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Contribution of using a photovoltaic unified power quality conditioner in power quality improvement

Introduction. *With the increasing complexity of power systems and the integration of diverse energy sources, issues such as voltage sags, swells, and signal distortions have emerged as critical challenges. These power quality problems can result in equipment malfunction, production downtime, and financial losses for industries, as well as inconvenience and potential damage to electrical appliances in households. There is an urgent need for enhanced system efficiency.* ***Methods.*** *This objective is effectively achieved through the utilization of the newly proposed power theory, which is rooted in solar photovoltaic (PV) control, in conjunction with the Unified Power Quality Conditioner (UPQC).* ***Purpose.*** *The proposed method incorporates a modified synchronous reference frame scheme, coupled with a phase-locked loop mechanism. This control strategy enables the UPQC to effectively mitigate power quality issues.* ***Novelty.*** *PV-UPQC is utilized to uphold power integrity in the presence of diverse current and voltage distortions. This device, known as a multi-objective power conditioning apparatus, serves the purpose of maintaining power quality. PV-UPQC incorporates both a shunt and series voltage source converter, which are interconnected through a shared DC-link. Additionally, the PV system is interconnected at the DC-link of the UPQC in order to supply power to the load.* ***Results****. In this study, a novel approach is presented for controlling the UPQC, aiming to address power quality concerns such as unbalanced grid voltage and harmonic distortions and enabling us to control active and reactive power.* References 16, tables 2, figures 15.

Key words: **unified power quality conditioner, photovoltaic system, phase lock loop, reactive power, harmonics.**

Вступ*. Зі зростанням складності енергетичних систем та інтеграцією різних джерел енергії такі проблеми, як провали напруги, стрибки напруги та спотворення сигналу, стали критичними проблемами. Ці проблеми з якістю електроенергії можуть призвести до збоїв у роботі обладнання, простоїв виробництва та фінансових втрат для промисловості, а також до незручностей та потенційного пошкодження електроприладів у домашніх господарствах. Існує гостра необхідність підвищення ефективності системи.* ***Методи****. Ця мета ефективно досягається за рахунок використання нещодавно запропонованої теорії енергетики, що базується на управлінні сонячними фотоелектричними (PV) системами, у поєднанні з єдиним перетворювачем якості електроенергії (UPQC).* ***Мета****. Пропонований метод включає модифіковану схему синхронної системи координат у поєднанні з механізмом фазового автопідстроювання частоти. Ця стратегія керування дозволяє UPQC ефективно усувати проблеми з якістю електроенергії.* ***Новизна****. PV-UPQC використовується для підтримки цілісності електроживлення за наявності різних спотворень струму та напруги. Цей пристрій, відомий як багатоцільовий пристрій стабілізації потужності, служить підтримці якості електроенергії. PV-UPQC включає як шунтуючий, так і послідовний перетворювач напруги, які з'єднані між собою через загальне коло постійного струму. Крім того, фотоелектричну систему підключено до ланки постійного струму UPQC для подачі живлення на навантаження.* ***Результати****. У цьому дослідженні представлений новий підхід до управління UPQC, спрямований на вирішення проблем якості електроенергії, таких як незбалансована напруга мережі та гармонічні спотворення, що дозволяє контролювати активну та реактивну потужність.* Бібл. 16, табл. 2, рис. 15.

Ключові слова: **єдиний стабілізатор якості електроенергії, фотоелектрична система, фазове автопідстроювання частоти, реактивна потужність, гармоніки.**

