Single Stage Three-Phase Solar PV Integrated Unified Power Quality Conditioner (UPQC)

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Abstract -This paper presents a solar PV (photovoltaic)-integrated UPQC (Unified Power Quality Conditioner) that employs a fractional open-circuit algorithm, and it analyses its performance under both steady-state and dynamic operating conditions using MATLAB/Simulink. In the UPQC configuration, the shunt and series Voltage Source Converters (VSCs) are connected back-to-back and share a common DC link.

The shunt compensator performs dual functions: it extracts power from the solar PV array and provides current compensation. The series compensator, on the other hand, offers voltage compensation by injecting voltage (in-phase or out-of-phase) into the grid at the Point of Common Coupling (PCC) during voltage sag and swell conditions. A fractional open-circuit algorithm with a single-stage topology is used for maximum power extraction from the PV array. This algorithm is not only easy to implement but also provides smooth, oscillation-free responses.

Overall, the proposed system operates as a multifunctional solution, supplying clean energy to the grid while simultaneously improving power quality.

Index Terms—Maximum Power Point Tracking (MPPT), Power Quality (PQ), Photovoltaic (PV), Unified Power Quality Conditioner (UPQC), Fractional Open-Circuit Voltage (FOCV), Dynamic Voltage Restorer (DVR), Moving Average Filter (MAF), Total Harmonic Distortion (THD), Series Active Power Filter (SAPF), Parallel Active Power Filter (PAPF)

1.INTRODUCTION

Power quality issues have increasingly arisen due to the widespread use of solid-state semiconductor devices, switched-mode power supplies (SMPS), adjustable-speed drives, and other power electronic equipment. The proliferation of these electronic appliances and nonlinear loads has led to greater penetration of non-sinusoidal currents into the power system.

Such power quality disturbances can cause equipment malfunction, false triggering of electronic switches, data loss, and memory errors in sensitive devices such as computers, programmable logic controllers, protection relays, and other digital equipment. Additionally, they can hasten the breakdown of cables, transformers, and other transmission parts. The consequences become even more severe when biomedical equipment is affected.

Historically, power quality has been recognised as a two-sided issue, where electronic equipment often plays both the villain and the victim. Despite their high efficiency, power electronic devices distort the electrical waveform by drawing current in brief bursts. Because of this distortion, lower-quality power is injected back into the grid, forcing utilities to make significant investments in filters and capacitors to clean up the "dirty" power.

Another major challenge currently facing power system engineers is the need for clean energy generation. Rooftop solar installations—whether in commercial buildings or residential apartments—provide an effective solution. However, the intermittent nature of solar photovoltaic systems can introduce voltage-quality issues, particularly in weak distribution networks.

Taking into account both of these situations, it is clear that there is an increasing need for systems that can both improve power quality and supply clean energy to the grid. Extensive research has been conducted on active power filtering to mitigate power quality problems. However, conventional shunt active power filters have limitations: they inject only reactive power and cannot provide both voltage compensation at the Point of Common Coupling (PCC) and current compensation (for maintaining unity power factor) at the same time.

The development of Dynamic Voltage Restorers (DVRs) and STATCOM devices marked a significant advancement in power quality mitigation. The first DSTATCOM installation was carried out at a sawmill in British Columbia, Canada. A solar PV system integrated with a DVR was proposed in [19]. Several researchers have also explored single-phase and three-phase multifunctional and single-stage solar energy conversion systems [4]–[8].

Furthermore, Flexible AC Transmission System (FACTS) devices have been adapted for use in distribution networks. The introduction of the Unified Power Quality Conditioner (UPQC), derived from the Unified Power Flow Controller (UPFC), was first reported in 1998. These solutions can address a wide range of power quality phenomena. The integration of PV systems with UPQC has been demonstrated in [10] and [12]. A comparative analysis of major MPPT techniques is presented in [20].

Reference signal generation plays a crucial role in the control methodology of a UPQC system. These signals can be generated using either time-domain or frequency-domain techniques [3]. Generally, time-domain techniques are preferred for real-time implementation because they require less computational effort. In this paper, a time-domain method based on the synchronous reference frame (d–q theory) [13] is employed.

