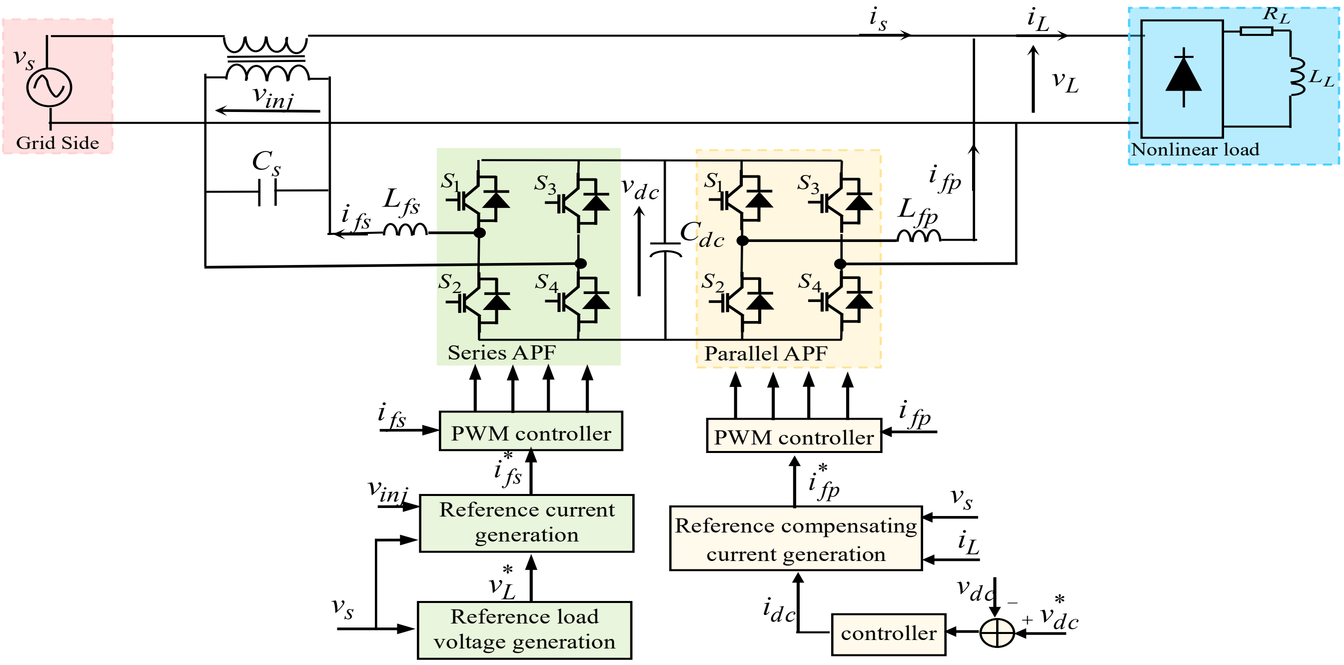


Fig.4. Overall Structure control of UPQC circuit

IV. RESULTS & DISCUSSION

This section details the experimental arrangement developed to validate the proposed control strategy for the single-phase UPQC. The test bench consists of a single-phase AC supply feeding a nonlinear load represented by a diode bridge rectifier with interchangeable R-L loads, generating voltage and current distortions. The UPQC prototype integrates series and shunt inverters sharing a common DC-link to simultaneously compensate voltage disturbances and current harmonics under steady-state and dynamic load variations. The control algorithm is executed in real time using MATLAB/Simulink with dSPACE Control Desk at a 20 kHz sampling frequency using dSPACE 1103, producing PWM pulses for both inverters in accordance with the UPQC's compensation requirements.

The experimental prototype is illustrated in Figure (5), where the main components of the prototype include:

- ✓ (1): DC sources.
- ✓ (2) & (3) inverter.
- ✓ (4): Diode bridge.
- ✓ (5): Power analyser.
- ✓ (6): Nonlinear RL load.
- ✓ (7): Voltage and current sensors.
- ✓ (8): gate drives.
- ✓ (9): Digital oscilloscope.
- ✓ (10):Drive cart with IGBT switch across the additive resistance.

