Optimizing Power Quality: Simulation of UPQC Integrated PV with Comprehensive Reliability and Performance Analysis

Zakaria REGUIEG * ‡, Ismail BOUYAKOUB *, Fayçal MEHEDI *, Fatiha BOUHADJI*

* Laboratoire Génie Electrique et Energies Renouvelables (LGEER), Faculty of Technology, Hassiba Benbouali University of Chlef, Chlef 02000, Algeria

(z.reguieg@univ-chlef.dz, i.bouyakoub@univ-chlef.dz, f.mehedi@univ-chlef.dz, f.bouhadji@univ-chlef.dz)

‡ Corresponding Author; Zakaria REGUIEG, Chlef, Algeria,

Tel: +213541126997, z.reguieg@univ-chlef.dz

Received: 14.03.2024 Accepted:30.03.2024

Abstract- The integration of Photovoltaic (PV) systems with a Unified Power Quality Conditioner (UPQC) is examined in this presentation. Shunt and series voltage compensators linked back-to-back with a common dc-link compose the PV-UPQC. The series active power filter ensures the maintenance of the desired magnitude without distortion. Meanwhile, the shunt active power filter injects harmonic currents into the grid with equal amplitude and opposite phase, obtained by utilizing the PQ theory technique for shunt APF control and the Unit Vector Template Generation (UVTG) approach for series APF control. The study reveals promising results in terms of improved power quality, harmonics reduction, and effective voltage stabilization.

Keywords: UPQC, Power Quality, Harmonics, PV systems.

1. Introduction

Power quality (PQ) is really an important issue in the power systems because it affects how well sensitive machines work in industries and networks. With all the electronic devices we use today, PQ matters even more. Some modern machines can break or stop working if the power isn't good. That's why it's important to pay attention to PQ, especially for machines that can easily be affected by power problems.

In summary, the simulation results underscore the UPQC's efficiency in optimizing power quality, validating its potential application in real-world scenarios with PV integration, nonlinear loads, and dynamic load variations.

In today's world, the widespread usage of non-linear and delicate devices relying on power electronics within distribution systems has led to an increase in power quality issues [1]. These problems encompass voltage and current harmonics, voltage flickers and current imbalances, among others [2]. Such power system complications, like voltage sag/swell, can trigger malfunctions in digital devices and other sensitive loads [3]. Recent advancements in power quality enhancement techniques have spotlighted the UPQC as a comprehensive solution for voltage and current challenges [4,5]. This innovative concept was first introduced in 1998, with initial experimental results presented [6].

The UPQC comprises interconnected series and shunt Active Power Filters (APF), linked through a shared dc link capacitor [7]. The shunt APF works in parallel with the load, the shunt active power filter injects harmonic currents into the grid with equal amplitude and opposite phase [8,9], while the series APF, connected to the power source, maintains load terminal voltage stability [10]. Through the injection of compensating currents, the UPQC negates harmonics and stabilizes voltage [11,12]. It continuously senses load terminal voltage and current, utilizing a control algorithm to generate compensating currents [13]. The UPQC proves remarkably efficient in enhancing power quality, reducing losses, and boosting system efficiency. Its applications extend to industrial and commercial sectors where a consistent and high-quality power supply is paramount for the reliable operation of equipment in the present era [14].

PV systems harness solar energy to generate electricity, playing a critical role in sustainable energy solutions [15]. By using semiconductor materials, PV panels convert sunlight into electrical energy, contributing to clean, renewable energy sources [16].

The integration of a UPQC with PV systems improves their efficiency and reliability [17,18]. This synergy enables optimal use of clean energy, alleviates power quality issues, and ensures a stable and constant power supply by actively compensating for voltage fluctuations and harmonics in the power grid [19,20]. In [21], The integration of PV and battery-storage systems with the UPQC addresses power quality issues effectively. Through this method, significant improvements are observed in reducing total harmonic distortion (THD) and voltage fluctuations, consequently enhancing power factor. In [22], the author explores the use of UPQC to effectively tackle power quality issues within the grid and mitigate harmonics caused by non-linear loads.

This paper presents the design and performance evaluation of a three-phase PV-UPQC. The research examines the dynamic behavior of the PV-UPQC, taking into account grid voltage fluctuations and changes in nonlinear loads. Specifically, the load utilized consists of an uncontrolled bridge rectifier connected to a voltage-fed load.