Introduction. Power electronic-based loads play a crucial and influential role in the propagation of harmonic currents within the electrical grid at the point of common coupling (PCC), serving as substantial contributors to this phenomenon [1, 2]. Voltage Source Converters (VSCs) are extensively utilized in various power quality (PQ) enhancement applications owing to their exceptional capacity to absorb or deliver reactive power, thereby providing enhanced versatility [1, 3]. Enhancing PQ is paramount for ensuring the dependability and efficiency of electrical systems, guaranteeing a stable and uninterrupted supply of electricity to meet the varied requirements of consumers [1, 2]. In the context of solar PV integration for PQ improvement, a combined utilization of photovoltaic (PV) systems and Unified Power Quality Conditioners (UPQC) has been implemented [3, 4]. This paper presents comprehensive research into the design and performance analysis of a three-phase Photovoltaic-Unified Power Quality Conditioner (PV-UPQC). To enhance dynamic performance during active current extraction an advanced Phase-Locked Loop (PLL) based Direct Current Control (DCC) theory approach is employed [5-7]. The proposed system offers numerous notable advantages, including seamless integration of clean energy generation and PQ enhancement. It achieves simultaneous improvements in both voltage and current quality, while significantly enhancing load current compensation through the utilization of DCC control of PV-UPQC [7-9]. Furthermore, the PV-UPQC operates to stabilize the system amidst a plethora of dynamic scenarios, encompassing voltage sags/swells, load unbalance, and variations in irradiation [10, 11]. To thoroughly evaluate the performance of the proposed system, extensive analysis is conducted under both dynamic and steady-state conditions, employing the MATLAB/Simulink, simulating real-world distribution system scenarios such as voltage sags/swells, load unbalances, and variations in irradiation.

System configuration of PV-UPQC and control strategy. The system is shown in Fig. 1 showcases the configuration block diagram of the considered setup. It comprises a shunt VSC and a series VSC, which are interconnected through a shared DC link capacitor. The shunt VSC is connected to the load side through interfacing inductors, while the series VSC is linked in series with the grid via coupling inductors, in order to facilitate the integration of the PV-UPQC system [4].

To facilitate the injection of the voltage signal generated by the series VSC, the PV-UPQC system uses a series transformer. The shunt VSC is connected at the

PCC on the load side, serving a dual role of compensating for load current harmonics and delivering PV power to the load [8, 12].

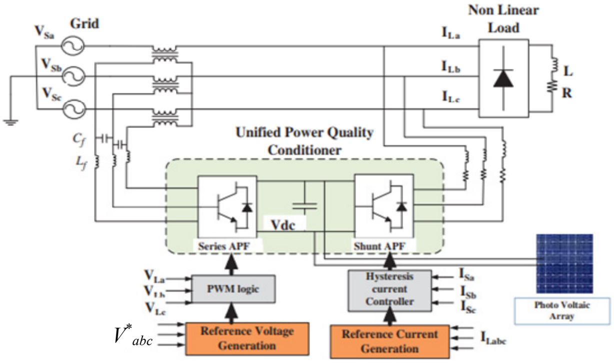


Fig. 1. General structure of PV-UPQC in grid

Series active power filter control. The series active power filter (APF) plays a crucial role in voltage compensation by determining the required voltage injection into the grid to achieve a sinusoidal voltage waveform with the correct magnitude and frequency [10]. The reference voltage V^*_{abc} is subtracted from the supply voltage, and the resulting voltage error is calculated and compared to the system's internal error voltage. The hysteresis voltage controller governs the switching pattern of the inverter, ensuring precise regulation of the output voltage of the series APF [11]. Figure 2 illustrates the fundamental schematic of a fixed hysteresis band (HB) voltage control. Whenever the sensed output signal deviates from the reference by a predetermined margin, a comparison is made between the instantaneous value of the output voltage and the reference voltage V^*_{abc}. Subsequently, the inverter is activated to minimize the discrepancy. Consequently, switching occurs each time the output voltage crosses the HB threshold. The output voltage signal of the series APF is provided by this control mechanism:

$$V_c = V_c^* + HB \quad \text{– in rising case;}$$

$$V_c = V_c^* - HB \quad \text{– in decreasing case.}$$

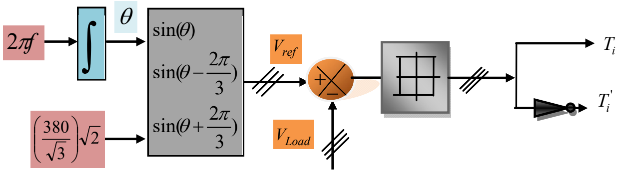
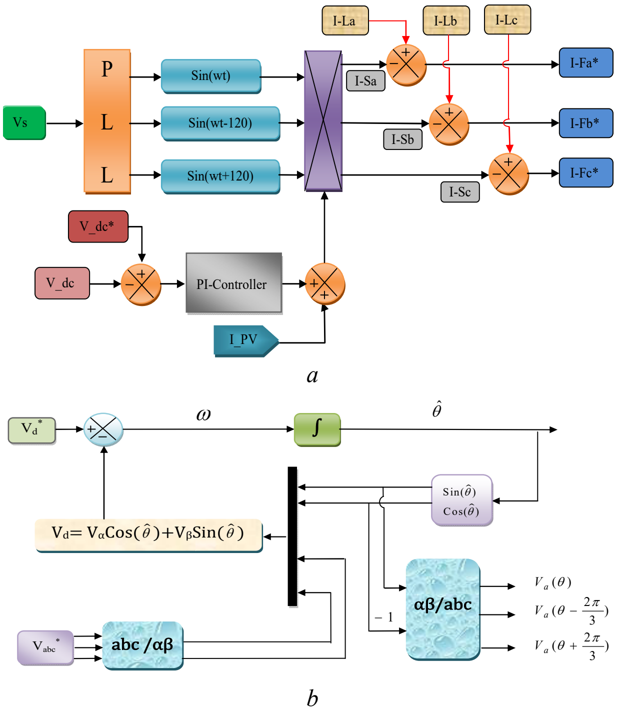


Fig. 2. Simplified model for fixed HB voltage control

Shunt APF control. Figure 3,*a* illustrates the fundamental principle of compensation of an APF controlled by DCC. The control architecture for the APF is designed to supply harmonic currents and compensate for reactive power in non-linear loads, alleviating the burden of supplying anything beyond the fundamental active current [9]. The objective of this identification strategy is to generate high-quality reference currents using a simplified algorithm. After calculating the 3 sinusoidal signals through the application of the PLL technique, as illustrated in Fig. 3,*b*, the output of the PI controller in the DC voltage regulation stage is utilized as the peak current (I_{sp}) [5-7]. This peak current can be multiplied by the sinusoidal signals to obtain the reference source currents, expressed in:

$$\begin{cases} i^*_{sa}(t) = I_{sp}\sin(\omega t); \\ i^*_{sb}(t) = I_{sp}\sin(\omega t - 120); \\ i^*_{sc}(t) = I_{sp}\sin(\omega t - 240). \end{cases} \tag{1}$$



a

b

Fig. 3. Model of DCC (*a*) and PLL mechanism (*b*)

In accordance with the diagram presented in Fig. 3, the source current at the PCC is represented as:

$$i_s(t) = i_L(t) - i_f(t)\,, \tag{2}$$

where $i_s(t)$, $i_L(t)$, $i_f(t)$ denote, in sequence, the instantaneous magnitudes of the source current, load current and filter current.

In the presence of a nonlinear load, the load current can be disintegrated into a fundamental component and harmonic components, which can be expressed through a Fourier series expansion in the following manner:

$$\begin{gathered} i_L(t) = \sum\nolimits_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n); \\ i_L(t) = I_1 \sin(\omega t + \phi_1) + \sum\nolimits_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n), \end{gathered} \tag{3}$$

where I_n and ϕ_n denote the magnitude and phase angle of the n^{th} harmonic current, while I_1 and ϕ_1 represent the magnitude and phase angle of the fundamental current. Moreover, the instantaneous load power $P_L(t)$ can be determined by the following:

$$P_L(t) = V_s(t) \cdot i_L(t)\,. \tag{4}$$

By utilizing (3) and (4), the load power can be rewritten as follows:

$$\begin{gathered} P_L(t) = V_m I_1 \sin^2(\omega t)\cos(\phi_1) + \\ + V_m I_1 \sin(\omega t)\cos(\omega t)\sin(\phi_1) + \\ + V_m \sin(\omega t)\sum\nolimits_{n=2}^{\infty} I_m \sin(n\omega t + \phi_n). \end{gathered} \tag{5}$$

Furthermore, the load power can be represented as:

$$P_L(t) = P_{fun}(t) + P_r(t) + P_h(t)\,, \tag{6}$$

where $P_{fun}(t)$, $P_r(t)$, $P_h(t)$ correspond, respectively, to the fundamental power (real power), reactive power and harmonic power consumed by the nonlinear load.