Table.1 illustrates the system's parameters

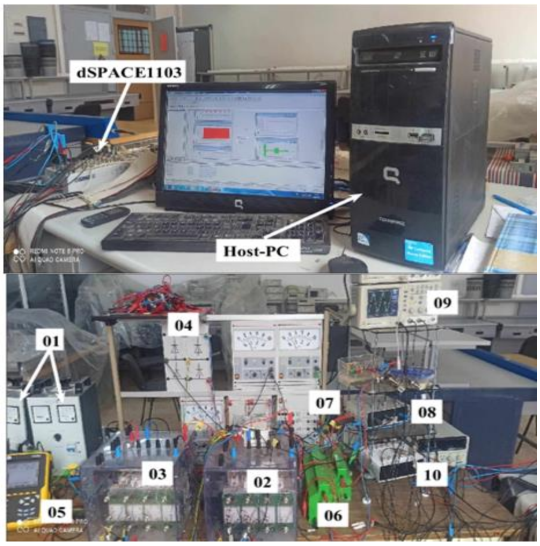
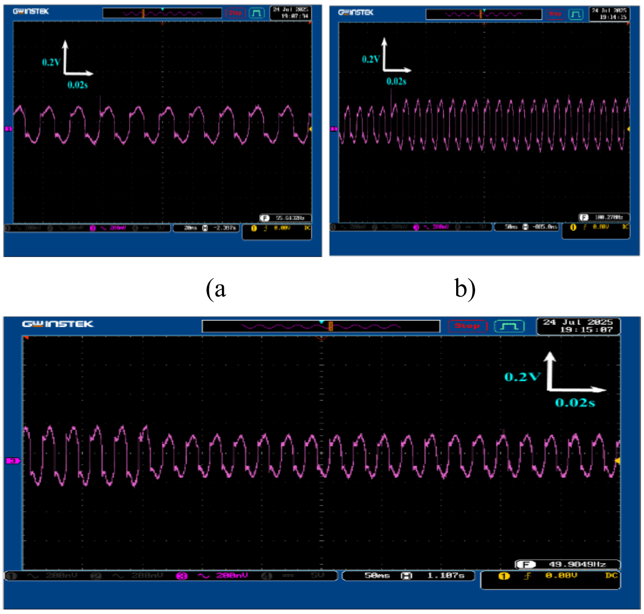


Fig.5. Experimental setup of Single-phase UPQC prototype.

TABLE.1 PARAMETER VALUES OF THE DESIGNED SINGLE PHASE UPQC PROTOTYPE

Parameter	Value
grid voltage v_s	v_s^{rms}=31.14V , f_s=50Hz
Main Load	R_L=100Ω , L_L=35mH
resistor and inductor of parallel APF	R_f=0.25Ω, L_f=9mH
resistor and inductor of series APF	R_f=0.1Ω, L_f=18mH
Series filter capacitor	C_s=70μF
DC voltage	V_{dc}=54.9V
Capacitance of DC-side	C_{dc}=2000μF
Sag/swell ratio	∓ 15%

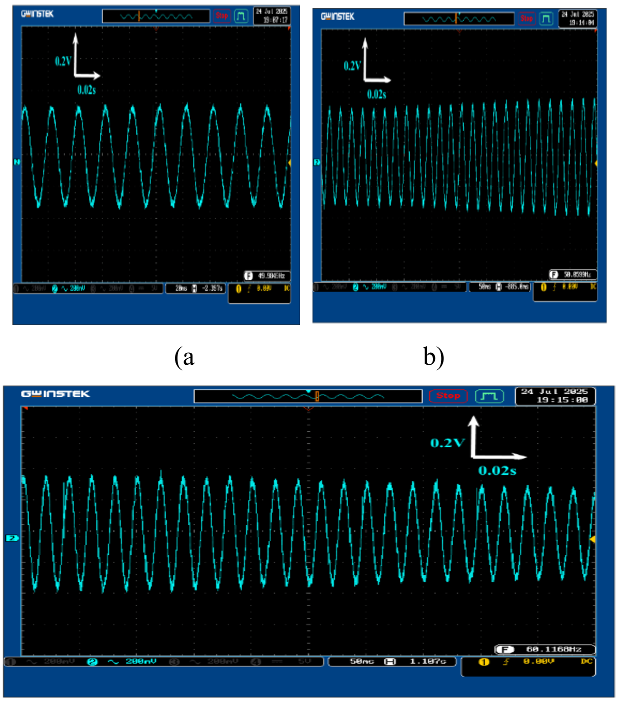
A. *Swell signario*



(a b)

c)