2. Design of Proposed System

2.1. UPQC Control Strategy

In the case of voltage sag/swell or fluctuations, the series compensation devices known as Dynamic Voltage Restorer (DVR) provide the load with an interrupted voltage supply. The shunt APF is employed to address various current-related issues, including power factor enhancement, reactive power compensation, harmonic current compensation, and load imbalance correction. Conversely, the series APF is linked to the line through a series transformer. Additionally, Figure 1 illustrates the general structure of UPQC.

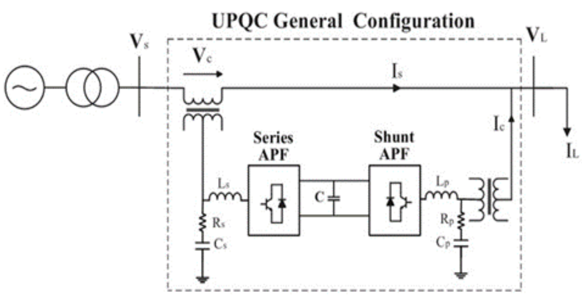


Fig. 1. General structure of UPQC in the network

2.1.1 Control of Series APF

Achieving sinusoidal and balanced load voltage (VL_{abc}) with the necessary strength entails employing an inverter configured with the correct voltage setting between the Point of Common Coupling (PCC) and the load. This inverter injects voltages opposing the imbalances and distortions present in the source voltage, effectively nullifying them. Consequently, the load voltage is kept balanced, ensuring a consistent magnitude without distortion [23].

UVGT Method involves calculating the three-phase supply voltages, Vsa, Vsb, and Vsc, which are then multiplied by *k=1/Vm.*

$$V_m = \sqrt{\frac{2}{3}\left(V_{sa}^2 + V_{sb}^2 + V_{sc}^2\right)} \tag{1}$$

A phase-locked loop (PLL) is utilized to generate sinusoidal unit vectors (Ua, Ub, Uc) by extracting the transformation angle (ωt) and synchronizing the supply voltage as described below:

$$U_a = \sin(wt)\,, \quad U_b = \sin\left(wt - \frac{2\pi}{3}\right), \quad U_c = \sin\left(wt + \frac{2\pi}{3}\right) \tag{2}$$

Next, by comparing the sinusoidal unit vectors (Ua, Ub, and Uc) to *Vm*, the load reference voltages (V_{Labc}^{*}) are generated as follows:

$$V_{Labc}^{*} = V_{Lm}^{*} * U_{abc} \tag{3}$$

The modulation unit receives the measured load voltages (*Vla*, *Vlb*, and *Vlc*) and the load reference voltages in order to generate switching pulses (S1 to S6) that activate the DC/AC inverter's switches. The Series APF control diagram based on the UVGT approach is shown in Figure 2.

Functioning of this hysteresis controller relies on the error signal produced when comparing the load's reference voltage and the instantaneous load voltage signals [24].

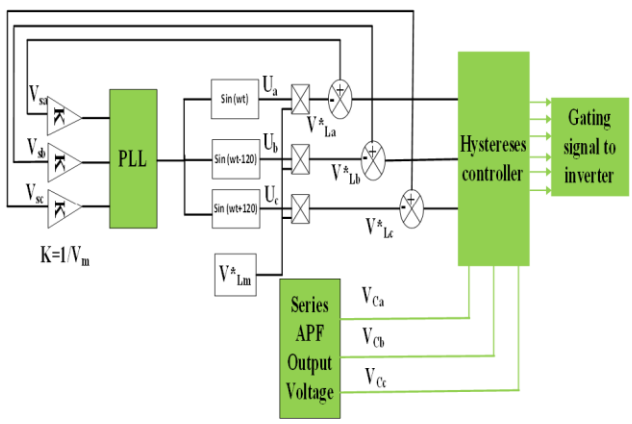


Fig. 2. Series converter controller employing UVTG technique

2.1.2 Control of Shunt APF

A key factor in improving the efficiency and accuracy of shunt active power filters is the estimation of harmonic extraction. The reference current can be found using either time domain analysis or frequency domain analysis. Time domain analysis uses circuit analysis and algebraic transformations to decrease computation and speed up control procedures. However, frequency domain analysis requires a large amount of processing memory and is more complex.

