UDC 621.314 https://doi.org/10.20998/2074-272X.2024.6.06

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Power quality enhancement of grid-integrated solar photovoltaic system with unified power quality conditioner

Introduction. *To enhance the quality of power and ensure a consistent electricity supply, this study proposes the utilization of a unified power quality conditioner (UPQC) system integrated with solar photovoltaic (PV) technology. The innovation involves single DC-link connecting back-to-back voltage-compensating components arranged in series and shunt, forming the PV-UPQC. The shunt compensator utilizes energy from a PV array to address harmonics in the load current. The objective is to mitigate voltage dips and spikes by injecting voltage that is either in phase with or out of phase with the common coupling point through a series compensator. The method combines the benefits of generating renewable energy to enhance electrical quality. The* ***goal*** *of the paper is the power quality enhancement of grid-integrated solar PV system. The* ***novelty*** *of the proposed work consists of enhancement of grid-integrated solar PV system with UPQC. The purpose of integrating a UPQC into a grid-connected solar PV system is to enhance power quality by mitigating issues such as voltage fluctuations, harmonics and reactive power imbalance.* ***Methods.*** *The proposed topology is implemented in MATLAB/Simulink with grid-integrated solar PV system with UPQC.* ***Results****. Integrating UPQC with a grid-connected solar PV system yields substantial improvements in power quality. This includes effectively mitigating voltage fluctuations and harmonics, resulting in smoother operation and reduced disturbances on the grid.* ***Practical value.*** *The proposed topology has proven to be extremely useful for grid-integrated solar PV system with UPQC applications.* References 15, table 2, figures 9.
Key words: **grid integration, unified power quality conditioner, power quality, photovoltaic array.**

Вступ*. Для підвищення якості електроенергії та забезпечення безперебійного електропостачання пропонується використовувати систему уніфікованого стабілізатора якості електроенергії (UPQC), інтегровану із сонячною фотоелектричною (PV) технологією. Інновація включає одиночну лінію постійного струму, що з'єднує зустрічно-паралельні компоненти компенсації напруги, розташовані послідовно, і шунт, утворюючи PV-UPQC. Шунтуючий компенсатор використовує енергію від масиву PV батарей для усунення гармонік струму навантаження. Мета полягає в тому, щоб пом'якшити провали та стрибки напруги шляхом подачі напруги, яке або збігається по фазі із загальною точкою з'єднання, або не збігається по фазі з нею через послідовний компенсатор. Метод поєднує переваги генерації відновлюваної енергії підвищення якості електроенергії.* ***Метою*** *статті є підвищення якості електроенергії інтегрованої в мережу сонячної фотоелектричної системи.* ***Новизна*** *запропонованої роботи полягає у покращенні інтегрованої у мережу сонячної PV системи за допомогою UPQC. Метою інтеграції UPQC у мережеву сонячну PV систему є підвищення якості електроенергії за рахунок пом'якшення таких проблем, як коливання напруги, гармоніки та дисбаланс реактивної потужності.* ***Методи****. Запропонована топологія реалізована у MATLAB/Simulink з інтегрованою в мережу сонячною PV системою з UPQC.* ***Результати****. Інтеграція UPQC із підключеною до мережі сонячною PV системою дає суттєве покращення якості електроенергії. Це включає ефективне пом'якшення коливань напруги і гармонік, що призводить до більш плавної роботи і зменшення перешкод в мережі.* ***Практична цінність****. Запропонована топологія виявилася надзвичайно корисною для інтегрованої в мережу сонячної PV системи із застосуваннями UPQC.* Бібл. 15, табл. 2, рис. 9.
Ключові слова: **мережева інтеграція, уніфікований стабілізатор якості електроенергії, якість електроенергії, фотоелектрична батарея.**