In an ideal compensation scenario, only the fundamental power needs to be provided by the source. The reactive and harmonic components are supplied by the active filter. By examining (5) and (6), it can be inferred that the absorbed fundamental power by the nonlinear load can be expressed as:

$$P_{fun}(t) = V_m I_1 \sin^2(\omega t)\cos(\phi_1) = V_s(t) i_s(t)\,. \tag{7}$$

Based on (7) after compensation the current supplied by the source is:

$$i_s(t) = \frac{P_{fun}(t)}{v_s(t)} = I_1\cos(\phi_1)\sin(\omega t) = I_{sm}\sin(\omega t)\,. \tag{8}$$

Taking into account certain losses in the inverter, the total peak current I_{sp} shown in Fig. 3 can be defined as:

$$I_{sp} = I_{sm} + I_{sl}\,, \tag{9}$$

where I_{sp}, I_{sm}, I_{sl} denote, respectively, the total peak current, the maximum source current and the inverter loss component.

In the DCC algorithm, the estimation of the peak current relies on the DC current at the output of the DC bus controller, and it can be expressed as:

$$I_{sp} = I_{dc}. \tag{10}$$

The three-phase reference currents of the filter can now be expressed as:

$$\begin{cases} i_{sa}^*(t) = I_{sp}^* \sin(\omega t); \\ i_{sb}^*(t) = I_{sp}^* \sin(\omega t - 120); \\ i_{sc}^*(t) = I_{sp}^* \sin(\omega t - 240). \end{cases} \tag{11}$$

PV system control. There are several maximum power point tracking (MPPT) control methods and techniques available in the literature. However, the most commonly used is Perturb and Observe (P&O) control [13] used in this work. This algorithm maximizes power output in solar energy systems through system perturbations and monitoring the effects on output power. It compares current and previous power values to determine the optimal perturbation direction for maximum power. It is a widely used and renowned algorithm in MPPT [13-16] (Fig. 4).

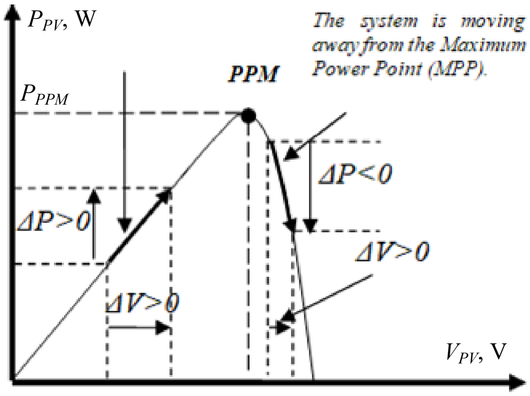


Fig. 4. Characteristic $P_{PV} = f\,(V_{PV})$ of a solar panel

Figure 5 shows the flowchart of P&O algorithm.

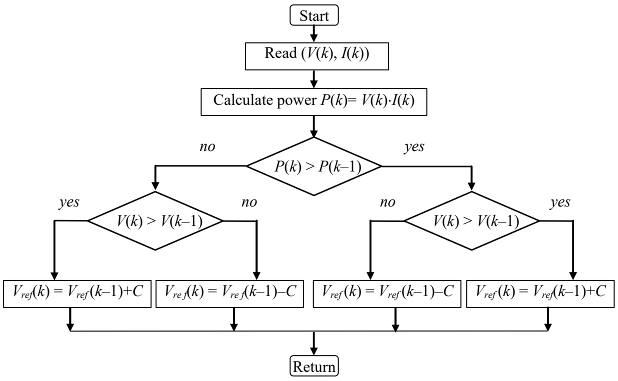


Fig. 5. P&O algorithm

Simulation results. The simulation parameters are detailed in Table 1.

Table 1

Parameters of simulation

Parameter	Value
Source voltage	380 V
Line frequency	50 Hz
Line impedance	$R_s = 0.01$ Ω, $L_s = 0.1$ H
DC voltage	700 V
DC capacitor	2.35 mF
Load impedance 1	$R = 90$ Ω, $L = 1$ mH
Load impedance 2	$R = 55$ Ω, $L = 50$ mH

After deciding which perturbations to apply to the grids such as: voltage sag, swell and variation load to test the response of our active filter, simulations were performed using MATLAB/Simulink. The disruptions follow the timeline shown below:

From 0 s to 0.2 s – UPQC.