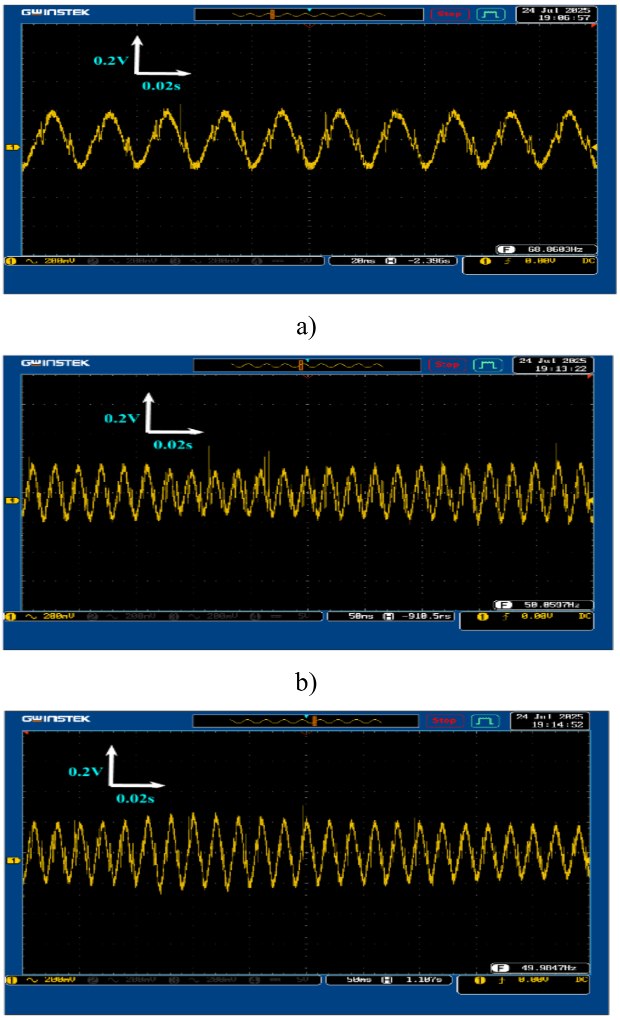
Fig.6: Load current waveform i_L: (a) i_L in steady-state conditions (b) i_L at load augment (c) i_L when load reduction



(a b)

c)

Fig.7. Grid current waveform i_{grid}: (a) i_{grid} in steady-state conditions (b) i_{grid} at load augment (c) i_{grid} when load reduction



a)

b)

c)

Fig.8. Waveform of the parallel filter current i_{fp}: (a) i_{fp} in steady-state conditions (b) i_{fp} at load augment (c) i_{fp} at load reduction.

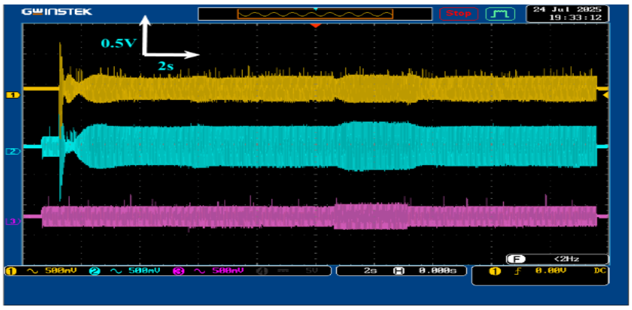


Fig. 9. Waveform of the grid, load and parallel filter currents during swell scenario test.

