ISRES Publishing

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 38, Pages 121-134

IConTES 2025: International Conference on Technology, Engineering and Science

Performance Improvement of Predictive Direct Power Control of a Unified Power Quality Conditioner

Noureddine Khenfar
Djillali Liabes University of Sidi Bel-Abbes

Abdelhafid Semmah
Djillali Liabes University of Sidi Bel-Abbes

Abstract: This paper presents an analysis and comparison of classical Direct Power Control (DPC) and Predictive Direct Power Control (P-DPC) strategies applied to the parallel side of a Unified Power Quality Conditioner (UPQC). Classical DPC is known for its simplicity and direct control of active and reactive power but has limitations in harmonic suppression and dynamic response under varying grid conditions (Chaoui et al., 2008 ; Gui et al., 2020 ; Zhao et al., 2019). The P-DPC strategy overcomes these challenges by predicting system behavior and optimizing control actions via a cost function, resulting in faster dynamic responses, enhanced harmonic mitigation, and improved power quality. On the series side, an adaptive hysteresis control method is combined with a synchronous reference frame identification technique. This dynamically adjusts the hysteresis band to ensure precise voltage compensation and reduce switching losses. Additionally, a fuzzy logic controller regulates the DC-link voltage, maintaining stable operation during transient and steady-state conditions. Simulation results demonstrate that P-DPC significantly outperforms classical DPC in harmonic suppression. Moreover, adaptive hysteresis control on the series active filter further improves voltage compensation, reducing total harmonic distortion (THD) compared to fixed-band hysteresis. The fuzzy logic controller offers robust DC-link voltage regulation, enhancing stability during disturbances. The integration of P-DPC on the shunt converter, adaptive hysteresis control on the series one, and fuzzy logic regulation of the DC-link voltage collectively demonstrate superior performance in harmonic mitigation, reactive power compensation, and voltage stabilization. These findings highlight the potential of predictive control techniques combined with intelligent controllers to achieve optimal power quality in modern electrical systems.

Keywords: Predictive direct power control, Unified power quality conditioner, Adaptive hysteresis control, Synchronous reference fuzzy logic controller

Introduction

In recent years, the increasing complexity of electrical networks and the widespread integration of nonlinear loads have significantly impacted power quality (PQ). Issues such as harmonic distortions, voltage sags, swells, and imbalances have become critical challenges for modern power systems. These disturbances can lead to equipment malfunctions, reduced efficiency, and financial losses in industrial and residential applications. To address these challenges, the Unified Power Quality Conditioner (UPQC) has emerged as a versatile solution capable of simultaneously mitigating voltage and current-related PQ problems (Swarna Latha et al., 2020).

The UPQC combines two active filters: a parallel active filter (FAP) that compensates for current harmonics and reactive power and a series active filter (FAS) that addresses voltage disturbances such as sags, swells, and harmonics. Both filters are interconnected through a common DC-link, which plays a crucial role in maintaining the stability and performance of the system. The effectiveness of the UPQC largely depends on the control strategies employed for its active filters (Das et al., 2023 ; Salim et al., 2013 ; Tripathi et al., 2016).

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

The Direct Power Control (DPC) technique has gained popularity for its simplicity and fast dynamic response in controlling active and reactive power. Derived from the Direct Torque Control (DTC) method used in electrical machines, DPC eliminates the need for internal current control loops, making it suitable for power quality applications. However, classical DPC suffers from limitations such as uncontrolled switching frequency and reduced performance under distorted or unbalanced grid conditions. These drawbacks necessitate advanced control strategies to enhance the UPQC's capabilities (Gui et al., 2018 ; Rath et al., 2024 ; Trivedi et al., 2024).

On the FAS side, an adaptive hysteresis current control strategy is implemented using a synchronous reference frame identification method. This approach dynamically adjusts the hysteresis band to ensure precise voltage compensation while reducing switching losses. Additionally, a fuzzy logic controller is integrated into the UPQC system to regulate the DC-link voltage, ensuring stable operation under transient and steady-state conditions.

The primary objective of this work is to evaluate and compare the performance of classical DPC and P-DPC strategies applied to the FAP while demonstrating the effectiveness of adaptive hysteresis control on the FAS. The proposed control strategies aim to improve harmonic suppression, reactive power compensation, voltage regulation, and overall system stability.

Proposed Control Diagram for the UPQC

The Unified Power Quality Conditioner (UPQC) is a hybrid compensating device that integrates a shunt active power filter (APF) and a series active power filter (APF), both connected through a common DC-link. The shunt APF mitigates current-related problems such as harmonic distortion and reactive power, whereas the series APF compensates for voltage disturbances including sags, swells, and voltage harmonics. Operating in coordination, both filters maintain sinusoidal source currents and stable, distortion-free load voltages. (Fujita & Akagi, 1998 ; Khadkikar, 2015 ; Kesler & Ozdemir, 2009). The schematic diagram of the studied system, along with the various adopted control approaches, is illustrated in Figure 1.

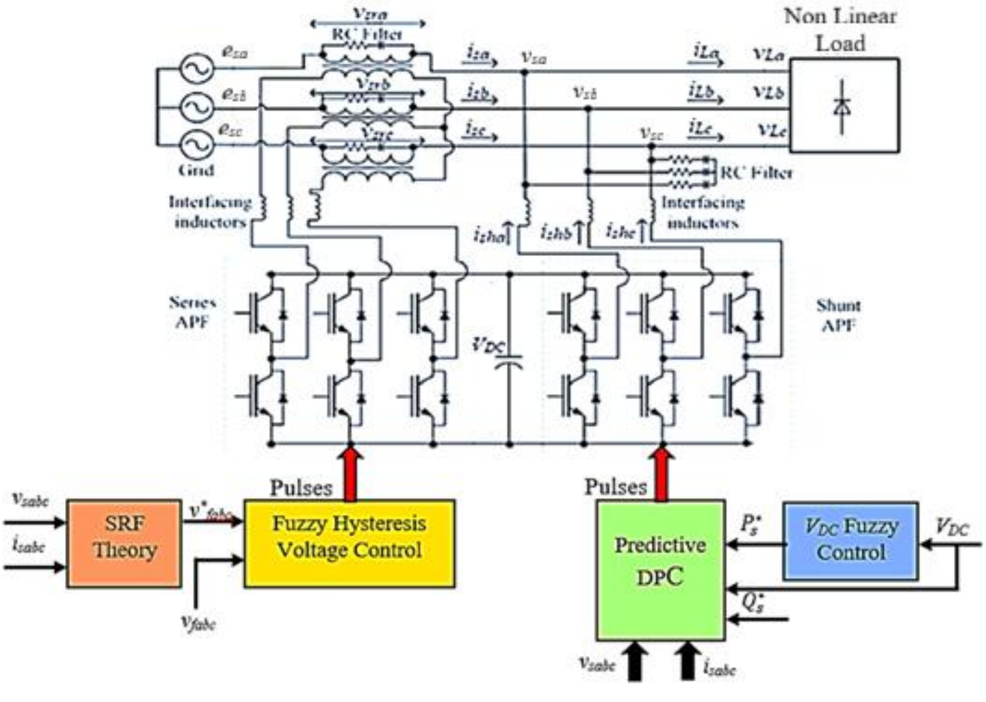


Figure 1. Schematic diagram of the UPQC device

This section outlines the methodology employed for implementing and evaluating the proposed control strategies for the Unified Power Quality Conditioner (UPQC). The study focuses on two key aspects: the application of Predictive Direct Power Control (P-DPC) on the parallel active filter (FAP) and an adaptive hysteresis current control strategy on the series active filter (FAS). The methods are designed to enhance power quality by mitigating harmonics, regulating voltage, and maintaining system stability under various operating conditions.