Under unbalanced load conditions, this method introduces double-frequency harmonic components into the d-axis current. To eliminate these unwanted components, a low-pass filter (LPF) with a very low cutoff frequency is typically required. However, the use of conventional LPFs degrades dynamic performance. Therefore, a Moving Average Filter (MAF) is used in this work to suppress the double-frequency components in the d-axis current [14]. MAF provides maximum attenuation without reducing system bandwidth [15]. Furthermore, applying MAF enhances the performance of the Phase-Locked Loop (PLL) used for grid synchronization [16], [17]. The MAF is simple to implement and effectively rejects frequency components that are integer multiples of the cutoff frequency.

This article focuses on the modeling and simulation of a three-phase, single-stage solar PV-integrated UPQC employing a d–q theory–based control method. To enhance dynamic performance during active current extraction, the MAF is integrated. The suggested system's capacity to concurrently enhance both voltage and current quality is one of its main advantages. The system maintains stability under numerous dynamic situations, including voltage sags and swells and unbalanced loads. MATLAB/Simulink is used to simulate and analyze the system in both steady-state and dynamic settings.

II. BASIC TOPOLOGY AND DESIGN

The basic topology of the proposed PV-UPQC power circuit, designed for a three-phase grid, is illustrated in Fig. 1. The system consists of shunt and series compensators (both implemented as Voltage Source Converters), also referred to as the Parallel Active Power Filter (PAPF) and Series Active Power Filter (SAPF), respectively. These converters share a common DC-link capacitor, which serves as the DC bus.

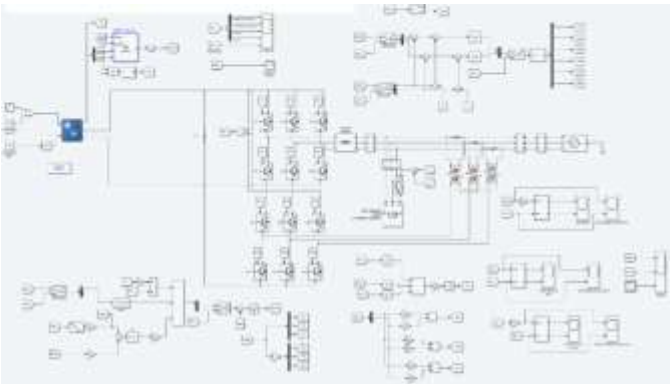
The shunt compensator is connected on the load side, while the series compensator is connected on the grid side through an injection transformer in each phase. These transformers inject the compensating voltage produced by the series converter into the grid. The PV array is directly connected to the DC bus through a diode, which prevents reverse power flow.

Voltage sags and swells occurring on the grid side are mitigated by the series compensator operating in voltage-control mode. Interfacing inductors are placed between the grid and both converters. Since the switching action of power electronic converters introduces harmonics into the system, RC ripple filters are employed to suppress them. A bridge rectifier with an RL load is connected on the load side, representing a nonlinear load.

The design of the PV-UPQC system involves selecting and sizing the PV module, choosing the MPPT algorithm, and designing the DC-link capacitor and DC-link voltage level. Subsequent design considerations include the interfacing inductors, injection transformers, and ripple filters [3].

The size of the PV module depends primarily on the DC-link voltage, as the maximum power point (MPP) voltage should match the DC-link voltage. The shunt compensator must be sized to handle both the maximum power output of the PV array and the required compensation for reactive power and load current harmonics. The detailed parameter design for a single-stage PV-UPQC system is provided in [1]. Ripple filter selection is based on the guidelines presented in [3].

