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Power Quality Enhancement of A PV Integrated System in A Distribution Network

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ABSTRACT: With the increasing adoption of photovoltaic (PV) integrated systems in distribution networks, ensuring high-quality power supply becomes essential. This paper focuses on addressing power quality issues in such systems through the utilization of Unified Power Quality Conditioners (UPQC). The integration of PV systems into distribution networks has brought about challenges related to voltage fluctuations, current harmonics, and poor power factor. To mitigate these issues, UPQC offers a promising solution by actively regulating voltage and current at the point of common coupling (PCC). This study proposes a novel approach leveraging UPQC with adaptive compensating techniques based on advanced algorithms, such as the Variable Leaky Least Mean Square (VLLMS) algorithm. Unlike conventional methods relying on filters, this approach directly extracts essential components from the power sources and loads, facilitating quicker and more efficient power quality enhancement. Through simulations, the effectiveness of the proposed system is demonstrated under various static and dynamic operating conditions. The results validate the capability of the PV-integrated UPQC system to efficiently manage power balance, resolve power quality issues, and ensure stable voltage regulation in distribution networks. Overall, this research contributes to advancing the understanding and practical implementation of UPQC-based solutions for enhancing power quality in PV integrated systems within distribution networks, thereby promoting the reliability and sustainability of renewable energy infrastructure. controller. To extract the greatest power from the PV use MPPT-based DC-DC converters.

KEYWORDS: UPQC, Three phase grid, Harmonics, PV system, Power quality, VLLMS, Voltage swell/sag.

I.INTRODUCTION

In recent years, the rapid expansion of renewable energy sources, particularly photovoltaic (PV) systems, has reshaped the landscape of electricity generation and distribution. With growing concerns about climate change and the need to transition towards sustainable energy solutions, the integration of PV systems into distribution networks has become increasingly prevalent. However, this transition has not been without its challenges, particularly concerning the maintenance of power quality within the electrical grid.

Power quality encompasses various aspects of electrical supply, including voltage stability, harmonic content, and power factor. The intermittent nature of solar energy, coupled with the complex power electronics associated with PV systems, can introduce disturbances and imbalances into the distribution network, leading to disruptions in power quality. Voltage fluctuations, harmonic distortions, and poor power factor not only compromise the reliability and efficiency of the electrical grid but also pose operational and safety risks to connected loads and equipment.

Addressing these power quality challenges requires innovative solutions capable of mitigating disturbances and regulating electrical parameters at critical points within the distribution network. One such solution is the Unified Power Quality Conditioner (UPQC), a sophisticated device designed to actively control voltage and current levels at the point of common coupling (PCC) between the utility grid and the customer's premises.

The primary objective of this project is to explore and develop a UPQC-based solution for enhancing power quality in PV integrated systems within distribution networks. By leveraging advanced algorithms and adaptive compensating techniques, the proposed solution aims to effectively mitigate power quality issues arising from PV system integration, thereby improving grid stability, reliability, and efficiency.

1.2. CONTRIBUTION

The main contributions of the proposed work are:

- (i) The implementation of a VLLMS-based adaptive compensation strategy facilitates precise and rapid tracking of the fundamental component within heavily distorted current and voltage signals. Unlike VSSLMS-based techniques, this approach eliminates the necessity for low-pass or moving average filters.
- (ii) Addressing current-related PQ issues, reactive power compensation, and dc-link voltage regulation is accomplished through shunt VSC. This allows for efficient power management between load, grid, and PV amidst varying PV generation and load demand, thanks to the incorporation of a feed-forward component for PV within the shunt controller.
- (iii) Enhancing the performance of the series controller under highly polluted grid voltage involves leveraging two distinct components for reference signal generation using voltage unit templates. One component is dedicated to voltage sag/swell, while the other targets voltage harmonics, effectively mitigating grid voltage pollution.

II. LITERATURE SURVEY

[1] Bhende, C.N., et al. (2017) - Voltage regulation in distribution networks with photovoltaic system using D-STATCOM. Provides specific insights into the application of D-STATCOMs for voltage regulation in distribution networks with PV systems. Offers a detailed discussion on control strategies based on proportional-integral (PI) controllers for mitigating voltage fluctuations. Addresses the importance of maintaining system stability under varying load and generation conditions. Limited discussion on alternative control strategies or comparative analysis with other D-STATCOM applications may restrict the exploration of optimal control methods. The study may not address potential challenges related to D-STATCOM integration with existing grid infrastructure, such as compatibility issues or retrofitting requirements.