From 0.2 s to 1.3 s – PV-UPQC is commissioned with 700 W/m^2.

From 0.4 s to 0.6 s – sag voltage (with 70 % of normal voltage).

From 0.6 s to 1 s – normal operation.

From 1 s to 1.2 s – swell voltage (with 120 % of normal voltage).

From 1.2 s to 2.3 s – normal operation.

From 1.3 s to 2 s – PV-UPQC commissioned with 1000 W/m^2.

1.65 s – another load is applied.

From 2 s to 2.3 s – UPQC.

All details are summarized in Table 2. These simulations were performed to analyze the behavior of the active filter under different operating conditions and disturbances.

Table2

Variations of voltage and load

Time, s	0–0.2	0.2–0.4	0.4–0.6	0.6–1	1–1.2	1.2–2.3	1.65–2.3
Voltage, pu	1	1	0.7	1	1.2	1	1
Load	Load 1						Load 2

Simulation results before using the PV-UPQC. Active and reactive powers transit from the green source to the load. This study encompasses 2 comprehensive tests to evaluate the performance of our system. In the first test, we conducted a simulation of the system involving a source and a non-linear load. Our observations revealed that the source dynamically provides active and reactive power in response to load variations, including voltage sag and swell. We meticulously explain the correlation between active and reactive power variations and changes in voltage and current, aligning them with the specific requirements of the load (Fig. 6). The Total Harmonic Distortion (THD) values are notably elevated in this case due to the presence of a non-linear load (Fig. 7).

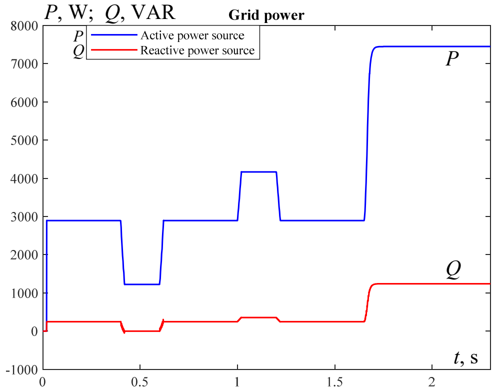


Fig. 6. Active and reactive power source

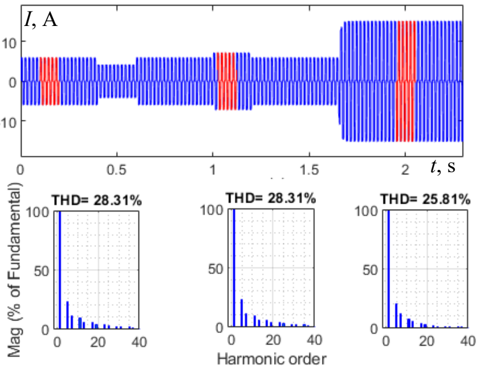


Fig. 7. Source current and its spectral analysis

Simulation results after using the PV-UPQC. The study is divided into 2 modes: the first mode is the exclusive use of an UPQC in the intervals [0–0.2] s and [2.1–2.3] s. The second mode involves using an UPQC in conjunction with a PV (PV-UPQC) generator between 0.2 s and 2.1 s, with a non-linear load variation at 1.65 s.

Figure 8 represents the variation of the irradiance on the PV system.

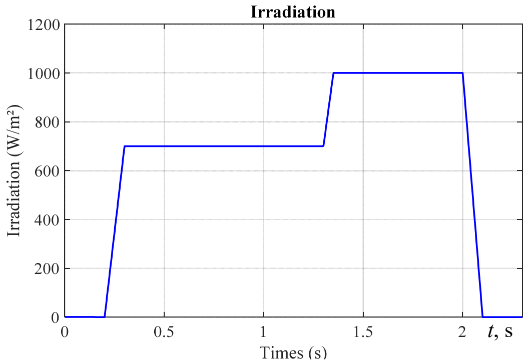


Fig. 8. Variation of irradiation

When the irradiance is zero, the source only provides active power equal to the power consumed by the load. The reactive power consumed by the load is handled by the UPQC (Fig. 9). This mode of operation is reflected in the voltage and current of the grid being in phase (Fig. 10).