Predictive Direct Power Control (P-DPC) for the Parallel Side of the UPQC

Predictive Direct Power Control (P-DPC) has emerged as an advanced control strategy for the parallel side of the Unified Power Flow Controller (UPFC), enabling precise and dynamic regulation of active and reactive power. Unlike classical control methods, P-DPC uses a predictive model to anticipate system behavior and optimize switching actions (Figure 2), resulting in enhanced harmonic mitigation, faster dynamic response, and improved power quality. Recent studies have demonstrated the efficacy of P-DPC in improving UPFC performance under varying grid conditions (Bekakra, 2021 ; Nishad et al., 2024 ; Wang et al., 2024).

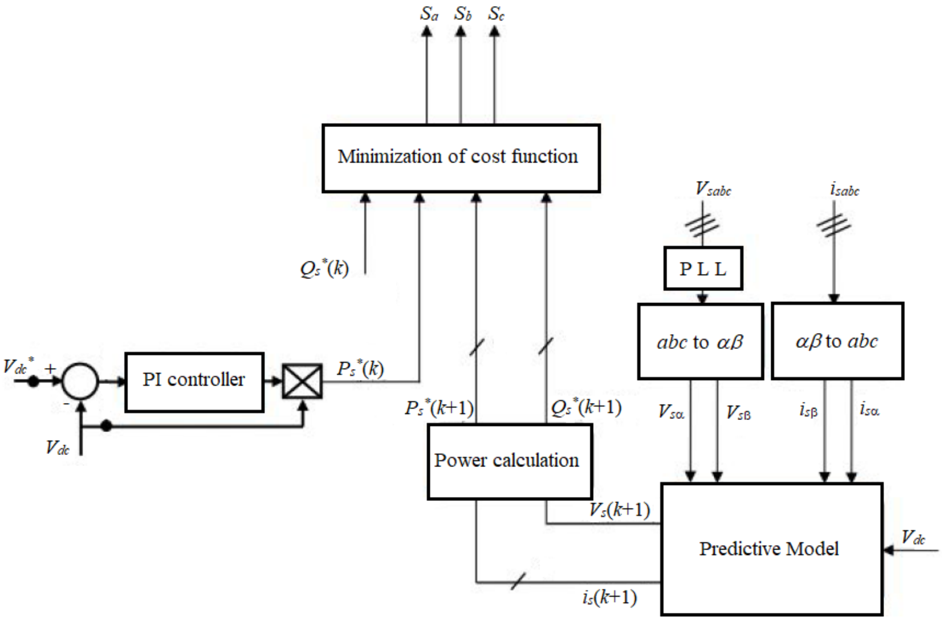


Figure 2. Schematic diagram of the predictive DPC technique

The reference for the active power P^*_s is generated by the outer loop of the DC-link voltage control through an anti-windup regulator. The reactive power reference Q^*_s, is externally provided and maintained at zero to ensure unity power factor operation. Assuming the DC-link voltage tracking error remains constant over two consecutive sampling periods, the instantaneous active power reference at the next sampling instant can be predicted using linear extrapolation, as illustrated in Figure 3.

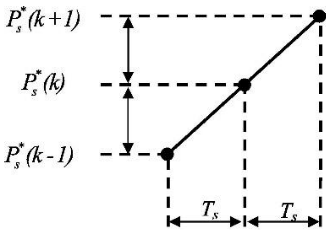


Figure 3. Estimation of predictive value of instantaneous active power reference.

The P-DPC strategy relies on a predictive model of the parralel converter to forecast system behavior and optimize control actions. The dynamic behavior of the source current is described by the following differential equation:

$$\frac{d}{dt}[i_s] = -\frac{R_s}{L_s}[i_s] + \frac{1}{L_s}([e_s] - [V_s]) \tag{1}$$

Where:

- $[e_s]$: Source back-emf vector,
- $[i_s]$: Source current vector,
- $[V_s]$: Inverter voltage vector,
- R_s and L_s represent source resistance and inductance respectively.

The discrete-time model predicts the next source current value at time step (k+1) using measured voltages and currents from the current sampling instant (k). The time derivative of the source current, $d[i_s]/dt$, is approximated using a forward Euler method as follows (Bekakra et al., 2021):

$$\frac{di_s}{dt} \approx -\frac{i_s(k+1)-i_s(k)}{T_s} \quad (2)$$

The source current at the next time step (k+1) is predicted as follows:

$$[i_s(k+1)] = \left(1 - \frac{T_S R_S}{L_S}[i_s(k)]\right) + \frac{T_S}{L_S}([e_s(k)] - [V_s(k)]) \quad (3)$$

Where T_s is the sampling time..

Active and Reactive Power Formulation

The predicted active (P_s) and reactive (Q_s) powers are calculated using:

$$P_s(k+1) = \mathrm{Re}\big[\mathrm{conj}\big(i_s(k+1)\big)V_s(k+1)\big] \quad (4)$$

$$Q_s(k+1) = \mathrm{Im}\big[\mathrm{conj}\big(i_s(k+1)\big)V_s(k+1)\big] \quad (5)$$

Where:

$$i_s = \sqrt{i_{s\alpha}^2 + i_{s\beta}^2} \quad (6)$$

and,

$$V_s = \sqrt{V_{s\alpha}^2 + V_{s\beta}^2} \quad (7)$$

$i_{s\alpha}$, $i_{s\beta}$ and $V_{s\alpha}$, $V_{s\beta}$ are source currents and voltages in $\alpha\beta$ frame, respectively, and are given by:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (9)$$

Cost Function Optimization

To determine the optimal switching state of the inverter, a cost function is minimized at each sampling interval:

$$g_i = |P_s^*(k) - P_s(k+1)_i| + |Q_s^*(k) - Q_s(k+1)_i| \quad (10)$$

Where P^*_s and Q^*_s are reference active and reactive powers, respectively, and i = 0,1,2,...,6 represents possible switching states. The switching state that minimizes this cost function is applied to the inverter, ensuring accurate tracking of power references.