[2] Khan, A.R., et al. (2019) - Fuzzy logic-based control strategy for D-STATCOM to enhance power quality in distribution systems. Introduces a novel control strategy based on fuzzy logic for enhancing power quality in distribution systems using D-STATCOMs. Focuses on real-time regulation of voltage and compensation for reactive power, addressing voltage sags and swells effectively. Offers potential for improved performance compared to traditional control methods. May lack detailed discussion on implementation challenges or comparative analysis with other advanced control techniques. The study may not discuss the robustness of the proposed control strategy in handling uncertainties or variations in network parameters, which could impact its reliability in practical applications.

[3] Gupta, A., et al. (2020) - Comparative analysis of control strategies for D-STATCOM in distribution networks. Conducts a comparative analysis of different control strategies for D-STATCOMs in distribution networks, including traditional PI controllers, model predictive control (MPC), and adaptive neuro-fuzzy inference system (ANFIS). Provides insights into the performance of various control strategies in terms of voltage regulation, harmonic suppression, and reactive power compensation. May lack detailed discussion on specific application scenarios or practical considerations for implementing different control strategies. Limited consideration of transient performance metrics or dynamic response characteristics may overlook important aspects of control strategy effectiveness, particularly in scenarios with rapid load or generation fluctuations. The study may not explore the impact of communication delays or data acquisition constraints on the implementation of advanced control strategies, potentially overlooking practical challenges in real-world deployment.

[4] Ahn, et al. (2016) - Voltage regulation and harmonic mitigation techniques in PV-integrated distribution networks. Ahn conducted a comprehensive analysis of voltage regulation and harmonic mitigation techniques in PV-integrated distribution networks. Their study highlighted the need for advanced control strategies to maintain power quality standards amidst varying solar output. Advanced control strategies enable effective maintenance of power quality standards despite fluctuations in solar output. Implementation of advanced control strategies may introduce complexity to system design and operation.

[5] Liu, et al. (2018) - Effectiveness of UPQC in mitigating voltage fluctuations and harmonics in PV systems. Liu evaluated the effectiveness of UPQC in mitigating voltage fluctuations and harmonics in PV systems, demonstrating its potential for improving power quality performance. UPQC demonstrates effectiveness in mitigating voltage fluctuations and harmonics, leading to improved power quality. Complexity of UPQC design and operation may pose challenges in practical implementation.

[6] Zhang, et al. (2019) - Novel control strategy for UPQC to enhance voltage regulation and harmonic compensation in PV systems. Zhang proposed a novel control strategy for UPQC to enhance voltage regulation and harmonic compensation in PV systems, achieving superior power quality enhancement compared to traditional methods. Novel control strategy results in superior voltage regulation and harmonic compensation compared to traditional methods but, Implementation of novel control strategy may require additional computational resources and expertise.

[7] Gómez & Quintero (2017) - Cost-benefit analysis of UPQC deployment in PV systems. They conducted a cost-benefit analysis of UPQC deployment in PV systems, considering factors such as installation costs, energy savings, and reliability improvements.- UPQC deployment offers long-term economic benefits through energy savings and enhanced system reliability. Initial investment costs of UPQC deployment may be significant, potentially limiting widespread adoption.

[8] Ghatge, et al. (2019) - Analysis of UPQC performance in PV-integrated distribution networks. Ghatge conducted an analysis of UPQC performance in PV-integrated distribution networks, focusing on its effectiveness in voltage regulation and harmonic mitigation. UPQC demonstrates robust performance in voltage regulation and harmonic mitigation, enhancing power quality in PV systems. Implementation complexity and cost may hinder widespread adoption, especially in smaller-scale PV installations.

[9] Khadkikar et al. (2018) - Evaluation of UPQC control strategies for PV systems. Khadkikar evaluated various UPQC control strategies for PV systems, assessing their impact on power quality improvement and system stability. UPQC control strategies offer versatility and adaptability to different PV system configurations, enhancing power quality under varying operating conditions Selection and implementation of appropriate control strategies require careful consideration of system dynamics and operational requirements.

III. PROPOSED SYSTEM

The following is the Proposed system of the PV fed UPQC system.