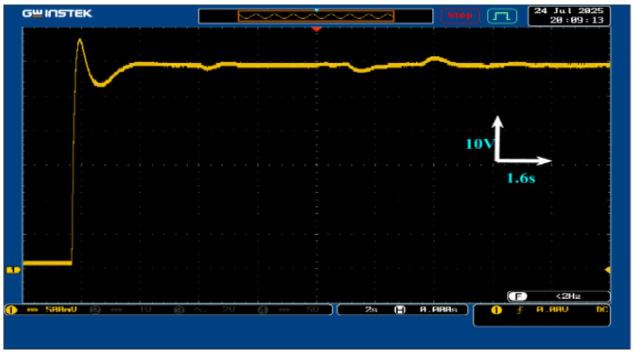
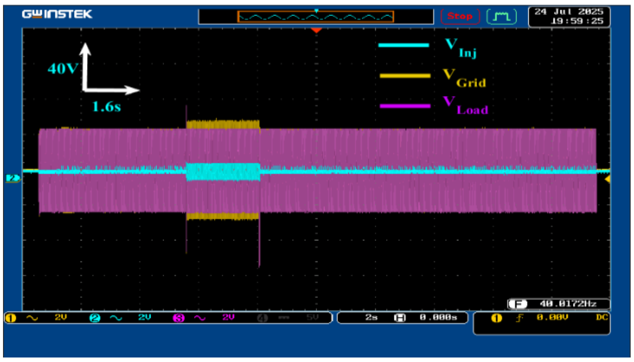
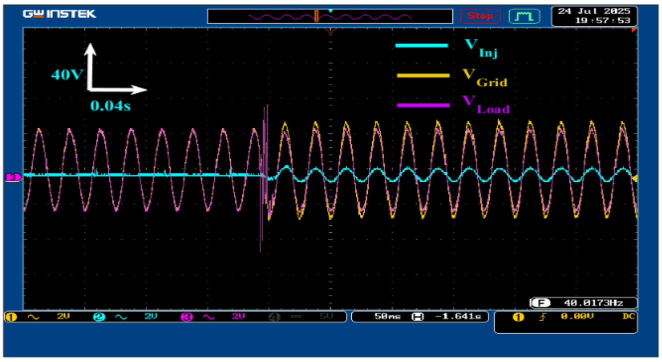


Fig.10. DC link voltage response v_{dc} during swell test scenario.

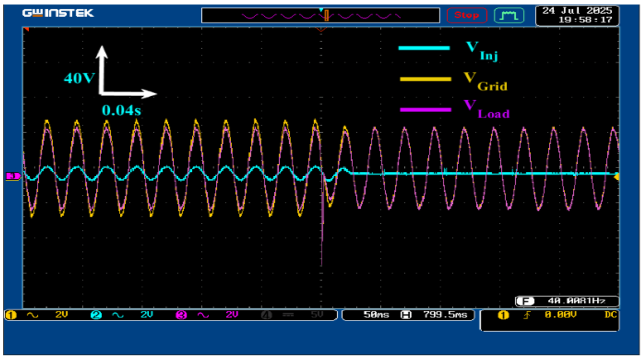
Fig.11. Responses of v^{eff}_{Grid}, v^{eff}_{Load}, v^{eff}_{Inj} during swell test scenario



a)



b)



c)

Fig. 9. Waveform of voltages v_{Grid}, v_{load} and v_{injec} during a sag scenario: (a) Full View (b) Zoom during sag occurrence and (c) Zoom post-sag recovery

Figure (6) presents the measured load current i_L waveforms under steady-state, load increase, and load reduction scenarios. In all cases, the current maintains a stable, periodic pattern typical of nonlinear loads, with consistent waveform quality during both abrupt load changes and steady operation. The absence of oscillations or instability demonstrates that the UPQC effectively sustains current quality and responds robustly to dynamic load variations, confirming the reliability of the proposed control strategy in practical conditions.