Introduction. In contemporary times, digital, electronic, and nonlinear devices under the control of microprocessors find extensive applications in various industries. The incorporation of these technologies has become indispensable across diverse sectors. Such systems can lead to power quality problems such as voltage sag, voltage swell, flickering, harmonics, over-voltage, lower power factor, etc. Data errors, memory loss, automated restarts, uninterruptible power supply alarms, equipment failure, circuit failure, software corruption, and distribution network overheating are occurred at various systems due to poor power quality. The significance of power quality has grown in light of these issues. Sensitive loads such as hospitals particularly diagnostic equipment, and classrooms have been affected severely due to poor power quality. This heightened dependence on digital and electronic devices raises concerns about the quality of electricity supplied to these systems. Consequently, ensuring optimal power quality has become a pressing concern to avoid disruptions and potential damage to sensitive equipment. Batteries, fuel cells, and ultracapacitors have been used for custom power devices so far. Among the most significant power quality issues is voltage swell, encompassing challenges related to harmonics, transients, flicker, and interruptions [1–4]. Protecting sensitive and important loads requires addressing power quality and voltage disruptions. Custom power devices have emerged as the most effective and efficient technique to addressing and correcting for voltage disturbances in this industry, while other solutions have been offered. Electric vehicles, microgrids, distribution static compensators, high-power and moderate-voltage motors, microcontrollers, and grid-integrated or standalone systems are just a few of the many industrial applications where multilevel inverters (MLIs) play a significant role. They also play a pivotal role in diverse sectors, such as active power filters, photovoltaic (PV) systems, and more. The integration of PV systems with dynamic voltage restorer (DVR) leads to the simultaneous minimization of harmonics, voltage dips, and improvement of power factors, effectively meeting energy requirements. In the context of a PV-supplied DVR, the implementation of a 23-level MLI utilizing a rotating *d-q* reference frame controller [5–8] plays a crucial role. The amalgamation of PV with MLI DVR significantly enhances power quality by reducing instances of voltage sags and swells. The following features are listed below for improving power quality:

- there are just 3 DC sources and 12 switches (7 unidirectional and 5 bidirectional) throughout the entire 23-level MLI;
- the majority of switches can function at medium voltages because of their minimal voltage stress.

A power quality conditioner with shunt and series compensators can modify load voltage and preserve sinusoidal grid current at one power factor. Active power filters [3] come in 2 main varieties: shunt and series. Using the unified power quality conditioner (UPQC) in conjunction with a PV array might make the system energy-independent and environmentally friendly. Improved grid power quality, protection for critical loads from grid side disturbances, and enhanced converter capacity to ride over faults during transients are just a few of how the solar PV integrated UPQC excels above conventional grid-connected inverters. PV-UPQC control faces a significant challenge in creating the reference signal. Time-domain and frequency-domain approaches are the 2 main subcategories of reference signal generation techniques. Because real-time implementation calls for less processing, time-domain methods are frequently employed. Theories of instantaneous reactive power, synchronous reference frames, and instantaneous symmetrical components are the most often used approaches [9–11]. The main difficulty for the synchronous reference frame theory method is producing a *d*-axis current with a two-harmonic component. This becomes particularly prominent when uneven loads are present. The double harmonic component is removed using low-pass filtering techniques with incredibly low cut-off frequencies. As a result, dynamic performance is compromised. In this study, the primary load active current is obtained by filtering the *d*-axis current using a moving average filter (MAF). This provides the best attenuation without affecting the controller's bandwidth [11–14]. Lately, MAF has been used to synchronize the grid utilizing phase-locked loops and increase the performance of DC link controllers.

The goal of the paper is listed below for improving power quality enhancement of grid-integrated solar PV system:

- Power quality improvement and renewable energy generation together.
- Improving both current and voltage quality simultaneously.
- Better load current compensation as a result of *d-q* PV-UPQC's control using the MAF.

Using PV technology helps provide cleaner, greener power while lowering pollution. In the case of a grid outage, it can keep critical loads operating, improving dependability and tackling energy issues simultaneously.

Grid-integrated solar PV system with UPQC.