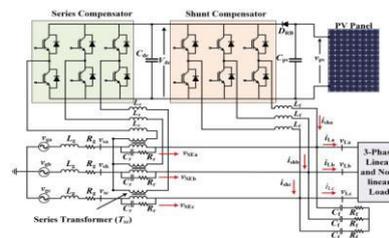


Figure 1: Proposed Structure of a PV fed UPQC system

The Proposed system block diagram is shown in figure 2 which consists of a PV cell, Series compensator, Shunt compensator, Source, Load.

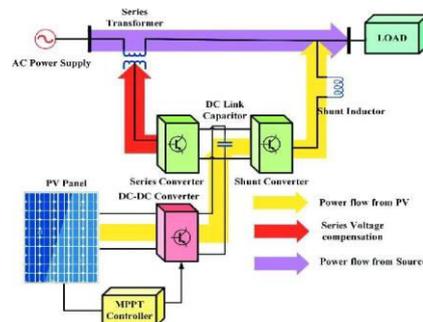


Figure 2: Proposed system Block diagram

2.2. PHOTOVOLTAIC SYSTEM

The photovoltaic (PV) system with a Maximum Power Point Tracking (MPPT) controller depicted in Figure 2 is a pivotal component. Harnessing freely available solar irradiance, PV panels stand out for their exceptional energy efficiency. These panels convert solar energy into electrical power, serving as the fundamental source of electricity generation in such systems.

The key components of this PV system include a DC-DC boost converter and a PV panel equipped with an MPPT controller. The MPPT-based boost converter is specifically designed to optimize power extraction from the PV panel. By continuously adjusting voltage and current levels, the MPPT controller ensures that the PV panel operates at its maximum power point (MPP), even amid changing environmental conditions. This dynamic adjustment maximizes the overall power output of the PV system, contributing to its efficiency and effectiveness in harnessing solar energy.

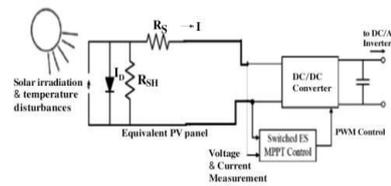


Figure 3: Line Diagram of PV System with Dc-Dc Converter

$$I = I_{ph} - I_D - I_{sh}$$

$$I = I_{ph} - I_0 \left[e^{\frac{qV_D}{nKT}} \right] - \left(\frac{V_D}{R_s} \right) \quad \dots (1)$$

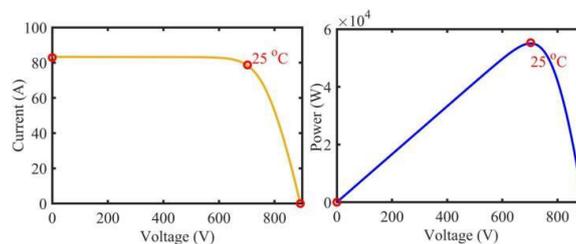


Figure 4: I-V and P-V characteristics of a PV array

The IV (current-voltage) and PV (power-voltage) characteristics of a photovoltaic (PV) array provide vital insights into its behavior and performance. These characteristics illustrate how the array responds to changes in solar irradiance and temperature.

2.3. PROPOSED SYSTEM ARCHITECTURE

The grid-integrated PV-UPQC system, as depicted in Figure 1, ingeniously combines a series compensator and a shunt compensator within a back-to-back configuration, sharing a common DC-link. The series compensator, interfaced with the grid side through three-phase series injection transformers (Tse), works adeptly to address voltage irregularities such as sags, swells, harmonics, and reactive power fluctuations. On the other hand, the shunt compensator, linked to the load side via interfacing inductors (Lf), diligently regulates voltage at the load end while compensating for reactive power demand. The inclusion of interfacing inductors is pivotal, limiting high-frequency current components resulting from dynamic conditions like sharp load current changes. Meanwhile, the PV array, connected to the DC link through a reverse blocking diode, serves as the primary energy source, converting solar irradiance into electrical energy. Its operation is optimized through the implementation of the Perturb and Observe (P&O) MPPT algorithm, maximizing power extraction from the PV modules. Finally, the R-L load, facilitated by a three-phase diode bridge rectifier, represents the consumer load that the system aims to furnish with stable and high-quality power. This comprehensive configuration ensures efficient power management and enhanced performance of the grid-integrated PV-UPQC system, balancing grid stability with renewable energy utilization.