Fig -1: Basic Topology

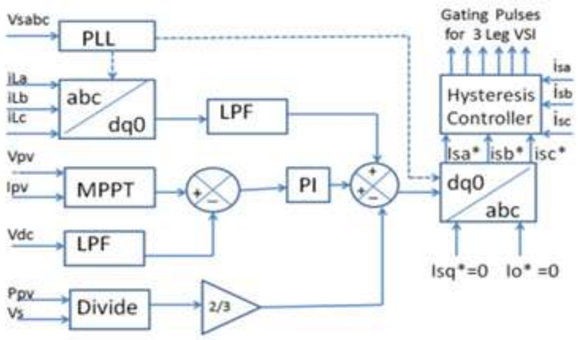


III. CONTROL OF PV-UPQC

The shunt and series active power filters, along with their respective control circuits and the FOCV-based MPPT algorithm, constitute the major subsystems in the modeling and simulation of the proposed system. The shunt VSC, or PAPF, injects compensating currents into the system to eliminate load-side current harmonics and to maintain a sinusoidal current waveform, thereby ensuring unity power factor operation. The series VSC, or SAPF, mitigates voltage harmonics and injects compensating voltage into the grid to counteract voltage sag and swell conditions at the PCC.

During a grid voltage sag, the SAPF injects voltage in phase with the grid voltage to restore the PCC voltage. Conversely, during a swell condition, the injected voltage is phase-opposed to the grid voltage in order to regulate and maintain the desired PCC voltage level.

Fig. 2. Control for shunt compensator.



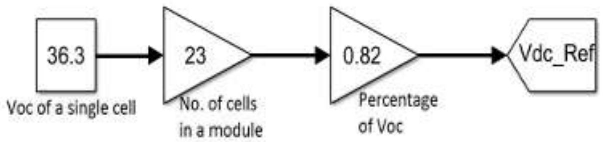
A. Control Algorithm for Shunt APF

The MPPT algorithm determines the reference voltage for the DC bus of the PV-UPQC system. In this work, the Fractional Open-Circuit Voltage (FOCV) method is selected and implemented to track the maximum power point of the solar PV module. This algorithm is simple, easy to implement, and particularly suitable for the proposed system, as only the reference DC-link voltage needs to be computed.

The voltage of a PV module at its maximum power point exhibits an approximately linear relationship with its open-circuit voltage under varying irradiance and temperature conditions. The FOCV algorithm is based on this fundamental principle. Unlike double-stage conversion topologies—where the duty cycle must be calculated to control a boost converter—this single-stage configuration eliminates the need for an additional converter. This simplifies the system while maintaining both effectiveness and efficiency.

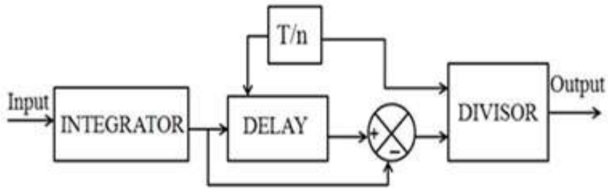
The DC-link voltage is regulated at a constant value of 700 V using a Proportional–Integral (PI) controller. The controller gains, Kp and Ki, are obtained using the Ziegler–Nichols tuning method.

Fig. 3. Fractional open circuit voltage algorithm



To function as a load current compensator, the shunt converter must extract the fundamental active component of the load current. For this purpose, the control of the shunt compensator is carried out using the Synchronous Reference Frame (SRF) technique to isolate this fundamental component. The block diagram of the control structure used in this paper is shown in Fig. 2. A Phase-Locked Loop (PLL) measures the phase and frequency of the PCC voltage, which are then used to transform the load currents into the d–q–0 reference frame. The d-axis component of the load current (Old) is filtered to obtain its pure DC component (IDF). In this work, a Moving Average Filter (MAF) is used instead of a conventional LPF to enhance dynamic performance. The block diagram of the MAF is illustrated in Fig. 4. The reference DC-link voltage (V*dc) is obtained from the MPPT algorithm (FOCI) and is compared with the filtered actual DC-link voltage. The resulting error is fed to a PI controller, which plays a key role in maintaining a constant DC-link voltage.

Fig. 4. Block diagram representation of MAF.