DVR setup for solar power input. Figure 1 shows the system's components, which include solar PV array, a three-phase, three-wire digital voltage regulator, a load, and a boost converter. A power source, a voltage-applying transformer, an LC filter, and a DC link capacitor make up the DVR. The second part of the PV system is the DVR equivalent circuit (Fig. 2). It includes both boost and maximum power point tracking controller. A voltage source V_{Comp} is established in the DVR circuit by connecting it to a load voltage V_L, another voltage source V_s and the impedances of the 2 sources (Z_S and Z_L). The current I_S divided in half at the point of common coupling (PCC) source: I_L, which stands for a sensitive load current, and I_{OT}, which stands for a different type of load current [15]. A voltage representation for PCC is V_G and DVR rectifies the voltage, which is V_{DVR}. By integrating the equivalent components of R_{DVR} and X_{DVR} with V_{DVR}, we can determine the resistance R and inductance L from the impedance ratings of the filter and injection transformer. There is an impedance of Z_S for the supply, Z_L for the load, and Z_{DVR} for the DVR. The voltage of a sensitive load is depicted as:

$$V_L(t) = V_{DVR}(t) + V_G(t) + Ri_L(t) + L\frac{di_L}{dt}. \quad (1)$$

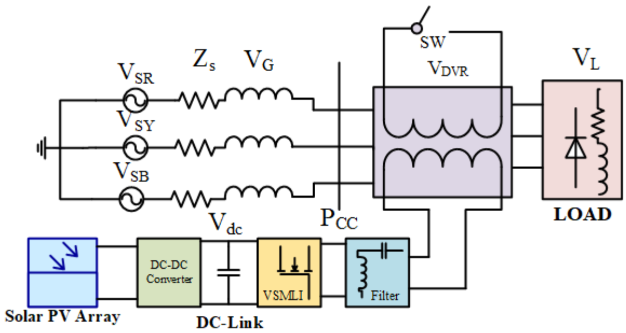

Fig. 1. MLI-DVR setup was merged by PV

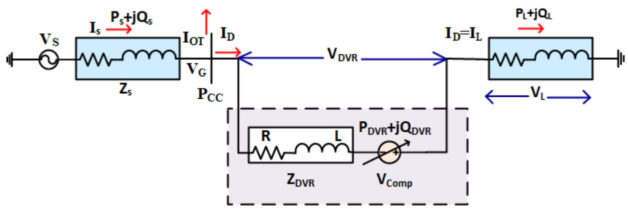

Fig. 2. DVR equivalent circuit

23-level MLI. In this particular setup, 3 DC sources (V_a, V_b and V_c) together with 7 one-way switches and 5 two-way switches are recommended [4] a cross-linked arrangement of 4 bidirectional switches. The DC voltage sources' magnitudes are configured for asymmetric operation as:

$$V_a = 1V_{dc}; \quad V_b = 3V_{dc}; \quad V_c = 7V_{dc}. \quad (2)$$

According to levels N_{Lev}, the following provides the necessary DC sources N_{DC}:

$$N_{DC}^{Asym} = \frac{(N_{Lev} - 5)}{6}. \quad (3)$$

According to the levels N_{Lev}, the number of switches N_{SW} needed is calculated as:

$$N_{SW}^{Asym} = \frac{(N_{Lev} + 1)}{2}. \quad (4)$$

All of the switches in the recommended architecture are unidirectional power switches:

$$N_{GDK}^{Asym} = N_{SW}^{Asym} = \frac{(N_{Lev} + 1)}{2}. \quad (5)$$

The following factors influence the highest voltage output $V_{L.\max}$:

$$V_{L.\max}^{Asym} = \frac{(N_{Lev} - 1)}{2} . \quad (6)$$

By the suggested design, the output voltage has 23 levels and magnitudes that range from 0 V, positive ($+V_{dc}$ to $+11V_{dc}$) and negative ($-V_{dc}$ to $-11V_{dc}$) respectively.

Boost converter analysis for solar PV. Selecting the appropriate PV panel is vital as the voltage and current produced by the solar array are affected by factors such as heat, irradiation, and the configuration of series and parallel strings [5]. In this setup, the series combination of two Trina Solar TSM-200 DC/DA01A solar panels is connected in parallel with another two such stacks to form a PV system.

Output power P_{PV} can be expressed as:

$$P_{PV} = V_{PV} \cdot I_{PV} \quad (7)$$

where V_{pv}, I_{pv} are respective the PV panels output voltage and current.