Adaptive Hysteresis Voltage Control

The UPQC employs an adaptive hysteresis voltage control strategy, on his series side, combined with a synchronous reference frame (SRF) identification method. The SRF transforms three-phase voltages (V_a,V_b,V_c) into a rotating dqo frame using Park's transformation. This method isolates fundamental components for precise voltage compensation.

The adaptive hysteresis control, shown by Figure 4, dynamically adjusts the hysteresis band based on system conditions to ensure consistent performance. Unlike fixed-band hysteresis control, this method reduces switching losses while maintaining accurate tracking of reference currents (Khenfar et al., 2021).

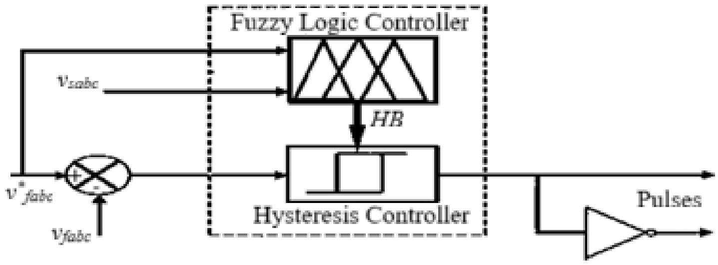


Figure 4. Schematic diagram of the fuzzy hysteresis control

Five triangular membership functions (NL, NM, AZ, PM, PL) define the input and output variables, and 25 fuzzy rules form the inference matrix (Table 1).

Table1. Inference rules of the fuzzy hysteresis controller

dvf*/dt\vs	NL	NM	AZ	PM	PL
NL	NL	NL	NL	NM	AZ
NM	NL	NL	NM	AZ	PM
AZ	NL	NM	AZ	PM	PL
PM	NM	AZ	PM	PL	PL
PL	AZ	PM	PL	PL	PL

N: Negative; P: Positive; AZ: Approximately Zero; L: Large; M: Medium.

The switching logic is defined as:
- Upper switch ON if $v_{fa} > v^*_{fa} + HB(t)$,
- Lower switch ON if $v_{fa} < v^*_{fa} - HB(t)$,

where $HB(t)$ is the adaptive hysteresis band width.

DC-Link Voltage Regulation with Fuzzy Logic Controller

A fuzzy logic controller (FLC) is implemented to regulate the DC-link voltage shared by FAP and FAS. The controller operates in real time to adaptively adjust control actions based on input error ($e=V^*_{DC}-V_{DC}$) and its derivative ($\Delta e=e(t)-e(t-1)$). This ensures stable operation under varying load conditions and grid disturbances. Seven triangular membership functions are adopted, with the inference rules organized in Table 2.

Table 2. Inference Table of the DC voltage controller

dif*/dt \ vs	NL	NM	NS	AZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	AZ
NM	NL	NL	NL	NM	NS	AZ	PS
NS	NL	NL	NM	NS	AZ	PS	PM
AZ	NL	NM	NL	AZ	PS	PM	PL
PS	NM	NS	AZ	PS	PM	PL	PL
PM	NS	AZ	PS	PM	PL	PL	PL
PL	AZ	PS	PM	PL	PL	PL	PL

N: Negative; P: Positive; AZ: Approximately Zero; L: Large; M: Medium; S: Small.

Results and Discussion

The effectiveness of the proposed control techniques was evaluated through simulation in the MATLAB/Simulink environment. To demonstrate the UPQC's capability to simultaneously compensate for both current and voltage disturbances, various operating scenarios are considered. These scenarios involved source voltage disturbances, including sags, overvoltages, and harmonic distortions (Figure 5), as well as nonlinear loads drawing distorted currents. Such nonlinear loads are also subject to abrupt variations in their operating conditions.

Thus, multiple control strategies are combined to enhance the filtering performance of the UPQC. Predictive DPC is employed to determine the switching instants of the parallel converter, while fuzzy hysteresis control is adopted for the series converter, with harmonic identification in this branch achieved using the SRF technique. The regulation of active power exchange between the UPQC and the grid is ensured by introducing a fuzzy logic controller within the DC-link voltage regulation loop.

The current waveform absorbed by the nonlinear load and its corresponding frequency spectrum are presented in Figure 6. The current drawn by the nonlinear load contains substantial harmonic components, leading to a Total Harmonic Distortion (THD) of 27.24% in the source current before filtering.

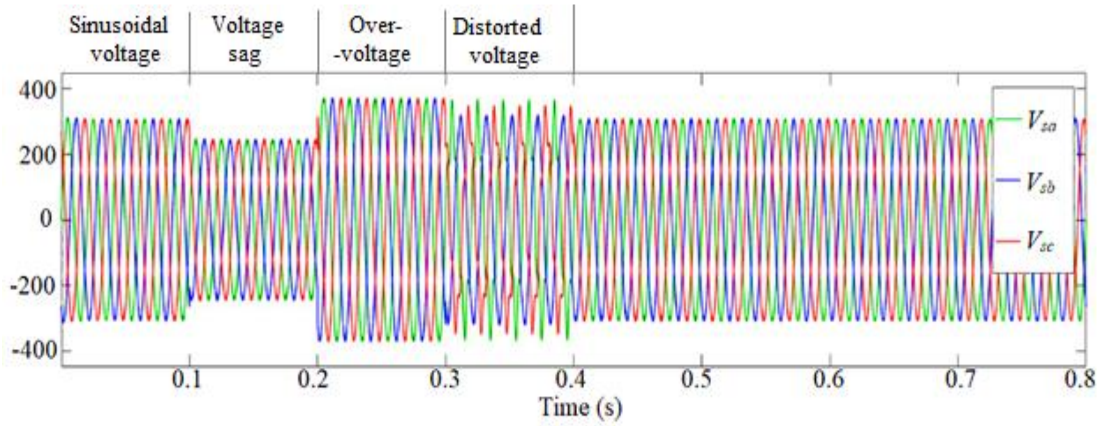


Figure 5. Source voltage waveform for four fault scenarios.