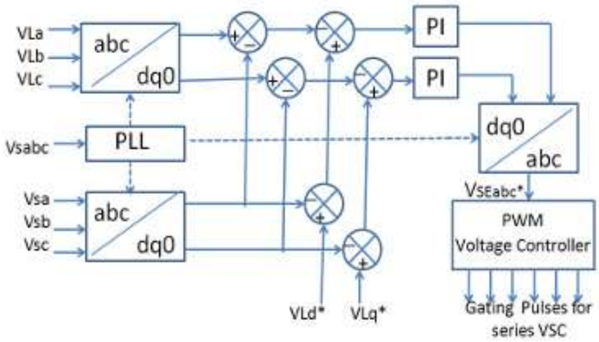


Equivalent value of current due to photo-voltaic module canbe calculated using the below equation Ipvg = 2Ppv 3Vs (1) where Ppv is the power of the PV module and V is the PCC voltage magnitude. The d-axis component of reference grid current is given by I sd =ILdf +IlossIpvg (2) I sd is converted to grid currents in abc domain reference frame. The reference grid currents are then compared with the measured grid currents using hysteresis controller and obtained the gate pulses for triggering the shunt VSC circuit.

B. Control Algorithm for Series APF

Different compensation topologies for series converters are discussed in [14]. In this paper, the voltage injected by the Series APF is kept in phase with the grid voltage, thereby minimizing the amount of compensation required. The control method for the series converter is illustrated in Fig. 5. The fundamental component of the PCC voltage is extracted using a Phase-Locked Loop (PLL), which provides the reference axis signals for transformation into the d–q–0 domain. The PLL also measures the phase and frequency of the grid voltage. Both the PCC voltage and the load-side voltage are then transformed into the rotating reference frame for further processing.

Fig. 5. Control for series compensator.

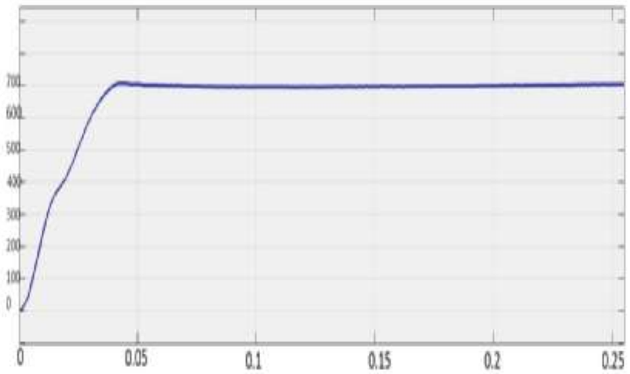


The quadrature-axis component is assumed to be zero [3]. The reference voltage for the series compensator is obtained by taking the difference between the voltage at the Point of Common Coupling (PCC) and the reference load voltage. The difference between the actual load voltage and the PCC voltage produces the required SAP compensating voltage. The error between the reference SAP voltage and the actual SAP voltage is then processed through Proportional–Intelligible (PI) controllers to generate the appropriate reference signals. These reference signals are subsequently transformed back into the three-phase stationary reference frame and applied to a Pulse-Width Modulation (PWM) voltage controller, which generates the gated pulses for the series VSC.

IV. SIMULATION REULTS

The modeling and analysis of the FOCV based PV inte grated UPQC is done by simulating the system in MATLAB using SimPower system tools. Three phase diode bridge rec tifier with RL load is used as nonlinear load.