The current flow can be expressed as:

$$I_{PV} = I_s - I_p - I_d = I_s - I_p - I_0 e^{(V_D/V_T) - 1} . \quad (8)$$

Saturation current can be expressed as:

$$I_{s(T)} = I_{s(TR)}[1 + (T - T_R)\beta] \quad (9)$$

where I_p is the photocurrent generated by light; I_d is the recombination current; I_0 is the reverse saturation current; V_D is the voltage across PV; V_T is the thermal voltage; f_s is the switching frequency, and the ripple factors for the output voltage (V_{dc}) and current (I_L) are crucial parameters. It is essential to conduct a thorough assessment of inductors and capacitors.

The change in current (ΔI_L) should be restricted to 30 %, while the variation in voltage (V_{dc}) is conventionally considered as 5 %. Table 1 provides a concise overview of the solar PV and boost converter characteristics.

Table 1

PV module and boost converter's specifications

Module of 200 W		Boost converter	
V, V	37.6	L, mH	1.28
P, W	200	C, μF	1.31
I, A	5.32	$V_{in} = V_{PV}$, V	112.8
V_{oc}, V	46	Duty cycle, D	0.718
I_{sc}, A	5.6	V_{dc}, V	400

Management of PV-fed MLI-DVR. Various compensation techniques are used by DVR to handle different loads and voltage sag scenarios. A PV-fed DVR is an integrated system designed to address voltage fluctuations and provide a stable electricity supply using both PV technology and dynamic voltage restoration capabilities. It is recognized that not all loads are sensitive to changes in voltage magnitude; some respond to both variations and others to changes in phase angle. Depending on the characteristics of the load, a control strategy is chosen. One approach is the pre-sag compensating method, which takes into consideration both the magnitude and phase angles of the voltage sag [6]. The PI controller for a DVR, which makes sure that the amplitude and phase angle of the load voltage and pre-sag voltage are equal, keeping them at the same level, respectively. The DVR's ability to provide active power from an energy source and inject reactive power during sag becomes increasingly crucial. Moreover, the DVR's regulation of external power consumption impacts the efficiency ratings of batteries and grid electricity.

System construction of UPQC. PV-fed UPQC is a specialized power electronic device used in electrical power systems to mitigate power quality issues while integrating PV systems into the grid.

The proposed system comprises series-shunt compensating converters arranged in a basic block diagram (Fig. 3). These basic blocks serve the purpose of injecting voltage in series with the load to rectify the sinusoidal nature of the voltage, thus mitigating the effects of harmonics.

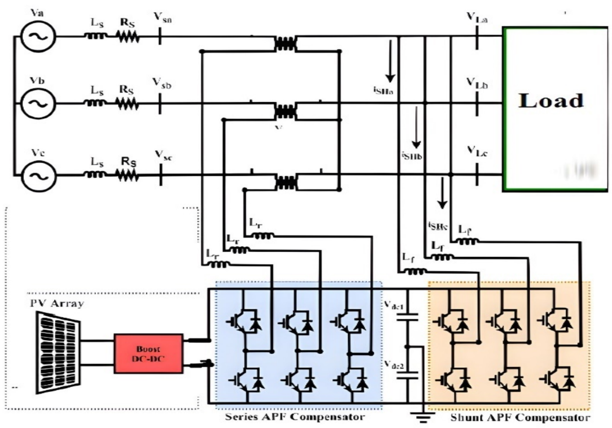

Fig. 3. PV fed UPQC

Additionally, the shunt converter plays a crucial role in regulating the DC link and provides reverse blocking capability for enhanced control. Power filtration is employed to improve the reliability of the power supply. The PV-UPQC is constructed using converters with series-shunt compensation, where shunt and series compensators are interconnected through a single DC bus. The shunt converter is connected to the load side and assists in voltage management. The series compensator addresses grid voltage fluctuations such as sags and swells while operating in voltage management mode. Interface inductors facilitate the connection between the grid and the shunt and series compensators. The proposed system incorporates series-shunt compensating converters to rectify voltage irregularities and mitigate harmonics, with additional features like reverse blocking capability and power filtration to enhance the supply reliability. Since the proposed system is a hybrid system, it meets the load demand from a PV source and from a grid.