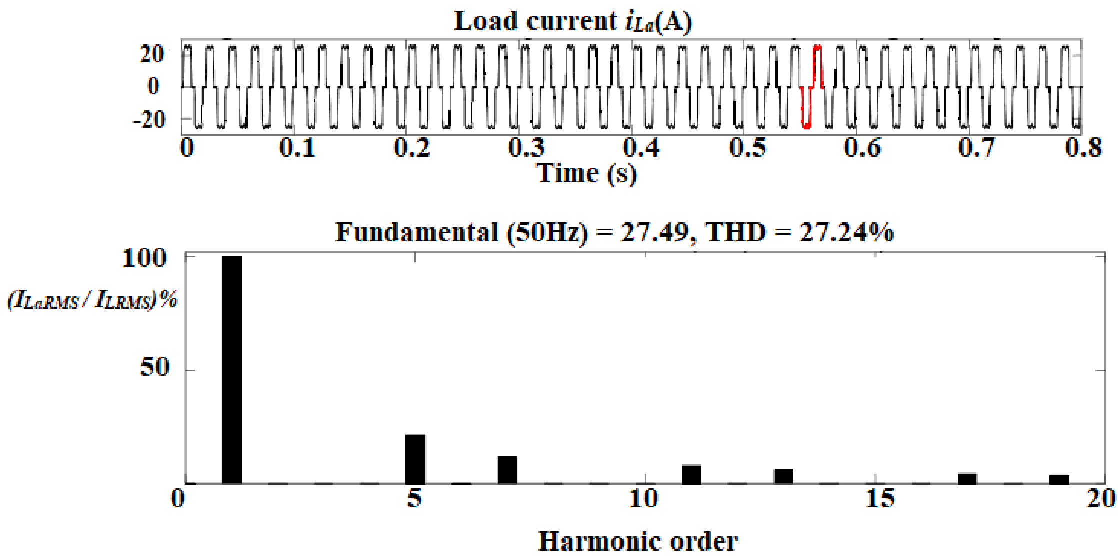


Figure 6. Waveform of the current drawn by the nonlinear load with its spectral representation.

Performance Without DC Voltage Variation

Harmonic Currents Compensation

With the application of classical Direct Power Control (DPC), the source current waveform improves somewhat, yet it retains visible oscillations and distortions, particularly following voltage perturbations (Figure 7). The harmonic spectrum shows a reduction in THD to 8.90% (Figure 8), but this value still exceeds the universally accepted IEEE Std 519-1992 limit of 5%. Consequently, power quality is improved but remains suboptimal.

The adoption of predictive DPC greatly enhances performance. After filtering, the source current waveform is noticeably smoother and rapidly regains its sinusoidal shape (Figure 9), even after aggressive grid disturbances. The corresponding harmonic spectrum shows a dramatic reduction in THD to 3.79%, well within international standards. This result demonstrates the superior filtering capability and dynamic response of the P-DPC scheme, allowing the UPQC to deliver clean supply currents despite the presence of nonlinear loads and network events.

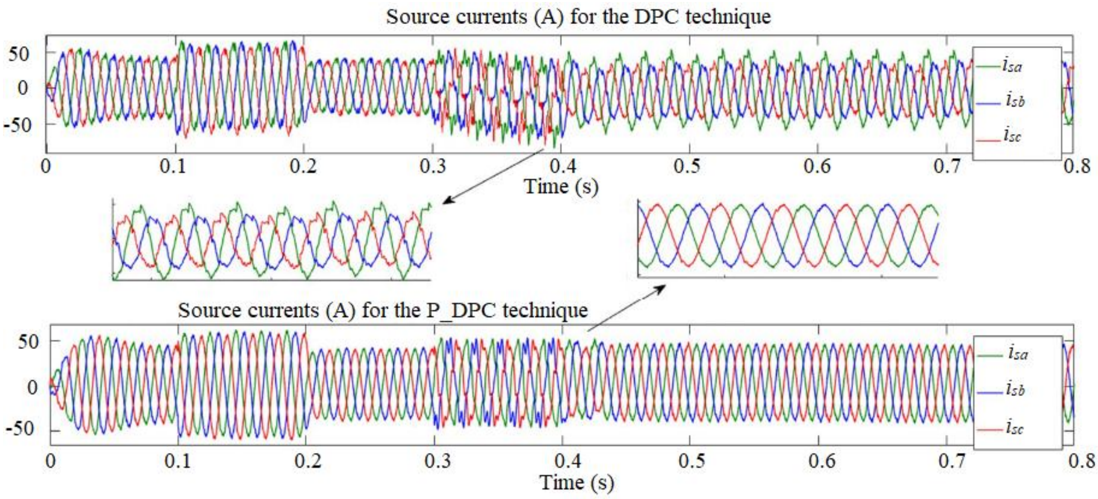


Figure 7. Waveforms of the UPF Source currents with classical DPC and P-DPC techniques

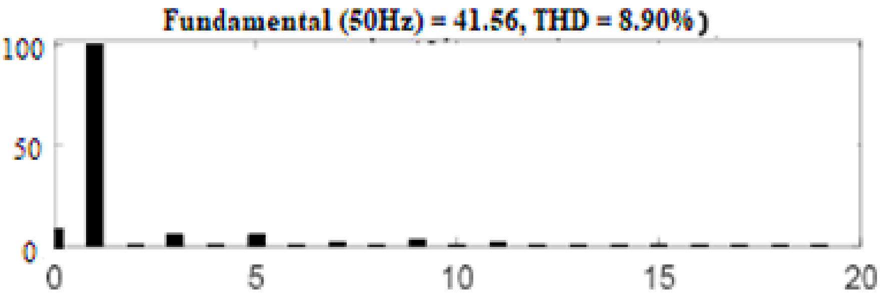


Figure 8. Spectral representation of the UPQC source current using classical DPC technique

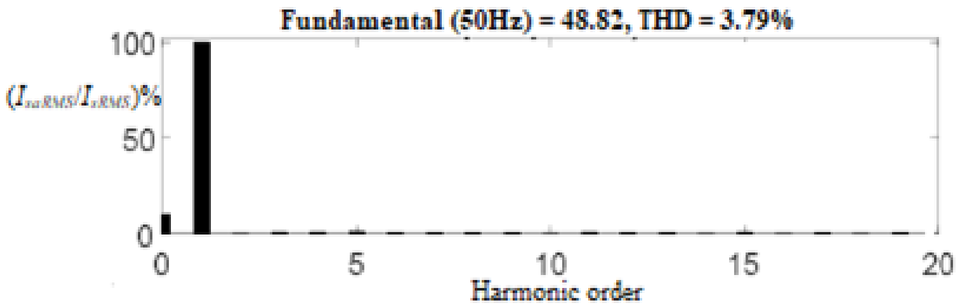


Figure 9. Spectral representation of the UPQC source current using predictive DPC technique

DC-Link Voltage Stability

Figures (10-13) show how the DC-link voltage evolves for different control approaches (Fuzzy, PI) under classical DPC and predictive P-DPC, both with and without step DC voltage changes. When there is no step DC voltage variation, all controllers tend to stabilize the voltage, but the Fuzzy controller reaches steady-state faster and with less overshoot compared to the PI controller, making the system more resilient to disturbances and improving overall stability (Figure 10).

Under step variations, the Fuzzy controller again outperforms the PI, quickly restoring the DC voltage with fewer oscillations and a shorter settling time (Figure 12). The use of predictive DPC technique generally enhances performance further, especially under dynamic conditions (Figure 11 and 13), showing that combining predictive control with fuzzy logic can yield a robust and adaptive compensation system for the UPQC. These results indicate that advanced controllers not only maintain stable DC voltage, but also help safeguard sensitive loads and ensure reliable operation under demanding, real-world scenarios.