The selection of a control method for APF requires careful consideration. In this context, the theory of Instantaneous Active and Reactive Power, often known as PQ theory, holds significant importance. This theory is utilized to identify harmonic current (in the case of shunt APF) and harmonic voltage (in the case of series APF), along with various other crucial time-domain control techniques [25].

Using MATLAB/Simulink for simulation, this study presents the P-Q theory in the time domain. The 0-α-β rotating coordinate system is created by applying a Clarke transformation to the a-b-c stationary reference coordinate system. Source voltages and currents are transformed into 0-α-β components through this transformation, as shown in Figure 3's block diagram representation.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

The system under study in this research is a three-phase, three-wire setup without a zero-sequence component. The system's voltages and currents are represented by the symbols v0, vα, and vβ in the 0-α-β coordinate system, and by the symbols ia, ib, and ic in the a-b-c coordinate system. In the α-β coordinate system, the complex sum of the active and reactive powers (P and Q) is stated as follows:

$$\begin{aligned} p &= V_\alpha i_\alpha + V_\beta i_\beta \\ q &= V_\alpha i_\beta - V_\beta i_\alpha \end{aligned} \tag{6}$$

Q stands for the reactive power, and P stands for the active power.

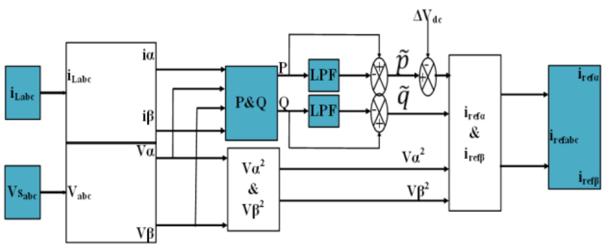


Fig. 3. Shunt converter controller employing PQ theory

In the event of nonlinear loads, the instantaneous active and reactive power components are divided into their AC and DC components. The DC component ($\bar{p}$) denotes the basic voltage and current components, which show how power is transferred from the source to the load. In the meantime, the energy transferred between the source and the load is shown by the AC component ($\tilde{p}$). A high-order low-pass filter is used to extract the instantaneous real power's average DC component. The Q, or instantaneous reactive power component, identifies the fundamental and harmonic components that are responsible for energy flow between load phases.

$$p = \bar{p} + \tilde{p} \quad and \quad q = \bar{q} + \tilde{q}$$

Both the total reactive power (Q) and the AC component ($\tilde{p}$) of active power are required to produce harmonic reference currents. To compensate for the voltage source inverter switching losses and preserve the DC-link voltage, the shunt active power filter draws a tiny amount of real power from an external power source or a three-phase AC source. After measuring the AC component ($\tilde{p}$) and calculating the compensating reference currents, an inverse transformation is performed to translate the results into the a-b-c coordinates.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} + \frac{1}{\Delta}\begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} 0 \\ \bar{q} \end{bmatrix} + \frac{1}{\Delta}\begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix}$$

$$\text{with : } \Delta = V_\alpha^2 + V_\beta^2 \tag{7}$$

Thus, the reference current will be calculated by the relationship:

$$\begin{bmatrix} i_{ref\ \alpha} \\ i_{ref\ \beta} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{8}$$

Applying the inverse transformation, we can write:

$$\begin{bmatrix} i_{ref\ a} \\ i_{ref\ b} \\ i_{ref\ c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ref\ \alpha} \\ i_{ref\ \beta} \end{bmatrix} \tag{9}$$

2.2. Modelling of Solar PV Systems

In the upcoming section, we will delve into the modeling of the solar panel, One of two diode models or a single diode model can be used to explain the equivalent circuit of the PV system, as shown in Figure 4. Compared to the double diode model, the single diode model is preferred due to its ease of use and less need for parameter evaluations [26]. Consequently, the single diode model is commonly adopted and is the focus of this study. For a single diode PV system with series and shunt resistance represented by Rs and Rsh respectively, the output current can be expressed as shown in equations (10) and (11).

$$I_{PV} = I_{Ph} - I_{d0}\left[esp\left(\frac{q}{nKT}V_{do}\right) - 1\right] - \left(V_{do}\frac{V_{PV} + R_S I_{PV}}{R_{Sh}}\right) \tag{10}$$

where I_{PV} = PV module current, I_{d0} = reverse saturation current of diode, V_{do} = the thermal voltage.