Figure 4 illustrates the DVR pre-sag voltage injection method and can be expressed as:

$$V_{DVRp} = \sqrt{2}\sqrt{(V_G^{Sag})^2 + ((V_L)^2) - (2V_L V_{G.p}^{Sag} \cos(\delta_p))} , \quad (10)$$

where V_{DVR} is the DVR injected voltage; φ is the phase angle between V_L and I_L; $V_{G.p}^{Sag}$ is the grid peak voltage at sag; δ is the corresponding angle of phase jump to V_G^{Sag} .

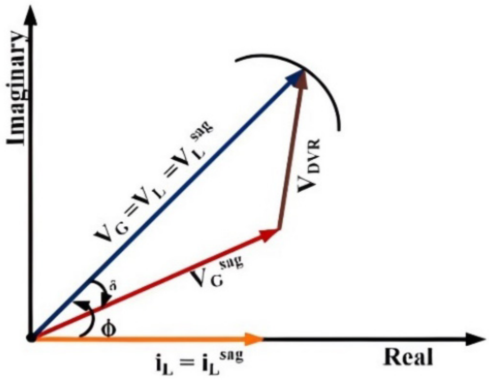

Fig. 4. DVR pre-sag voltage injection method

Results and discussion. PV-fed DVR. 10 kVA injection transformer rated at 400 V (1:1) connects the DVR to the system. The PV array's output voltage is increased to 400 V with the help of a boost converter. An 8 kW linear load running at a 0.85 lag power factor and a regular 400 V battery supply allow the system to maintain a steady DC connection voltage. At maximum power point the PV array's output voltage is 112.8 V; however, with the help of the boost converter, it is increased to 400 V, making it compatible with the DC connector. In addition, the phase voltage of the 23-level MLI is shown in Fig. 5.

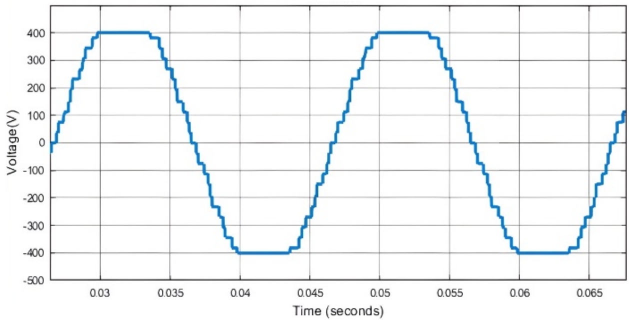

Fig. 5. The phase voltage of a 23-level MLI

Figures 6, 7 display the load voltages at 0.5 pu sag condition and 1.2 pu swell conditions and their associated total harmonic distortion (THD) voltage value at the load side.