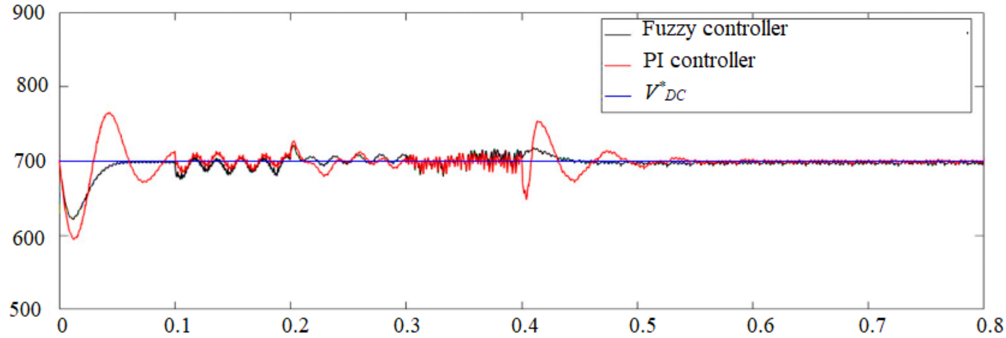


Figure 10. DC voltage behavior for classical DPC technique without step DC voltage variation

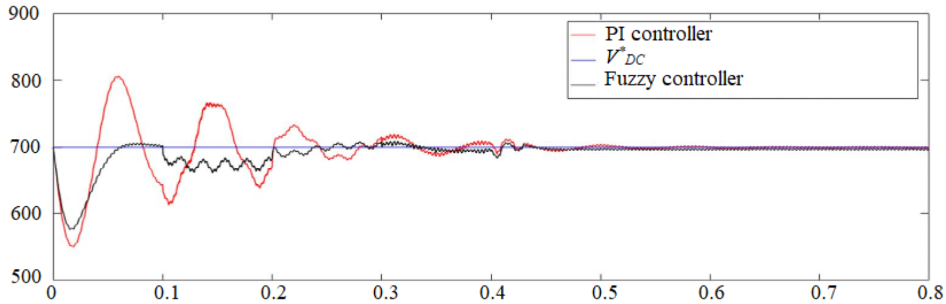


Figure 11. DC voltage behavior for predictive DPC technique without step DC voltage variation

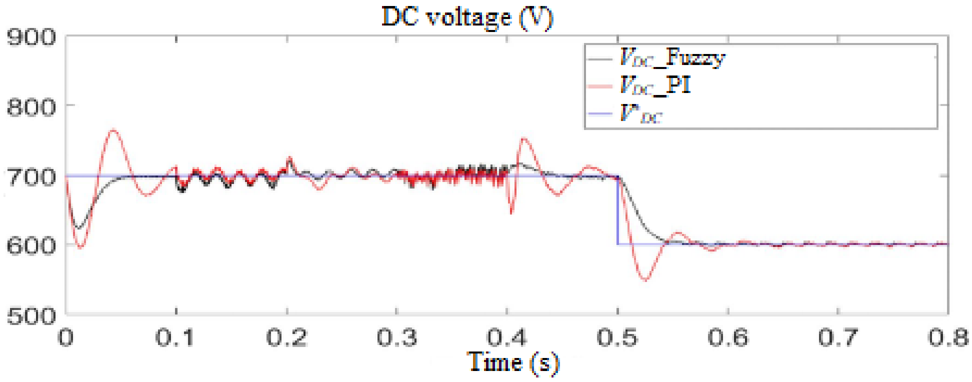


Figure 12. DC voltage behavior for classical DPC technique with step DC voltage variation

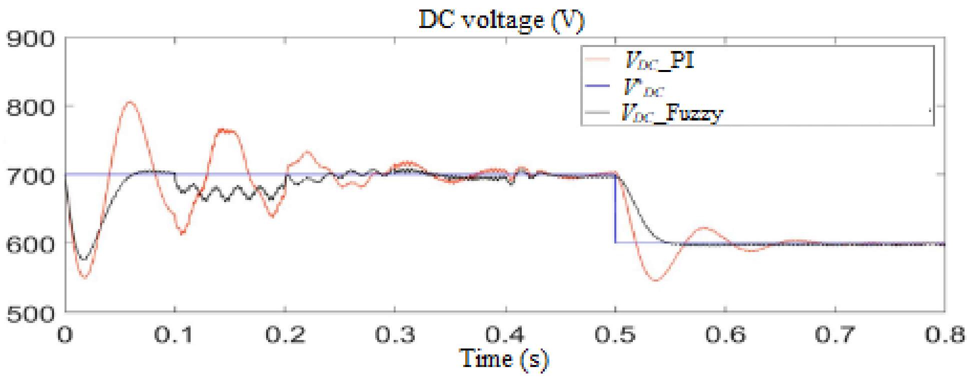


Figure 13. DC voltage behavior for predictive DPC technique with step DC voltage variation.

Active and Reactive Power Behavior

Figures 14 to 16 illustrate the dynamic behavior of the active power for both classical and predictive DPC techniques using PI and fuzzy controllers, with and without step DC voltage variation. In scenarios without step changes, the fuzzy controller delivers faster convergence and reduced oscillations compared to the PI controller

(Figure 14 and 15), reflecting superior adaptability and robustness. When abrupt changes occur, predictive DPC technique combined with fuzzy logic maintains a more stable and resilient active power response, quickly damping transients and minimizing overshoot (Figuref 16). Overall, integrating fuzzy logic in the control system noticeably enhances the UPQC's ability to regulate active power, especially under challenging and variable grid conditions.

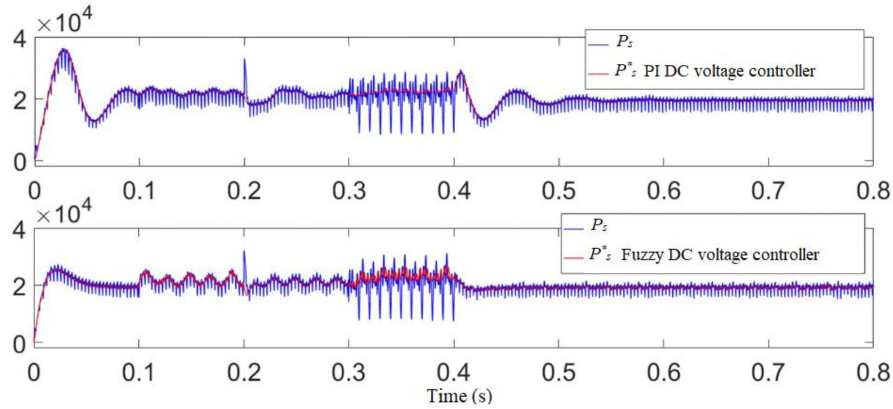


Figure 14. Active power behaviors for classical DPC technique without DC voltage variation