$$V_{PV} = V_{do} - R_S I_{PV} \tag{11}$$

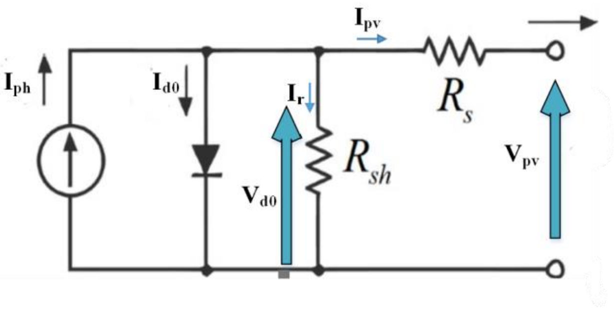


Fig.4. Solar Panel Modelling

2.3. Maximizing Power Output with INC

The energy output of PV cells is primarily affected by their sensitivity to changes in irradiance. Due to the fluctuating conditions of solar irradiance and temperature, it's crucial to continuously monitor and optimize the available maximum power of the PV cells. This is achieved through effective control of a commonly utilized boost converter, employing the Maximum Power Point Tracking (MPPT) technique. The core principle of this tracking method revolves around extracting the maximum power from the PV panels utilizing incremental conductance (INC) algorithms [27–29].

The INC algorithm is a crucial technique utilized within MPPT systems for optimizing PV power generation. Its primary objective is to dynamically regulate the operational point of the PV system, ensuring maximal power output amidst varying irradiance and temperature conditions. Below is a simplified outline of the INC algorithm's steps:

➢ Measure the current (I) and voltage (V) of the PV system.

➢ Calculate the incremental conductance (dP/dV) utilizing the current and voltage measurements.

➢ Compare the incremental conductance with the reference conductance.

➢ Slightly adjust the voltage:

- If the incremental conductance is higher than the reference, decrease the voltage.

- If the incremental conductance is lower than the reference, increase the voltage.

By iteratively adjusting the voltage based on the comparison between the incremental conductance and the reference conductance, the INC algorithm enables the PV system to efficiently track and extract maximum power from varying environmental conditions.

3. Simulation Results

The simulation analysis involves a three-phase source providing 230 V at 50 Hz to power a non-linear load comprising a thyristor converter connected to an RL circuit. Two distinct RL circuits are considered for the loads: the first load has parameters R1 = 58 Ω and L1 = 20mH, while the second load has parameters R2 = 300Ω and L2 = 20mH.

In this study, MATLAB/Simulink is employed to explore the application of the 3Phase-3Wire UPQC approach. This approach addresses prevalent issues such as voltage sag/swell, voltage dip, short circuit, and non-linear loads in distribution networks. Specifically, control techniques tailored for UPQC operation with non-linear loads are investigated in these scenarios.

In Figure 5, during a voltage sag that lasts from 0.7 to 0.8 seconds, the voltage is injected by the UPQC's series component to stabilize the load voltage at the load terminals. Similarly, in Figure 6, the UPQC injects voltage to maintain constant voltage at the load terminals when a voltage swell occurs between 1.3 and 1.4 s.