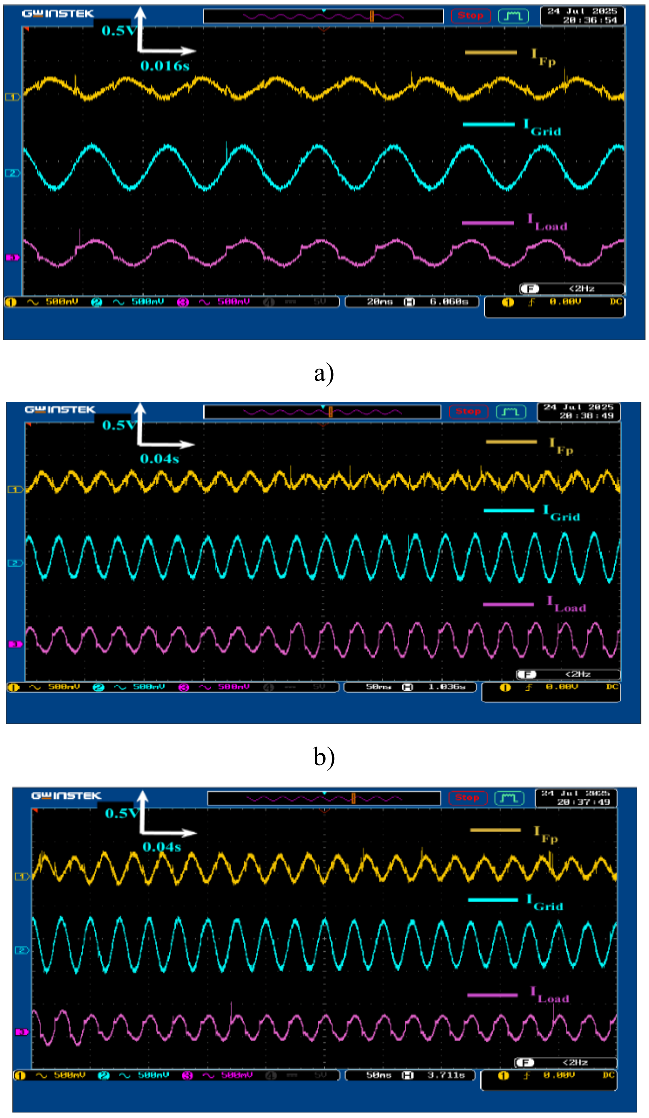
. Figure (7) illustrates the grid current i_{grid} waveforms under steady-state, load increase, and load reduction conditions. In each case, the current maintains a regular, nearly sinusoidal shape, with amplitude appropriately adjusting to changes in load. Figure (8) shows the parallel filter current i_{fp} waveforms during steady-state, load increase, and load reduction conditions. In each scenario, i_{fp} promptly adjusts its amplitude according to load changes while maintaining waveform stability and continuity. This consistent and rapid response highlights the UPQC's effectiveness in providing real-time harmonic compensation and reactive power support, even as load conditions fluctuate.

During the voltage swell scenario, Figures (9-11) demonstrate the UPQC's ability to maintain power quality and system stability. As shown in Figure 6, the compensating current increases to suppress the effects of the swell, allowing load current to remain stable and undistorted.

Figure (10) confirms that the DC-link voltage is effectively regulated, with only minor transients before returning to steady-state. In Figure (11), the injected series voltage precisely offsets the swell, keeping the load voltage consistently near its nominal value. These results collectively highlight the UPQC's robust performance in mitigating voltage disturbances and preserving reliable operation under grid perturbations.

Figure (12) illustrates the UPQC's response during a voltage sag scenario. When a sag occurs on the grid, the UPQC injects a compensating series voltage, as seen in the zoomed waveforms. This action keeps the load voltage steady and near its nominal value throughout the disturbance and recovery, demonstrating the UPQC's robust real-time compensation and its ability to maintain reliable power quality under adverse grid conditions.

B. *Sag scenario*



a)

b)

c)

Fig.13. Waveform of currents i_{fp}, i_{grid} and i_{Load}: (a) in steady-state conditions (b) at load augment (c) at load reduction.