Fig. 6. DC link voltage=700v



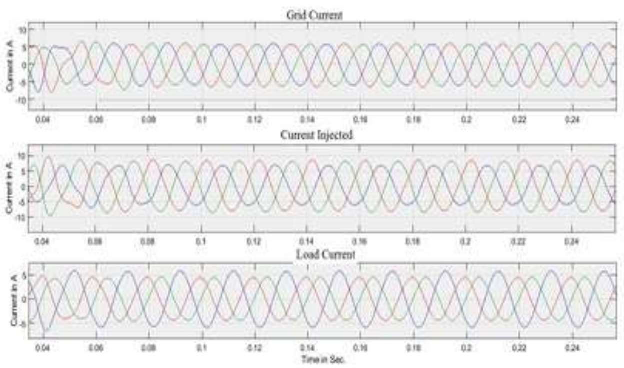


Fig. 7. Current compensation waveforms

The dynamic performance of the system during voltage surges and swells at the PCC is presented. The solar irradiance is maintained at 1000 W/m² and the temperature at 45 °C. The DC-link voltage (Vdc) is regulated at 700 V through the combined action of the PV array and the shunt controller. A voltage swell of 1.2 PU is applied to the grid between 0.2 s and 0.3 s. During this interval, the series compensator injects a voltage that is out of phase with the grid voltage to counteract the swell, thereby keeping the load voltage constant, as shown in Fig. 9. Similarly, during a voltage sag of 0.8 PU applied over the same time interval, the series compensator injects a voltage in phase with the grid to restore the load voltage to its nominal value of 1 pu. Current waveforms under unbalanced load conditions are shown in Fig. 7, where the shunt compensator successfully maintains a stable and sinusoidal grid Current. Harmonic analysis and THD measurements of both input and output waveforms were performed using MATLAB tools. According to IEEE Std. 519-1992, which specifies harmonic limits for power systems,

Fig. 8. Voltage compensation waveforms a)input gird voltage: 0.2pu swell is applied between 0.2sec and 0.3 sec b) Compensating voltage injected from VSC phase A c) Improved load voltage

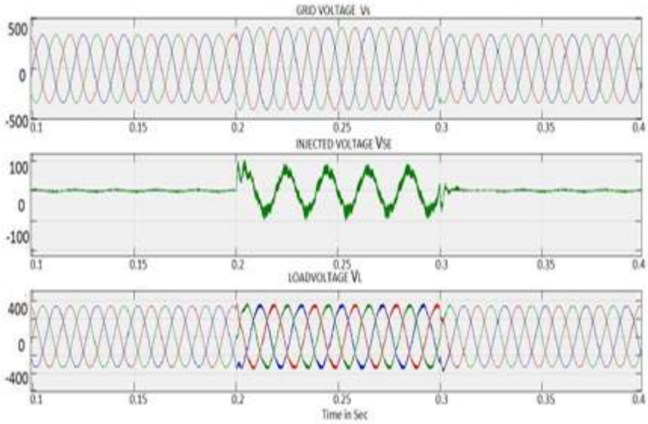
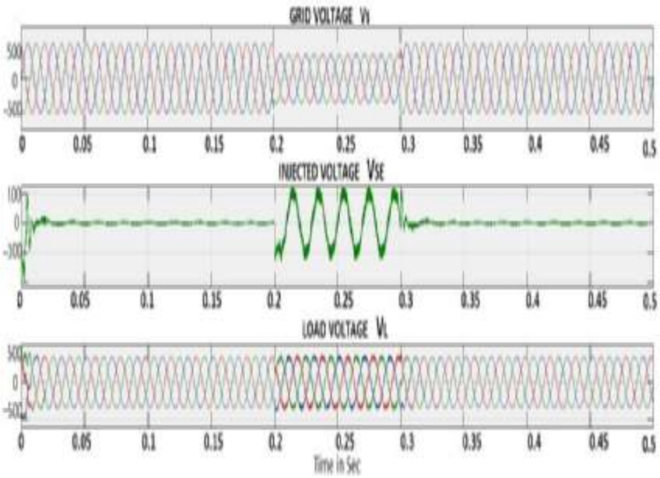


Fig. 9. Voltage compensation waveforms a)input gird voltage: 0.3pu swell is applied between 0.2sec and 0.3 sec b) Compensating voltage injected from VSC phase A c) Improved load voltage



the Total Harmonic Distortion (THD) should remain within 5%. the proposed system, the THD of the load voltage is approximately 2.84%, and the THD of the grid current is 1.18%, both of which comply with the IEEE standards.

V. CONCLUSIONS

The three-phase solar photovoltaic–integrated UPC system was designed , and its performance analyzed under various operating conditions, including grid voltage sags, swells, and unbalanced loads, using MATLAB/Simulink. The system demonstrated stable operation under all tested conditions. Maximum power extraction from the PV array was achieved using the Fractional Open-Circuit Voltage (FOCI) MPPT algorithm. The measured THD values of the grid current and load voltage were found to be within the limits specified by IEEE standards. These results indicate that the proposed solar PV–integrated UPC is a promising solution for modern power distribution systems, as it effectively combines clean energy generation with enhanced power quality.