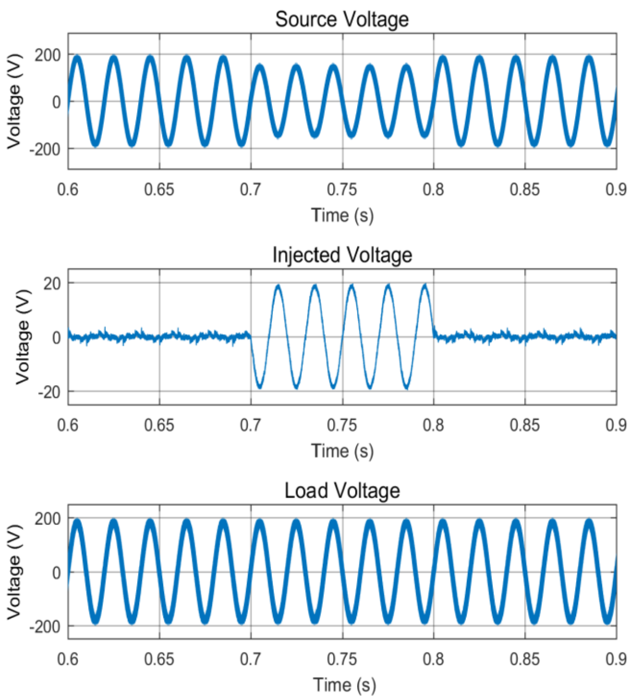


Fig.5 source voltage, injected voltage, and load voltage during voltage sag

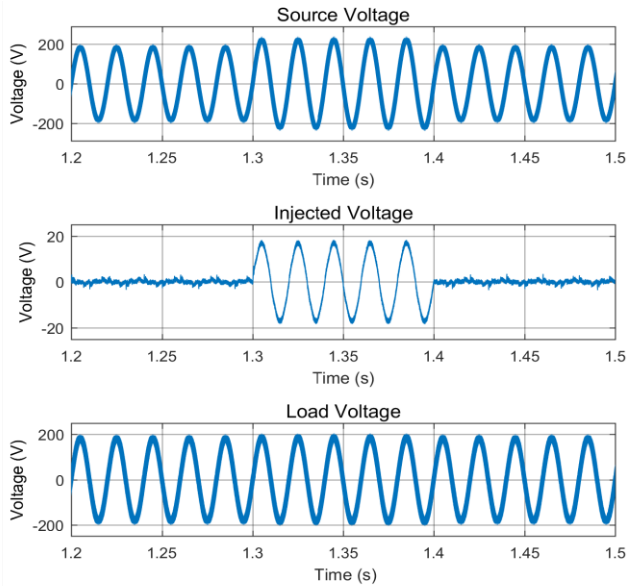


Fig. 6. source voltage, injected voltage, and load voltage during voltage swell

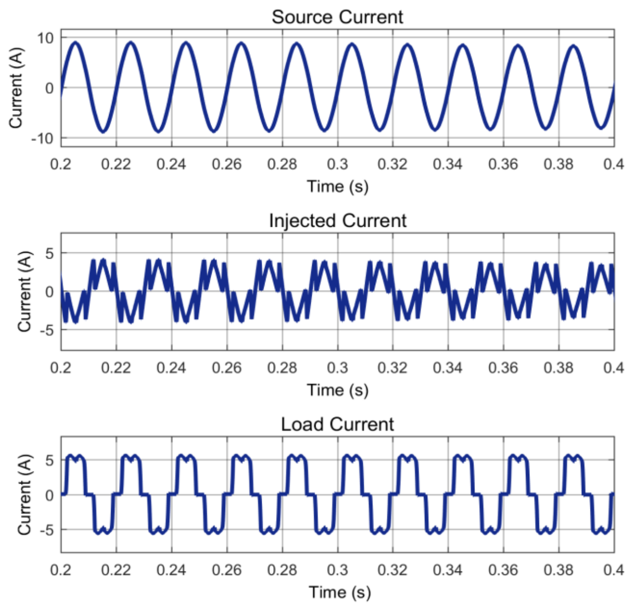


Fig. 7. Source Current, Injected Current, and Load Current During Nonlinear Load

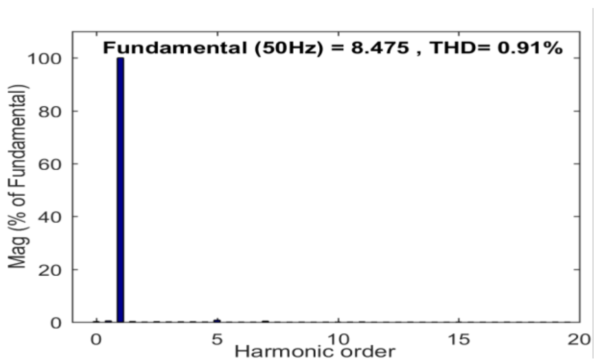


Fig. 8. THD of the Source Current

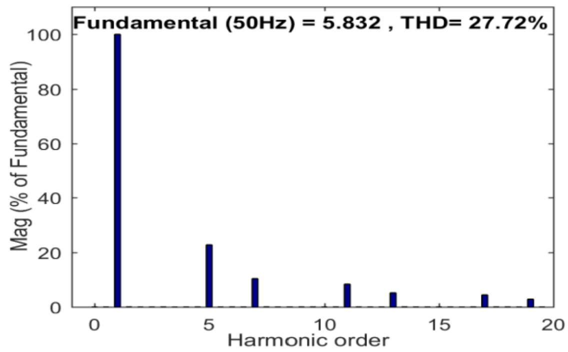


Fig. 9. THD of the Load Current

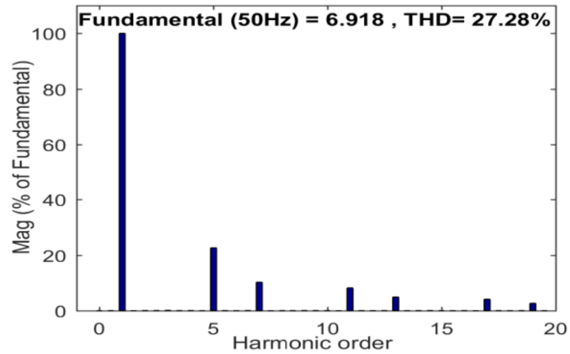


Fig. 10 THD of the Second Load Current

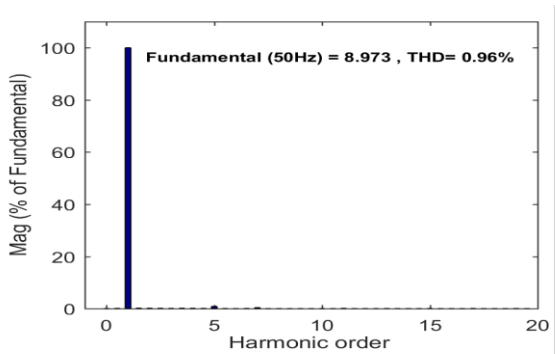


Fig. 11. THD of the Source Current under the Application of the Second Non-linear Load

In Figure 7, the non-linear load (NL) generates harmonics at the load side. The shunt part of the UPQC injects harmonic current with the same amplitude but opposite phase to mitigate harmonics at the source side.

In Figure 8, The source current in the case study has a THD of 0.91%. In addition, Figure 9 shows the THD of the NL, which is 27.72% higher than the international IEEE standard.