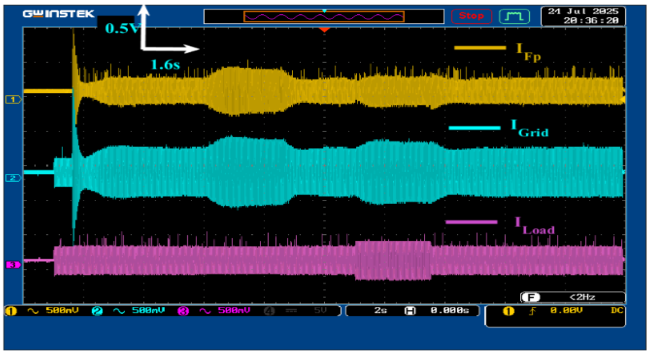


Fig. 14. Waveform of the grid, load and compensating currents during sag scenario (Full View)

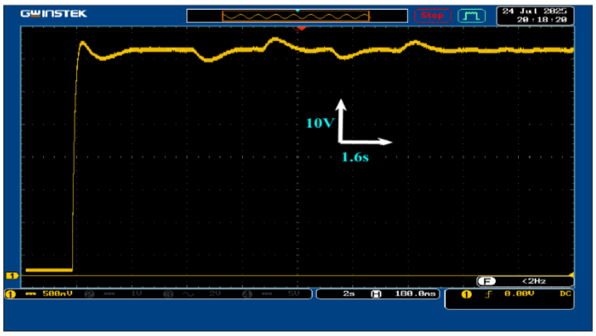


Fig.15. DC link voltage response v_{dc}during sag scenario

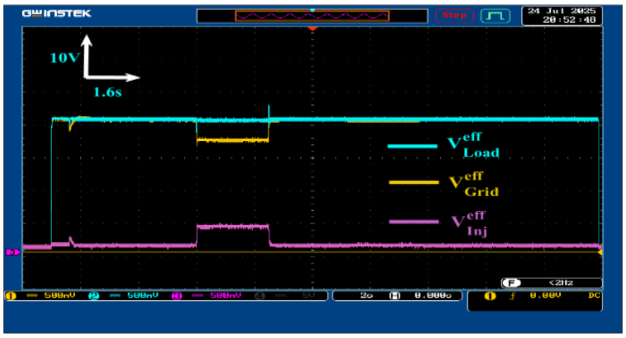
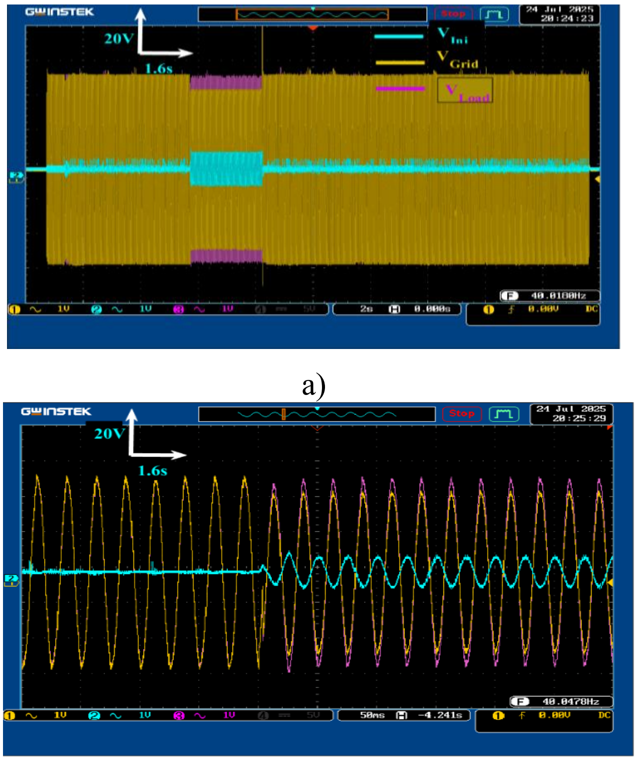


Fig.16. Responses of v^{eff}_{Grid}, v^{eff}_{Load}, v^{eff}_{Inj} during sag test scenario



a)