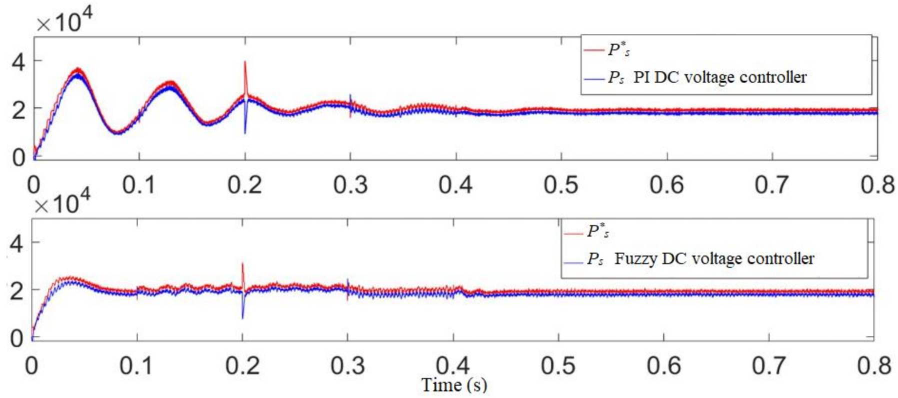


Figure 15. Active power behaviors for predictive DPC without DC voltage variation

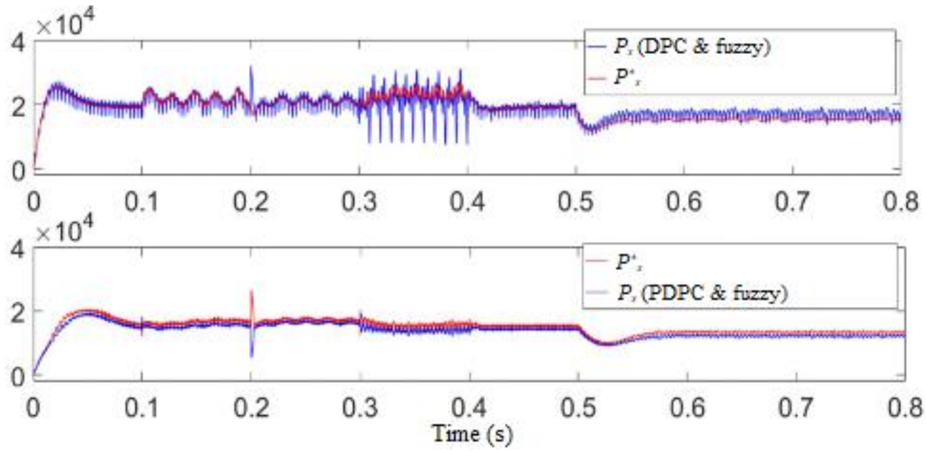
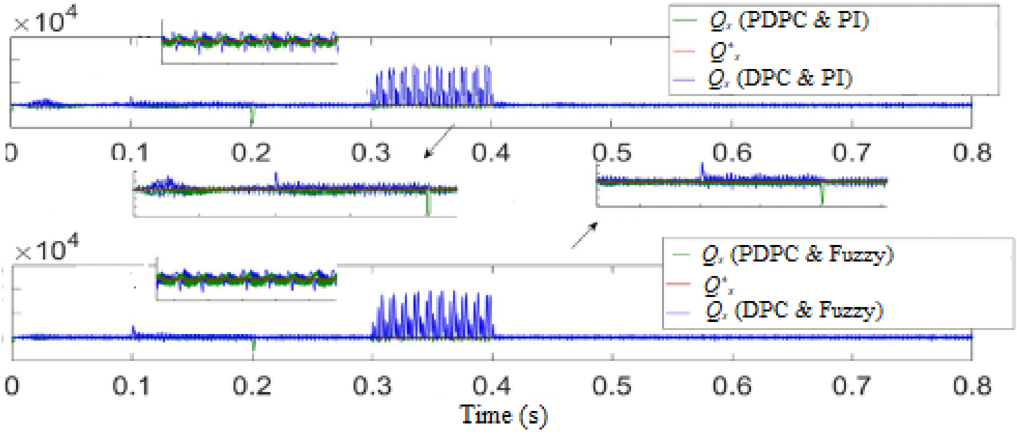


Figure 16. Active power behaviors for classical & predictive DPC with step DC voltage variation

The results in Figures 17 and 18 provide a detailed view of the reactive power response using both PI and fuzzy controllers within classical and predictive DPC schemes, under conditions with and without step variations. Without step variation, both control strategies (PI and fuzzy) are capable of maintaining the reactive power close to the reference, with the fuzzy controller generally demonstrating reduced oscillations and a more stable tracking performance (Figure 17). This indicates that fuzzy logic enhances the controller's ability to reject small disturbances and adapt to system uncertainties. When a step variation is introduced, the reactive power experiences larger transients, especially for the PI controller, which shows significant overshoot and prolonged oscillations before settling. By contrast, the fuzzy controller (and especially its combination within the predictive

DPC strategy) manages the transient more effectively, displaying quicker damping and more rapid return to steady-state (Figure 18).

In summary, these results illustrate that integrating fuzzy logic in the UPQC's DPC improves robustness and dynamic performance, allowing the system to better manage abrupt load or source changes and provide high-quality compensation. This ensures stable voltage conditions and reduced stress on electrical equipment, which is essential for maintaining reliable grid operation.



Figuref 17. Reactive power behaviors without step DC voltage variation

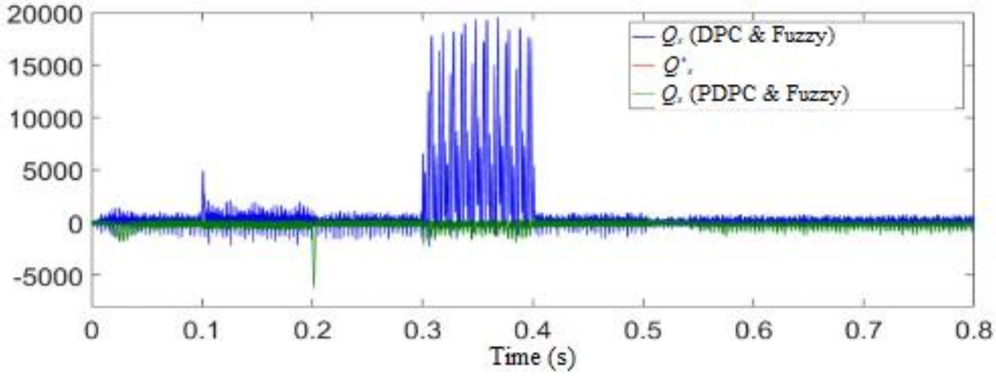


Figure 17. Reactive power behaviors with step DC voltage variation

Adaptive Fuzzy Hysteresis Control for Series Filter (FAS)

Harmonic Voltage Compensation

Figures 18 to 22 display the behavior of the load voltage after filtering using both fixed and fuzzy-band hysteresis for P-DPC control, along with their associated spectral representation. The waveforms show that fuzzy logic hysteresis controllers deliver a smoother and more stable load voltage, effectively tracking the sinusoidal reference even during periods with disturbances or switching events. Compared to fixed hysteresis, the fuzzy-band approach adapts better to dynamic system changes, reducing voltage spikes and oscillations that could impact sensitive loads (Figure 18).