The source current in the case study has a THD of 0.91%. In addition, Figure 9 shows the THD of the NL, which is 27.72% higher than the worldwide IEEE norm.

The source current in the case study has a THD of 0.91%. In addition, Figure 9 shows the THD of the NL, which is 27.72% higher than the worldwide IEEE norm.

At 0.5 s in Figure 10, we observe a change in the NL to assess the robustness of the UPQC. The filter injects current directly to maintain THD within international standards, showcasing its adaptability to load variations.

Figures 11 and 12 display the THD of the second NL and the source current when this load variation is applied.

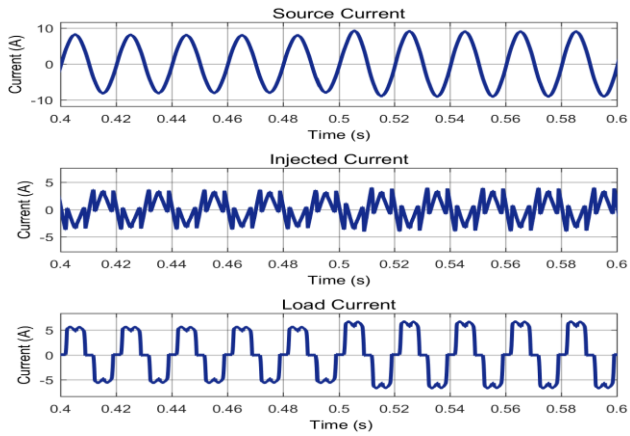
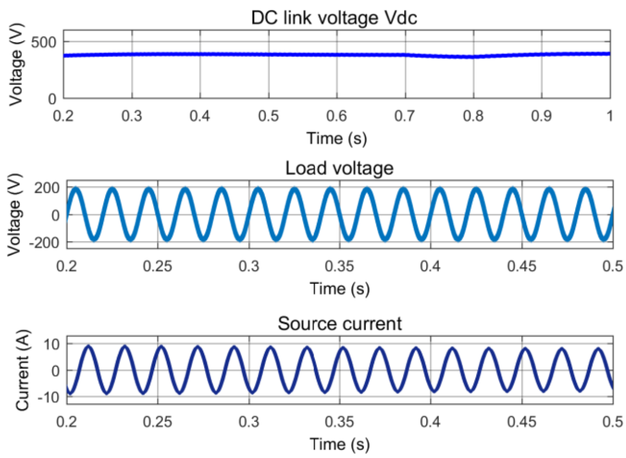


Fig. 12. Source Current, Injected Current, and Load Current During Nonlinear Load Variation



Fi

Fig. 13. DC Bus Voltage, Load Voltage, and Source Current

Figure 13 presents the DC bus voltage, load voltage, and source current, demonstrating the stabilization of the DC bus and the sinusoidal waveform of the voltage and current.