Fig. 10. Grid Current THD = 1.18 %

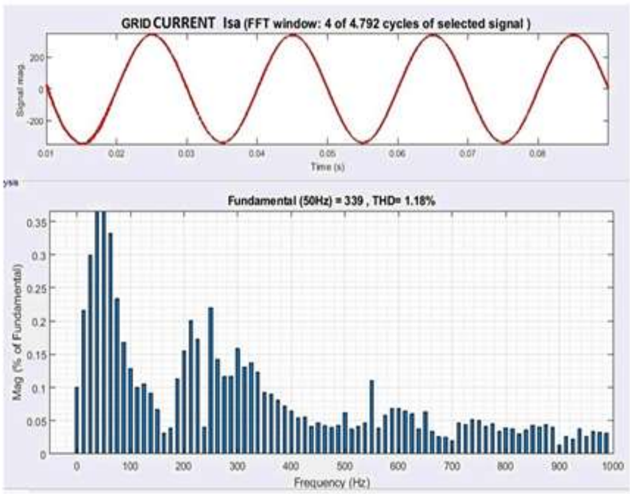
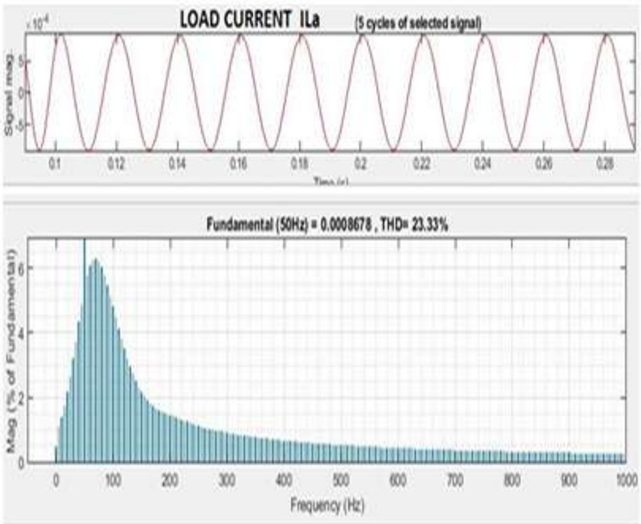


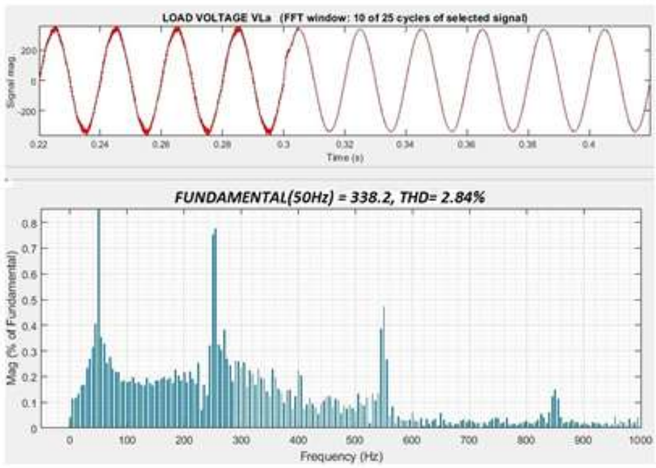
Fig. 11. Load current THD =23.33%



VI. FUTURE SCOPE

Although the FOCI algorithm is one of the simplest MPPT techniques and provides smooth, fast, and oscillation-free responses, measuring the Open-circuit voltage (Voc) presents a challenge. This issue has traditionally been addressed by introducing a pilot cell. Further improving accuracy and reduce power loss, the pilot cell was later replaced by a semi-pilot cell [22], [23]. During normal operation, the semi-pilot cell functions as part of the PV array and contributes to power generation. Open-circuit voltage is measured by temporarily disconnecting only the semi-pilot cell from the array, ensuring that the overall system output remains unaffected. The FOCI algorithm used in this paper can be substituted with more advanced variations of the FOCI Technique to achieve even better performance.

Fig. 12. Load Voltage THD =2.84%



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