The increase in irradiance is accompanied by a decrease in source current with reversed phases, signifying the grid's initiation of absorbing active power from the PV-UPQC (see Fig. 9, 10). Between 0.4 s and 0.6 s a deliberate voltage sag is applied, causing the voltage to drop to 0.7 times the nominal voltage. Source current flow intensifies to meet the load demand, as evidenced by Fig. 9, 10, highlighting the substantial contribution of the PV-UPQC in compensating for active power instead of relying solely on the source.

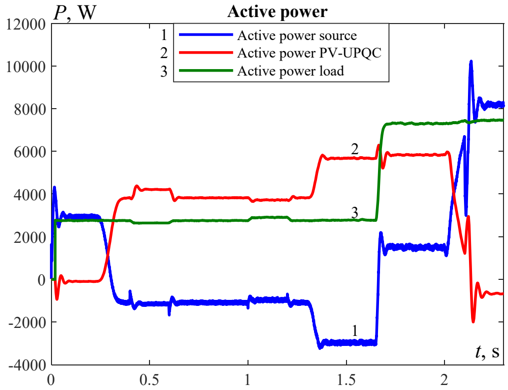


Fig. 9. Active power variation

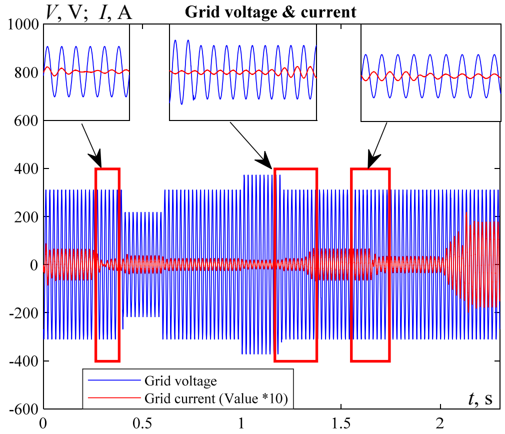


Fig. 10. Delay phase between grid voltage and current

The integration of PV-UPQC ensures optimized source current flow, effectively meeting load demand while minimizing losses and enhancing overall system efficiency. In contrast, during the time interval from 1 to 1.2 s, a voltage swell is introduced, resulting in the voltage rising to 1.2 times the nominal voltage, consequently, source current decreases.

Figures 9 – 11 illustrate the significant contribution of PV-UPQC in compensating for active power instead of relying solely on the source. At the instant 1.3 s, an increase in irradiation to 1000 W/m^2 leads to a subsequent rise in current value and, consequently, an increase in the active power of the PV-UPQC. However, the introduction of a new load at 1.65 s exceeds the capacity of the PV-UPQC to fully meet the load's power requirements, resulting in a portion of the source's power being utilized.

Figure 12 represents the evolution of the current injected by the PV-UPQC, which follows its reference accurately identified directly by the DCC method. We can see that in the absence of irradiance, the PV Fast Active Power (FAP) injects only harmonic currents. However, in the presence of irradiance, the PV-FAP injects both the PV current and the harmonic currents.