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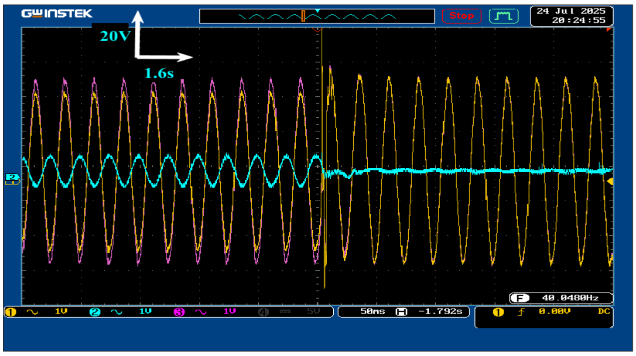

c)

Fig. 17. Waveform of voltages v_{Grid}, v_{load} and v_{injec} during a sag scenario: (a) Full View (b) Zoom during sag occurrence and (c) Zoom after sag clearance

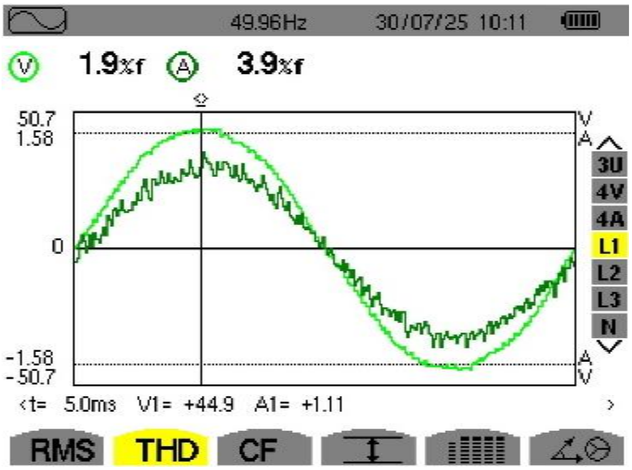

Fig.18. THD and spectrum of source current and voltage

Figure (13) presents the experimental waveforms of the parallel filter current i_{fp}, grid current i_{grid}, and load current i_{Load} under steady-state, load increase, and load reduction conditions. Across all scenarios, the grid current remains nearly sinusoidal and stable, while the filter current promptly adapts to compensate for the load's nonlinear and varying nature. These results highlight the UPQC's fast and reliable compensation capability, ensuring excellent power quality and maintaining clean source currents despite dynamic changes in load. Figures 14 to 16 demonstrate the UPQC's performance during a voltage sag event. When the sag occurs, the UPQC immediately injects compensating currents and series voltage, as evidenced by the stable grid and load currents (Figure 14) and the effective regulation of the DC-link voltage (Figure 15). As a result, the load voltage remains nearly constant despite the grid disturbance (Figure 16), confirming the UPQC's capability to maintain power quality and reliable operation under adverse grid conditions. Figure (17) illustrates the voltage waveforms during a sag event, showing that when the grid voltage drops, the UPQC immediately injects a compensating series voltage to maintain the load voltage close to its nominal value. The zoomed views confirm the UPQC's fast response during the disturbance and its ability to restore normal operation once the sag is cleared, demonstrating robust real-time voltage regulation and effective power quality improvement. Figure (18) shows the source current waveform and its THD, measured at 3.9%. The current is predominantly sinusoidal with minimal harmonic content, indicating that the implemented compensation effectively reduces distortion and maintains power quality at the source.

VII CONCLUSION

This work has presented the experimental validation of a single-phase Unified Power Quality Conditioner designed to address key power quality issues in low-voltage distribution networks supplying nonlinear loads. The developed prototype, integrating coordinated series and shunt active filtering, demonstrated effective mitigation of voltage sags, swells, current harmonics, and reactive power demands under both steady-state and dynamic conditions. The series inverter successfully maintained a stable load voltage during severe voltage disturbances, while the shunt inverter ensured sinusoidal source currents and improved power factor by dynamically compensating harmonic and reactive components. Experimental results, obtained using a real-time dSPACE 1103 platform, confirmed the UPQC's capability to preserve power quality, stabilize the DC-link voltage, and maintain reliable operation under diverse grid perturbations and load variations. These findings not only validate the proposed system model and control strategy but also demonstrate the UPQC's practical feasibility and effectiveness for deployment in residential and small commercial distribution systems. Future work will focus on enhancing control robustness, optimizing efficiency, and extending the concept to renewable-energy-integrated and multi-phase configurations.

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