2.4.VSC SIZING

The rating of the series Voltage Source Converter (VSC) is contingent upon the maximum compensating voltage and the maximum grid current. The maximum compensating voltage is determined by the extent of grid voltage sag that requires compensation. The VA (Volt-Ampere) rating of the series VSC is calculated using the formula:

$$S_{series} = P_{Series} = 3V_{SE}I_{SE} = 3 * \frac{bV_r}{\sqrt{3}} * \frac{P_{PV}^{MPP} - P_{load}^{min}}{\sqrt{3} * V_r}$$

$$= 3 * \frac{0.5 * 415}{\sqrt{3}} * 54.67 = 19.6 \text{ kVA} \quad \dots(2)$$

Here, I_{SE} represents the per-phase current rating of the series VSC, P_{MPP} is the PV power at Maximum Power Point (MPP), P_{load} is the rated line voltage of the system (415 V), P_{min} is the minimum load demand, and V_{SE} is the per-phase rms voltage injected by the series VSC. Additionally, b denotes the maximum amount of voltage sag per phase (0.5 p.u)

The rating of the shunt VSC, on the other hand, hinges on the PV-generated power at MPP, reactive power, and harmonic power necessary for compensating peak load. In addition, it has to handle the power injected by the series VSC during voltage sag condition as the series VSC power flows through the shunt VSC.

The VA rating of the shunt VSC is calculated by:

$$S_{sh} = \sqrt{(P_{PV}^{MPP} + P_{se})^2 + Q_{load}^2 + H_{har}^2}$$

$$= \sqrt{(55.3 + 19.6)^2 + (25 * 0.6)^2 + (0.2 * 0.8 * 25)^2}$$

$$= 76.5 \text{ kVA} \quad \dots(3)$$

Here, Q_{load} represents the maximum reactive power requirement of the load, and H_{har} signifies the maximum harmonic power corresponding to the maximum load. The value of 0.2 is a scaling factor. The grid provides the active power demand of the load, while the shunt VSC manages the non-active power (harmonic and reactive power) of the load demand and power produced by PV. To prevent damage to the switches within the VSC due to an uncertain rise in the non-active part of the load demand, the amount of non-active power provided by the shunt VSC is restricted to its rated value. This precautionary measure ensures the VSC operates within its rated capacity, safeguarding against potential damage.

IV.CONTROL SCHEME OF PV SYSTEM

The control strategy proposed for the PV-UPQC system in a distribution network aims to effectively manage both the shunt and series compensators to maximize the benefits of UPQC functionalities. The proposed controller, based on Neural Networks (NN), offers several advantages including the mitigation of grid and load-induced Power Quality (PQ) issues such as voltage sag/swell and harmonics. Additionally, it addresses current harmonics, ensures unity power factor operation at the Point of Common Coupling (PCC), regulates the dc-link voltage, and incorporates a feed-forward component for proper power balance among the PV system, grid, and load. Despite the higher cost associated with UPQC due to the inclusion of two Voltage Source Converters (VSCs) compared to compensators with only one VSC like DVR and DSTATCOM, UPQC is chosen to prioritize the overall health of the system, particularly for consumers' benefit. The implementation involves utilizing a Variable Leaky Least Mean Squares (VLLMS) algorithm-based control on a grid-integrated PV-fed UPQC to generate switching signals for both the series and shunt VSCs under dynamic and steady-state conditions. This control strategy ensures effective management of power quality issues while maximizing the utilization of renewable energy sources like PV.

4.2.VLLMS ALGORITHM

The block diagram in Fig. 5 represents the stepwise implementation of the VLLMS algorithm. The VLLMS algorithm is a neural network-based soft computing technique that adaptively updates the weight parameters to track the changes occurring in a system.