The harmonic spectrum analysis confirms this benefit: the source voltage under various disturbances shows a high THD equal to 15.76% (Figure 20), while the load voltage, with compensation and fuzzy-band hysteresis, achieves a much lower THD of around 3.13% (Figure 22). This substantial reduction in harmonic content ensures not only better power quality but also extended equipment life and improved operational reliability.

Ultimately, these results highlight the effectiveness of integrating fuzzy logic into the hysteresis control loop of the UPQC's series converter, particularly under predictive DPC, to deliver high-quality, disturbance-resilient voltage to the load, even under severe grid perturbations.

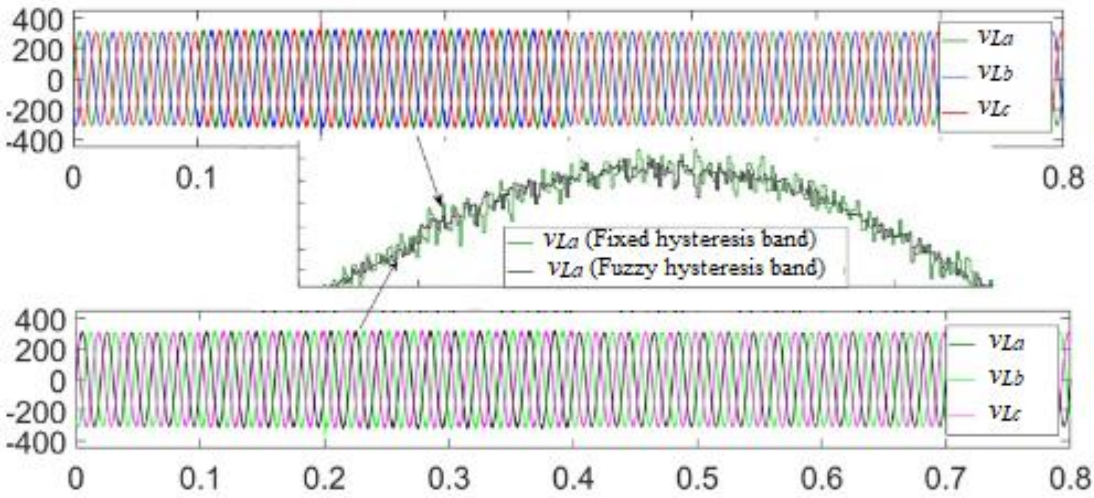


Figure 18. Waveforms of the load voltage after filtering with fixed hysteresis and fuzzy band hysteresis for P-DPC control with fuzzy logic controller.

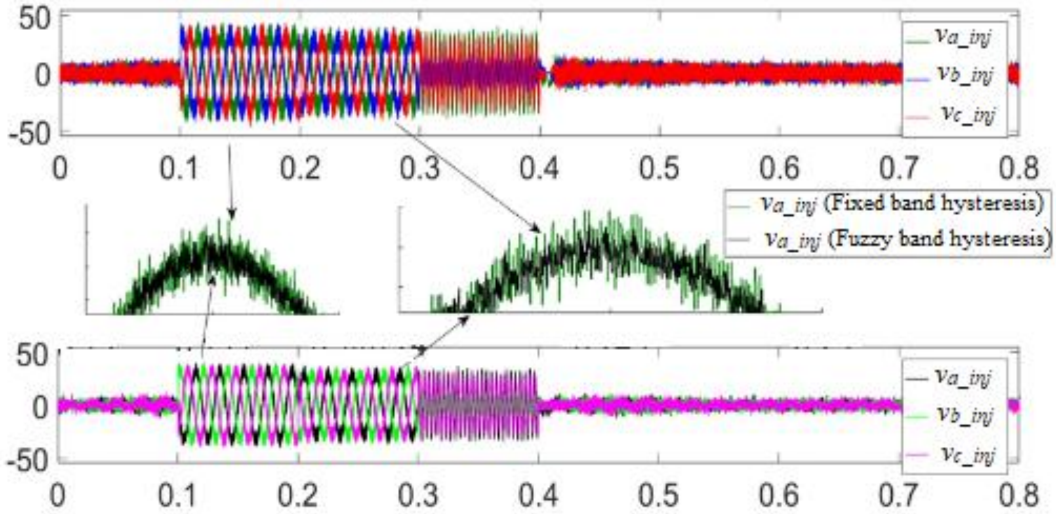


Figure 19. Waveform of the injected voltage with fixed hysteresis and fuzzy-band hysteresis for P-DPC control and fuzzy logic controller

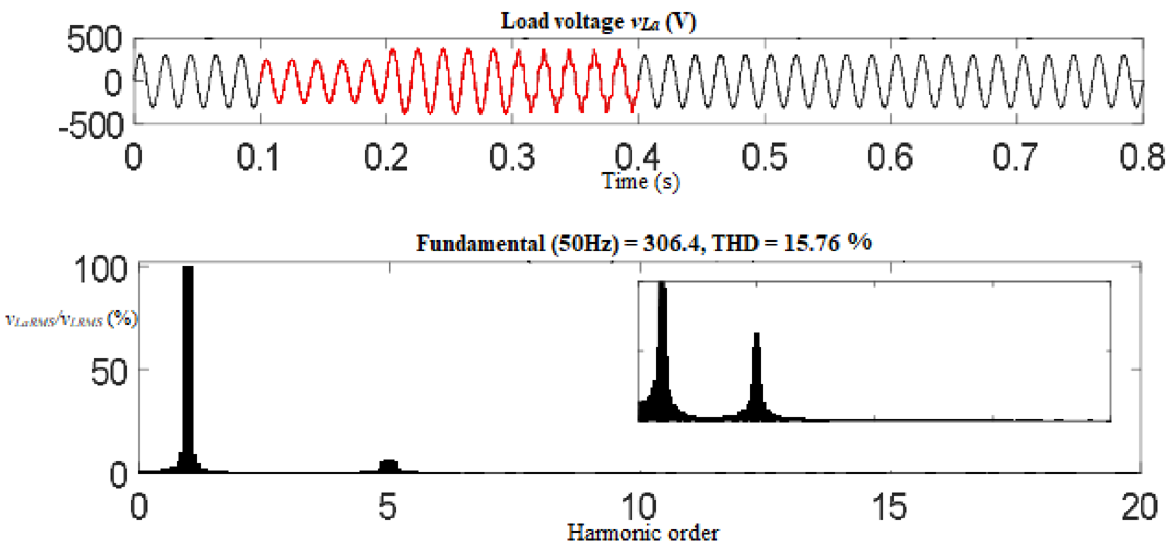


Figure 20. Spectral representation of the Source Voltage Representing Different Disturbances