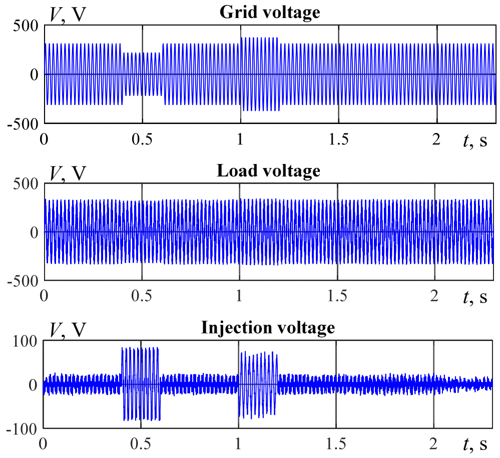


Fig. 11. Grid, load and injection voltage

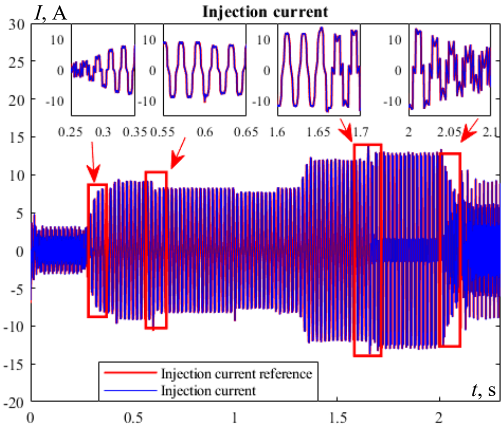


Fig. 12. Injection current of PV-UPQC and its reference

UPQC compensates reactive power through one of its main components, the shunt active power filter (SAPF). To compensate for reactive power, the SAPF injects a current into the system that is 180° out of phase with the reactive component of the load's current. This injected current interacts with the reactive power, effectively canceling it out and reducing the system's overall reactive power demand, as shown in Fig. 13. Thus reducing the system's reactive power demand and improving PQ.

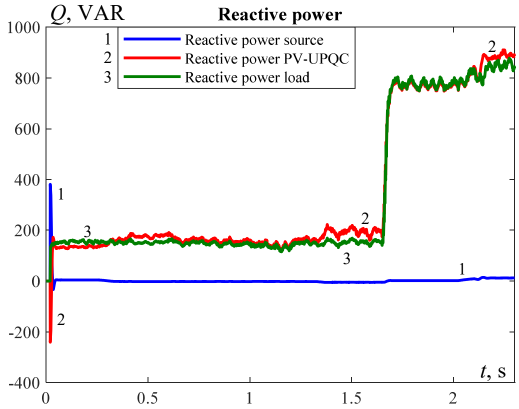


Fig. 13. Reactive power variation

UPQC-PV effectively reduces the THD of the current (Fig. 14).

Figure 15 demonstrates that DC bus voltage follows its reference after each interruption, which shows the effectiveness of the proposed controller.

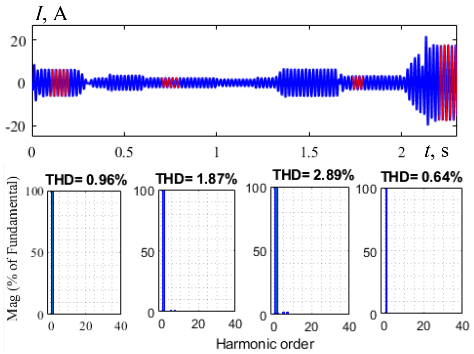


Fig. 14. Source current and its spectral analysis after using PV-UPQC

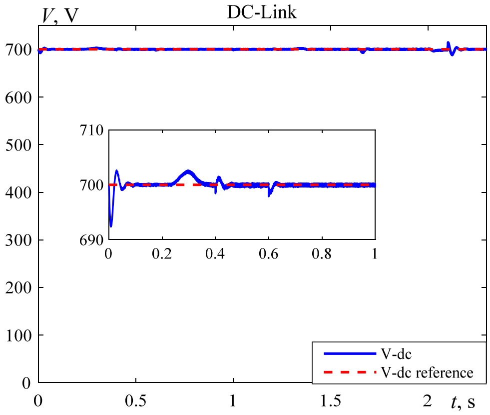


Fig. 15. DC bus V_{dc} and its reference

Conclusions. Photovoltaic-Unified Power Quality Conditioner (PV-UPQC) assumes a pivotal role in enhancing power quality. This paper underscores its valuable features, including its ability to improve instantaneous waveforms (both currents and voltages), mitigate voltage sags and swells, save active power, and compensate reactive power. These attributes are crucial for optimizing the utilization of electrical energy and reducing energy wastage.

Our proposed method involves employing the direct current control method for the parallel active power filter. This method enables real-time injection of harmonic currents equal in magnitude and opposite in phase to those absorbed by the nonlinear load. Additionally, for series active power filters, we utilize hysteresis control, which acts as a controllable voltage source and counters troublesome voltage variations such as sags and swells. This comprehensive control approach addresses multiple issues simultaneously, including the mitigation of voltage disturbances, improvement of current waveforms, compensation for reactive power, and utilization of solar energy when available (irradiation-based).

Finally, the positive results outlined in this paper affirm the effectiveness of the PV-UPQC device in enhancing the reliability and flexibility of energy systems. These benefits extend across a wide range of industrial and residential applications, thereby providing tangible advantages to users.

Conflict of interest. The authors declare that they have no conflicts of interest.

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