4. Conclusion

The study highlights how well PV and the UPQC work together. Power from the PV array is efficiently absorbed by the shunt compensator, which also reduces load current harmonics. In addition, the series compensator addresses grid-side power quality issues, including voltage sags and swells.

Acknowledgments

The authors thank the “Ministère de l’Enseignement Supérieur et de la Recherche Scientifique” of Algeria for supporting the present work.

References

[1] N. Abas, S. Dilshad, A. Khalid, M. S. Saleem, and N. Khan, “Power quality improvement using dynamic voltage restorer,” IEEE Access, vol. 8, pp. 164325–164339, 2020.

[2] S. Das, H. M. Ishrak, M. M. Hasan, and M. A. Kabir, “Empirical analysis of power quality using UPQC with hybrid control techniques,” Results Eng., vol. 20, no. October, p. 101527, 2023.

[3] M. Khaleel, Z. Yusupov, M. Elmnifi, T. Elmenfy, and Z. Rajab, “Assessing the Financial Impact and Mitigation Methods for Voltage Sag in Power Grid,” Int. J. Electr. Eng. Sustain., vol. 1, no. 2, pp. 10–26, 2023.

[4] K. Sabzevari, “Low-voltage ride-through capability in a DFIG using FO-PID and RCO techniques under symmetrical and asymmetrical faults,” Sci. Rep., vol. 13, no. 1, pp. 1–21, 2023.

[5] J. D. Vidal Leon, J. Ignacio Candela, and P. Rodriguez, “Unified Power Quality Conditioner with Energy Storage based on Active Transformer,” 9th Int. Conf. Renew. Energy Res. Appl. ICRERA 2020, pp. 242–247, 2020.

[6] D. Çelik and H. Ahmed, “Enhanced control of superconducting magnetic energy storage integrated UPQC for power quality improvement in EV charging station,” J. Energy Storage, vol. 62, no. January, p. 106843, 2023.

[7] S. Devassy and B. Singh, “Design and Performance Analysis of Three-Phase Solar PV Integrated UPQC,” IEEE Trans. Ind. Appl., vol. 54, no. 1, pp. 73–81, 2018.

[8] D. K. Dash and P. K. Sadhu, “A Review on the Use of Active Power Filter for Grid-Connected Renewable Energy Conversion Systems,” Processes, vol. 11, no. 5, 2023.

[9] W. Rohouma, R. S. Balog, M. M. Begovic, and A. A. Peerzada, “Use of D-STATCOM for Solid State LED Lamp Harmonic Power Mitigation,” 10th Int. Conf. Smart Grid, icSmartGrid 2022, pp. 149–154, 2022.

[10] A. Alhatim, F. Tahir, and A. N. Alsammak, “Optimization of Power Quality Using the Unified Power Quality Conditioner (UPQC) with Unbalanced Loads,” Al-Rafidain Eng. J., vol. 27, no. 2, pp. 101–109.

[11] A. Shirole, P. Biswa, S. P. Shukla, and D. Sharma, "Power Quality Issues Modelling and Simulation of UPQC for Mitigating Power Quality Issues," 2023.

[12] G. S. Rao, B. S. Goud, and C. R. Reddy, "Power quality improvement using ASO technique," 9th Int. Conf. Smart Grid, icSmartGrid 2021, pp. 238–242, 2021.

[13] R. S. Pawar, S. P. Gawande, R. N. Nagpure, and M. A. Waghmare, "Modified instantaneous symmetrical component algorithm-based control for operating electric spring in active power filter mode," IET Power Electron., vol. 12, no. 7, pp. 1730–1741, 2019.

[14] P. Kurukuri, "Fuzzy Logic Controller Based Unified Power Quality Conditioner (UPQC) By Mitigation of Power Quality Problems Fuzzy Logic Controller Based Unified Power Quality Conditioner (UPQC) By Mitigation of Power Quality Problems," Int. J. Advenced Technol. Inov. Res., vol. 09, no. September, pp. 16–22, 2018.