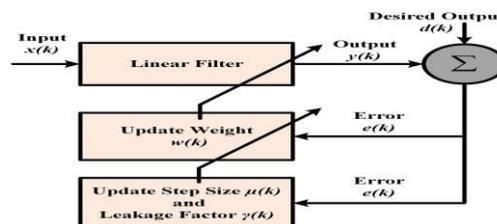


Figure 5: :Block diagram of VLLMS algorithm

The basic expressions involved in the VLLMS algorithm are given in the following :

$$y(\kappa + 1) = w^T(\kappa) \cdot x(\kappa) \quad \dots(4)$$

$$e(\kappa) = d(\kappa) - y(\kappa) \quad \dots(5)$$

$$w(\kappa+1) = \{1 - 2\mu(\kappa)\gamma(\kappa)\} w(\kappa) + 2\mu(\kappa)e(\kappa)x(\kappa) \quad \dots(6)$$

$$\gamma(\kappa+1) = \gamma(\kappa) - 2\mu(\kappa)\rho e(\kappa)x^T(\kappa)w(\kappa-1) \quad \dots(7)$$

$$\mu(\kappa+1) = \lambda\mu(\kappa) + \gamma(\kappa)P^2(\kappa) \quad \dots(8)$$

$$P(\kappa) = \beta P(\kappa-1) + (1-\beta)e(\kappa)e(\kappa-1) \quad \dots(9)$$

In these expressions, κ represents the discrete-time instant, $x(\kappa)$ denotes the input signal, $y(\kappa)$ represents the actual output, and $d(\kappa)$ is the desired output. $w(\kappa)$ signifies the weight or gain, which is iteratively tuned to minimize the error $e(\kappa)$. $\gamma(\kappa)$ serves as the variable leakage factor, balancing the weight's parameterization. $\mu(\kappa)$ represents the variable step size, while $P(\kappa)$ indicates the error autocorrelation of $e(\kappa)$ and $e(\kappa-1)$. Parameters β , λ , and ρ control averaging time, convergence time, and adjustment speed, respectively. By applying $x(\kappa)$ and $d(\kappa)$ from a system and passing them through the VLLMS algorithm, the weights are updated based on the outlined equations after each time instant.

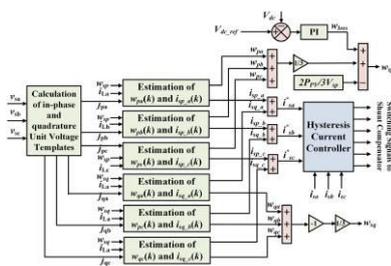


Figure 6: Proposed control scheme for shunt compensator

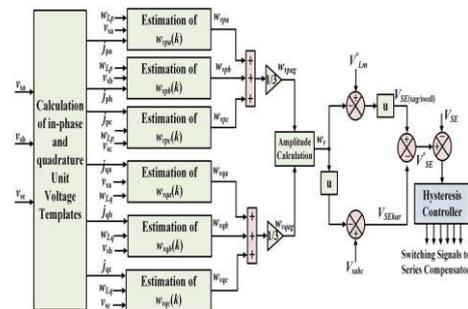


Figure 7: Proposed control scheme for series compensator

V.RESULTS AND DISCUSSIONS

The control scheme discussed earlier for the operation and regulation of the PV-fed UPQC system has been analyzed using the MATLAB/Simulink platform. The simulation employs parameter values as detailed in Table I.

Parameters	Value
Grid	415 V (line-line) RMS, 50
Interfacing inductor (shunt VSC)	
Interfacing inductor (series VSC)	1.6 mH
DC link capacitor	10 μF
DC link voltage	1.2 mH 700 V
Non-linear load	(i) 20 kVA 0.8 P.F (ii) 25 kVA 0.8 P.F
SPV voltage and current at MPP	702.7 V, 78.7 A
SPV power at MPP	55.3 kW

Table 1 : Parameters of PV-UPQC

A. Behaviour of PV-UPQC under voltage sag/swell condition.

Figure 8 illustrates instances of voltage sag and swell experienced on the grid side. At time instants $t = 0.2$ s and $t = 0.3$ s, the system encounters a voltage swell of 0.3 p.u and a voltage sag of 0.5 p.u, respectively. The series compensator promptly addresses both the swell and sag in the voltage without the need for a Low Pass Filter (LPF) to extract the fundamental component of the grid voltage. As a result, a pure sinusoidal voltage with a nominal magnitude is observed at the load end, demonstrating the effectiveness of the series compensator in mitigating grid disturbances and ensuring stable voltage supply to the load.