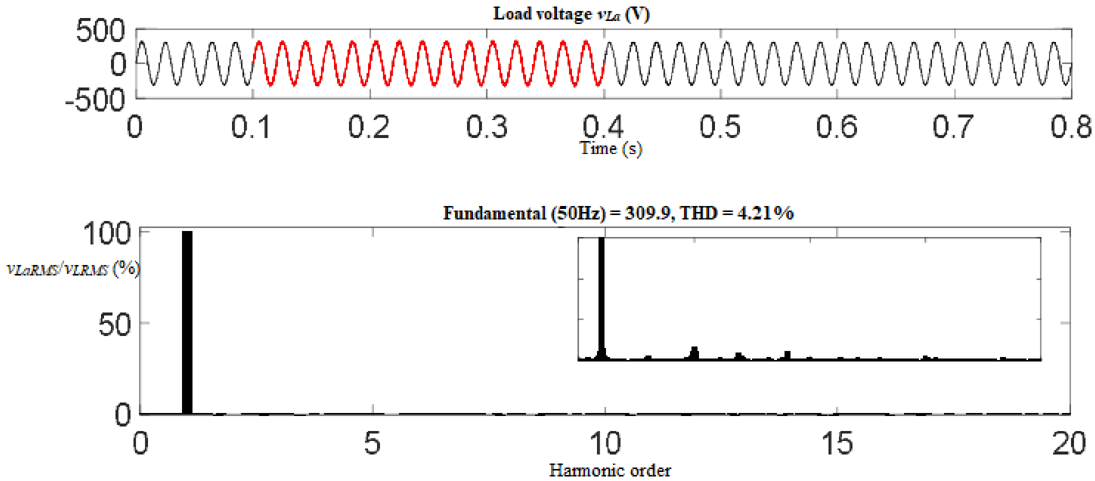


Figure 21. Spectral representation of the load voltage based on fixed-band hysteresis control

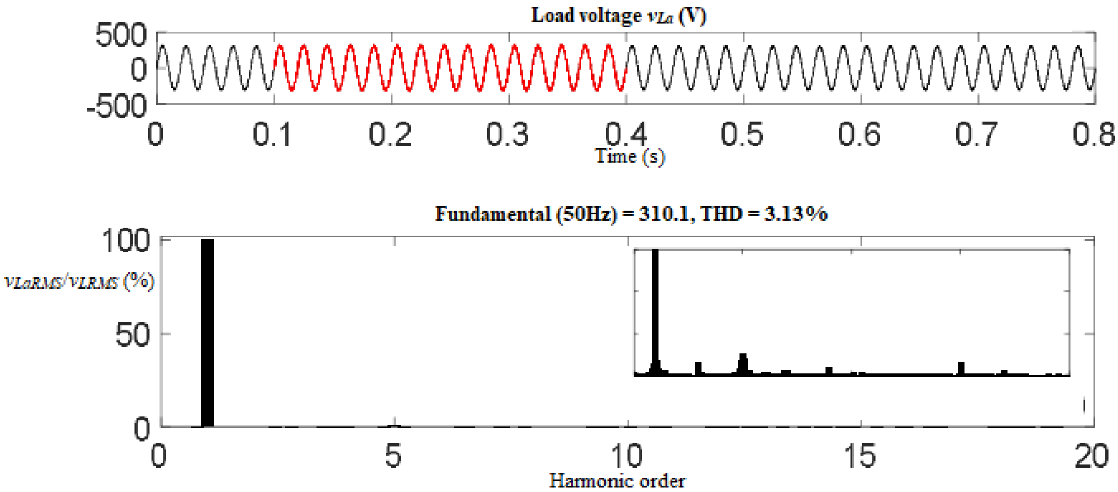


Figure 22. Spectral representation of the load voltage based on fuzzy-band hysteresis control

Conclusion

The simulation results presented in this work highlight the substantial benefits of integrating predictive direct power control (PDPC) with fuzzy logic controllers for the Unified Power Quality Conditioner (UPQC).

The Predictive DPC technique shows strong capabilities in anticipating system dynamics, delivering timely and precise switching actions for the parallel converter, enabling it to respond rapidly to power quality disturbances such as sags, overvoltages, and harmonic distortions. When the Predictive DPC technique is combined with fuzzy logic control, particularly in the regulation of the DC-link voltage and active/reactive power exchanges, the results obtained demonstrate a remarkable boost in tracking accuracy, transient speed, and overall robustness-surpassing the performance of classical PI-based approaches.

Furthermore, incorporating a fuzzy inference system into the hysteresis control of the series converter brings an additional layer of intelligence and adaptability. The fuzzy-band hysteresis method dynamically adjusts control boundaries based on real-time system changes, resulting in more stable load voltage waveforms, a dramatic reduction in voltage and current oscillations, and consistently lower total harmonic distortion (THD). These improvements are especially evident under abrupt load changes or complex grid disturbances, where classical fixed-band methods often struggle.

Overall, the proposed combination of PDPC, fuzzy logic, and fuzzy hysteresis control achieves not only compliance with the most demanding power quality standards but also ensures highly reliable and resilient power delivery in today's challenging and evolving grid environments. This hybrid intelligent framework makes the UPQC a powerful, flexible, and future-ready solution for comprehensive power quality management.

Recommendations

The experimental validation of the proposed Predictive Direct Power Control (P-DPC) and adaptive hysteresis control strategies will be extended beyond MATLAB-Simulink simulations through implementation on a physical prototype, thereby enabling the assessment of their applicability and robustness under practical operating conditions. Furthermore, a comprehensive investigation into the effects of these control methodologies on equipment lifespan is warranted, with particular emphasis on the reduction of switching losses and thermal stress, which could inform maintenance scheduling and operational cost optimization. Additionally, it is imperative to evaluate the performance of these control strategies within smart grid environments characterized by the integration of renewable energy sources and increased load variability, thereby addressing contemporary challenges in power system management and ensuring reliable and efficient system operation.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

* This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements or Notes

* This article was presented as a poster presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Türkiye on November 12-15, 2025.

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Author(s) Information

Noureddine Khenfar	**Abdelhafid Semmah**
Djillali Liabes University of Sidi Bel-Abbes	Djillali Liabes University of Sidi Bel-Abbes
ICEPS Lab. 22000 Sidi Bel-Abbes, Algeria	ICEPS Lab. 22000 Sidi Bel-Abbes, Algeria
	Contact e-mail: hafid.semmah@yahoo.fr

To cite this article:

Khenfar, N., & Semmah, A. (2025). Performance improvement of predictive direct power control of a unified power quality conditioner. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 38,* 121-134.