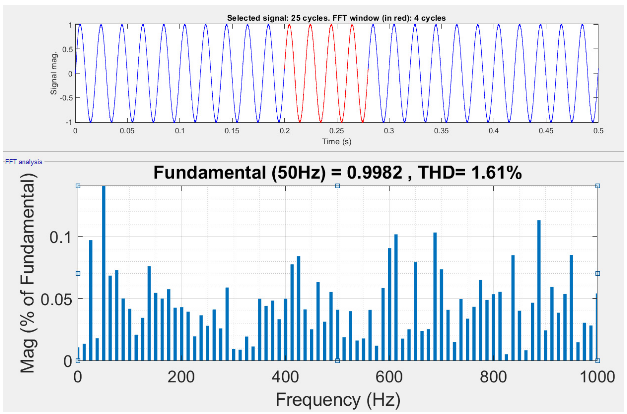

Fig. 6. Load voltages THD at 0.5 pu sag mode

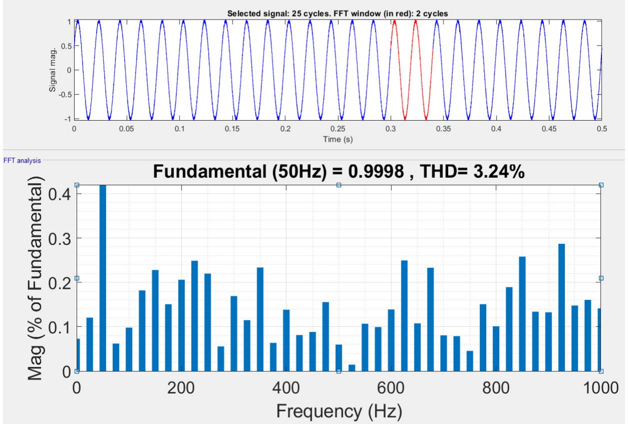

Fig. 7. Load voltage THD at 1.2 pu swell condition

PV fed UPQC. Figures 8, 9 display the load voltages at 0.5 pu sag condition and 1.2 pu swell condition and its associated THD voltage value at the load side.

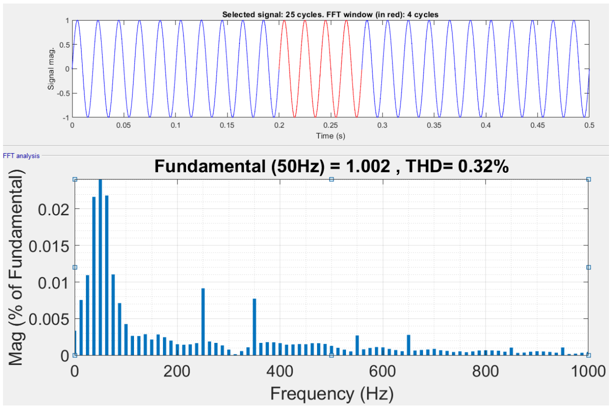

Fig. 8. Load voltage at 0.5 pu sag mode

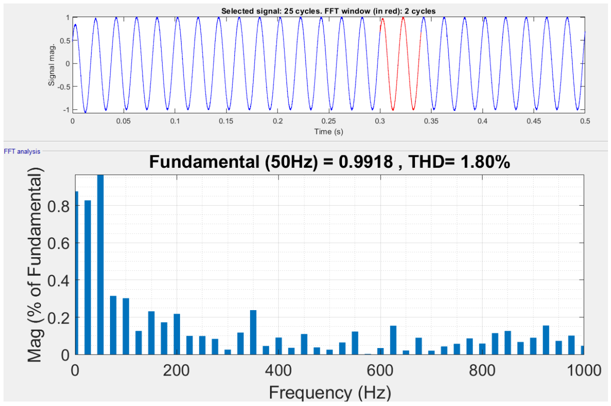

Fig. 9. Load voltage at 1.2 pu swell mode

In Table 2, a thorough comparison of the PV-fed DVR and PV-fed UPQC is shown.

Table 2

Comparison of PV-fed UPQC and PV-fed DVR

Conditions	Load voltage THD	
	PV-fed DVR	PV-fed UPQC
0.5 pu sag	1.61 %	0.32 %
1.2 pu swell	3.24 %	1.80 %

Conclusions. Solar photovoltaic (PV) systems are most impacted when connected to non-linear loads during sag-swell circumstances because harmonics are created. To mitigate these effects of harmonics, the unified power quality conditioner (UPQC) approaches help to improve the operation of such systems. It is discovered that the PV-fed UPQC system operates effectively while compensating for voltage sag. A solar-powered asymmetrical 23-level multilevel inverter (MLI) with dynamic voltage restorer is equipped with a rotating *d*-*q* reference frame controller. By using fewer circuit components, the proposed MLI's synthesized output voltage is produced with a lower THD. The PV-UPQC system simulation has been put into practice. It has been demonstrated that with such a configuration, THD is greatly minimized and the system's performance has increased to a decent level.

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

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Received 04.03.2024
Accepted 18.06.2024
Published 21.10.2024

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How to cite this article:
Manohara M., Muthukaruppasamy S., Dharmaprakash R., Sendilkumar S., Dattatreya Bharadwaj D., Parimalasundar E. Power quality enhancement of grid-integrated solar photovoltaic system with unified power quality conditioner. *Electrical Engineering & Electromechanics*, 2023, no. 6, pp. 44-48. doi: https://doi.org/10.20998/2074-272X.2024.6.06