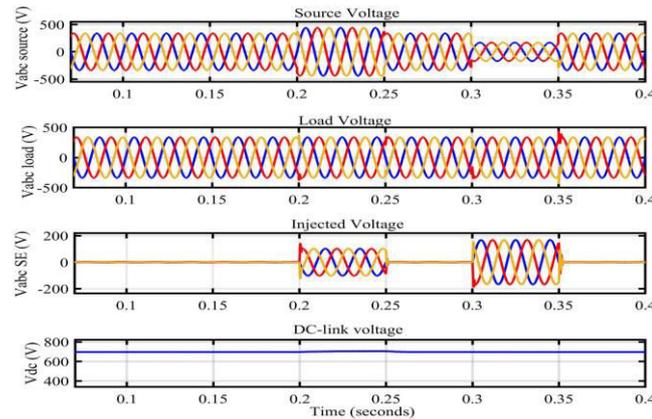


Figure 8: Behavior of the PV-UPQC during voltage sag and swell condition.

B. Performance under highly distorted Grid Voltage

Figure 9 depicts the effectiveness of the series compensator in compensating for harmonics present in the source voltage. It is evident that the harmonics are entirely eliminated from the load voltage, rendering it suitable for sensitive loads. Figures 10(a) and 10(b) illustrate the Total Harmonic Distortion (THD) of the source voltage and load voltage, respectively.

The proposed control technique has significantly reduced the THD of the voltage from 31.62% to 1.27%, which falls within the limits set by the IEEE 519 standards. This demonstrates the successful mitigation of harmonics and the improvement of power quality achieved by the implemented control scheme.

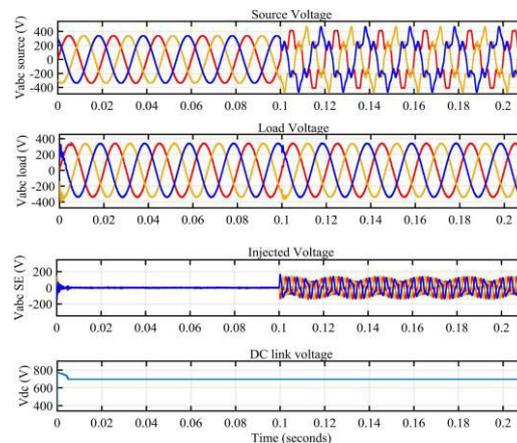


Figure 9: Performance of PV-UPQC under highly distorted grid voltage

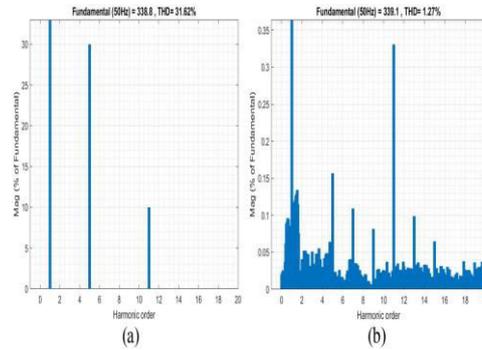


Figure 10: THD content of source voltage(a) and Load voltage(b)

C. Performance under Non-linear load condition

In Figure 11, the behavior of the shunt Voltage Source Converter (VSC) in the presence of a non-linear load is depicted. The shunt compensator effectively eliminates the harmonics introduced by the load into the grid current without the need for a Low Pass Filter (LPF). Furthermore, it's observed that with the assistance of the shunt VSC, both the PV system and the grid work in tandem to fulfill the load requirements

Figures 12(a) and 12(b) display the Total Harmonic Distortion (THD) of the load current and source current, respectively. The proposed control technique has successfully reduced the THD of the current from 14.73% to 1.50%, thereby complying with the IEEE standards. This highlights the efficacy of the control scheme in mitigating current distortions and enhancing PQ.

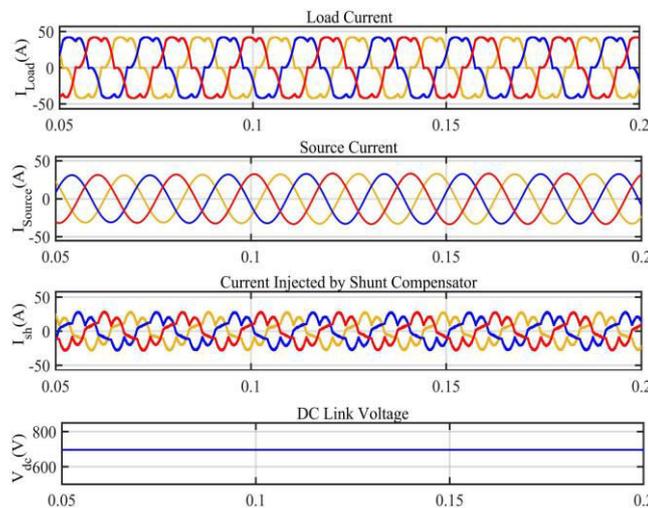


Figure 11: Behaviour of PV-UPQC under non-linear load condition

Through the proper implementation of shunt compensator control technique, unity power factor operation is achieved. This is evidenced by the voltage and current at the Point of Common Coupling (PCC) being in-phase with each other in the presence of a non-linear load, as illustrated in Figure 13.