[15] A. Ranjan and J. Choudhary, "Enhancement of power quality in grid-connected HRES using UPQC with self-improved Battle Royal Optimizer in IEEE 14 bus system," Eng. Res. Express, vol. 5, no. 4, pp. 0–26, 2023.

[16] S. Rabah, A. Zaier, J. Lloret, and H. Dahman, "Efficiency Enhancement of a Hybrid Sustainable Energy Harvesting System Using HHHOPSO-MPPT for IoT Devices," Sustain., vol. 15, no. 13, pp. 1–28, 2023.

[17] M. M. Tounsi, B. Meliani, N. Benaired, and F. Djaafar, "Fuzzy logic controller of photovoltaic panel-unified power quality conditioner with voltage compensation and stability," Int. J. Power Electron. Drive Syst., vol. 14, no. 1, pp. 577–588, 2023.

[18] G. Mohanbabu, G. S. Babu, and E. V. Sagar, "An Artificial Intelligent Hybrid Controller for Solar and Battery Fed Five-Level UPQC for Power Quality Improvement," Internatıonal journal of renewable energy research, vol. 14, no. 1, pp. 1–13, 2024.

[19] M. Khaleel, Z. Yusupov, Y. Nassar, H. J. El-khozondar, A. Ahmed, and A. Alsharif, "Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems," e-Prime - Adv. Electr. Eng. Electron. Energy, vol. 5, no. August, p. 100223, 2023.

[20] R. Kannan, B. Krishnan, K. Porkumaran, S. Prabakar, I. Elamvazuthi, and K. Srinivasan, "Power Quality Improvement Using UPQC for Grid Interconnected Renewable Energy Sources," Int. Conf. Intell. Adv. Syst. Enhanc. Present a Sustain. Futur. ICIAS 2021, pp. 1–6, 2021.

[21] K. Srilakshmi, K. Krishna Jyothi, G. Kalyani, and Y. Sai Prakash Goud, "Design of UPQC with Solar PV and Battery Storage Systems for Power Quality Improvement," Cybern. Syst., vol. 0, no. 0, pp. 1–30, 2023.

[22] M. A. Mansor, K. Hasan, M. M. Othman, S. Z. B. M. Noor, and I. Musirin, "Construction and Performance Investigation of Three-Phase Solar PV and Battery Energy Storage System Integrated UPQC," IEEE Access, vol. 8, pp. 103511–103538, 2020.

[23] A. Y. Qasim, F. R. Tahir, and A. N. B. Alsammak, "Voltage Sag, Voltage Swell and Harmonics Reduction Using Unified Power Quality Conditioner (UPQC) Under Nonlinear Loads," Iraqi J. Electr. Electron. Eng., vol. 17, no. 2, pp. 140–150, 2021.

[24] G. Venkata Anjani Kumar and M. D. Reddy, "Mitigation of Grid Current Harmonics by ABC-ANN based Shunt Active Power Filter," J. Adv. Res. Appl. Sci. Eng. Technol., vol. 33, no. 1, pp. 285–298, 2023.

[25] N. A. Gajjar, "A novel control of grıd tıed pv- dstatcom system," Thesis Ph.D, Gujarat Technological University, September, 2023.

[26] E. V. H. Udoka, K. U. Umaru, E. Edozie, R. Nafuna, and N. Yudaya, "The Differences between Single Diode Model and Double Diode Models of a Solar Photovoltaic Cells: Systematic Review," J. Eng. Technol. Appl. Sci., vol. 5, no. 2, pp. 57–66, 2023.

[27] S. Chtita, A. Derouich, S. Motahhir, and A. EL Ghzizal, "A new MPPT design using arithmetic optimization algorithm for PV energy storage systems operating under partial shading conditions," Energy Conversion and Management, vol. 289, pp. 117197, 2023.

[28] K. Bataineh, "Improved hybrid algorithms-based MPPT algorithm for PV system operating under severe weather conditions," IET Power Electronics., vol. 12, no. 4, pp. 703-711, 2019.

[29] M. Ahmad, A. Numan, and D. Mahmood, "A Comparative Study of Perturb and Observe (P&O) and Incremental Conductance (INC) PV MPPT Techniques at Different Radiation and Temperature Conditions," Eng. Technol. J., vol. 40, no. 2, pp. 376–385, 2022.