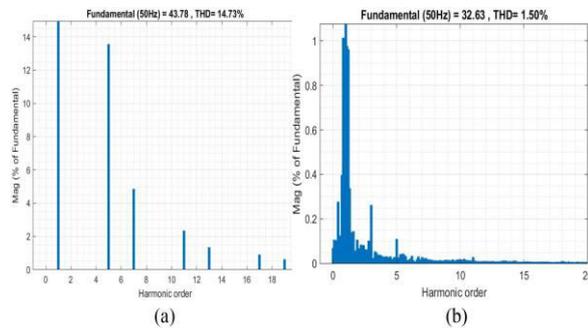


Figure 12: THD content of load current(a) and source current(b)

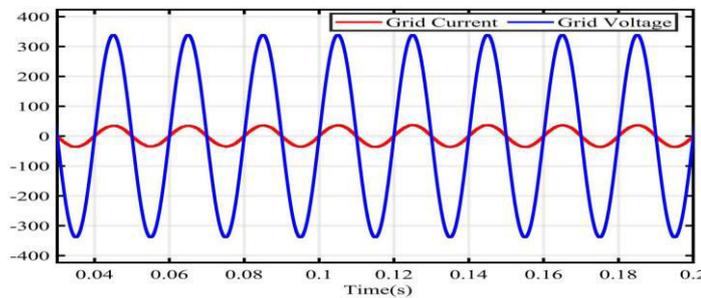


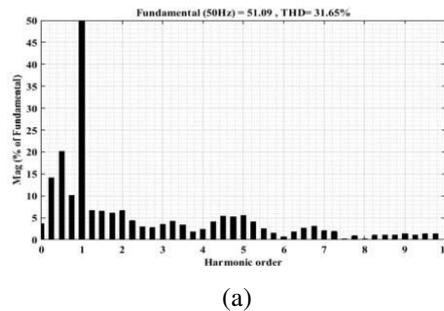
Figure 13: In phase relation between voltage and current at PCC

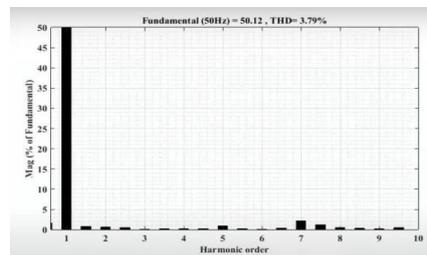
D. Comparison of DSTATCOM with UPQC

The THD(Total harmonic distortion) values of DSTATCOM and UPQC devices before compensation and after compensation are shown in table 2.

Table 2:Comparison of DSTATCOM with UPQC

Device	Before compensation (%THD)	After compensation (%THD)
DSTATCOM	31.65	3.79
UPQC	14.73	1.50





(b)

Figure 14: THD content before compensation(a) and after compensation(b) of DSTATCOM

VI. CONCLUSION

The introduced VLLMS-based control strategy for PV-fed UPQC demonstrates robust performance and effectiveness, as evidenced through comprehensive simulation. The shunt compensator effectively handles dynamic scenarios such as sudden load variations and unbalanced conditions, ensuring grid current sinusoidality while compensating for reactive power demand and load harmonics. Moreover, the series compensator adeptly addresses higher-order harmonics in the source voltage, maintaining load terminal voltage at the desired level even amidst voltage fluctuations like sag and swell.

Furthermore, the series compensator efficiently mitigates harmonics originating from the source side, safeguarding the load from their adverse effects. The integration of the PV array enhances system performance by alleviating grid burden. During load deficit situations, the PV array supplements additional power to the source, while during voltage swells, it contributes actively to the UPQC's operation, thereby enhancing its performance.

In summary, the proposed approach significantly improves the overall system performance by effectively managing dynamic conditions, reducing grid burden, and leveraging the PV array for enhanced operational efficiency and reliability.

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