Enhanced Power Quality and Sustainable Energy with a Grid-Tied Three-Phase Solar PV Integrated Unified Power Quality Conditioner (PV-UPQC)

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Abstract–This work focuses on the design and analysis of a three-phase single stage solar photovoltaic integrated unified power quality conditioner (PV-UPQC). The PV-UPQC is composed of shunt and series voltage compensators that are interconnected in a back-to-back configuration via a shared DC-link. The shunt compensator serves the twin purpose of harvesting electricity from the photovoltaic (PV) array and correcting for harmonics in the load current. A more advanced synchronous reference frame control, using a moving average filter, is used to extract the load's active current component, resulting in enhanced performance of the PV-UPQC. The series compensator is designed to mitigate power quality issues on the grid side, specifically addressing problems such as voltage sags and swells. The compensator introduces voltage that is either in-phase or out of phase with the point of common coupling (PCC) voltage, depending on whether there is a sag or swell situation, respectively. The suggested system integrates the advantages of sustainable energy production while enhancing power quality. The system's steady state and dynamic performance are assessed by conducting simulations in MATLAB-Simulink with a nonlinear load. The system performance is further validated by conducting experiments on a reduced-scale laboratory prototype, subjecting it to various disturbances like load imbalances, voltage sags/swells at the point of common coupling (PCC), and variations in irradiation.

Keywords — *Power Quality, shunt compensator, series compensator, UPQC, Solar PV, MPPT.*

I. INTRODUCTION

Due to the progress in semiconductor technology, power electronic loads are becoming more prevalent. These devices, such as computer power supplies, changeable speed drives, and switching mode power supplies, exhibit high efficiency yet use non-linear currents. The presence of nonlinear currents in distribution systems leads to voltage distortion at the point of common coupling. There is a growing focus on generating sustainable energy by installing rooftop photovoltaic (PV) systems in both small residences and commercial buildings [1], [2]. However, the sporadic nature of photovoltaic (PV) energy sources may cause voltage quality issues such as voltage sags and swells. This becomes more pronounced when there is a higher adoption of PV systems, especially in less robust distribution systems, ultimately resulting in grid instability. The range is from 3 to 7. These voltage quality issues may cause power electronic systems to trip falsely, electronic systems to fail or trigger falsely, and capacitor banks to overheat. The range is from 8 to 10. Modern distribution systems have significant challenges in terms of power quality concerns, which arise from both the load side and the grid side. Given the increasing need for clean energy and the strict power quality standards of advanced electronic devices, there is a need for multifunctional systems that can combine clean energy production with power quality enhancement. In [11], [12], a proposed three-phase multi-functional solar energy conversion system addresses load side power quality challenges. An article in [13], [14] introduces a solar PV converter that operates in a single phase and has the capacity to actively filter electricity. Significant research has been conducted on the integration of sustainable energy production with shunt active filtering. While shunt active filtering has the capacity to regulate load voltage, it does so by injecting reactive power. Therefore, shunt active filtering is unable to simultaneously adjust the voltage at the point of common coupling (PCC) and maintain a power factor of unity for the grid current. In light of the strict voltage quality standards for advanced electronic devices, the implementation of series active filters has been suggested for use in small residences and commercial buildings [15], [16]. In [17], a proposal was made for the integration of a solar photovoltaic system with a dynamic voltage restorer. A unified power quality conditioner (UPQC) is capable of simultaneously regulating load voltage and maintaining grid current sinusoidal at unity power factor. Unlike shunt and series active power filters, the UPQC achieves this by including both series and shunt compensators. Combining a photovoltaic (PV) array with a unified power quality conditioner (UPQC) provides the advantages of both producing clean energy and achieving universal active power. The combination of photovoltaic (PV) array with unified power quality conditioner (UPQC) has been documented in references [18]–[20]. The solar PV integrated UPQC has many advantages over traditional grid linked inverters. These include enhancing the power quality of the grid, safeguarding essential loads from disruptions originating from the grid, and boosting the converter's capacity to withstand transients during faults. Due to the growing focus on distributed generation and microgrids, there is a revived interest in UPQC systems [21], [22].

Generating a reference signal is a significant undertaking in controlling PV-UPQC. The strategies for generating reference signals may be categorized into two basic types: time-domain techniques and frequency-domain techniques [8]. Time domain methods are often used due to their reduced processing demands during real-time execution. Commonly used methodologies include instantaneous reactive power theory (p-q theory), synchronous reference frame theory (d-q theory), and instantaneous symmetrical component theory [23]. An inherent drawback of using the synchronous reference frame theory-based technique is the presence of a double harmonic component in the d-axis current under load imbalanced conditions. As a result, low pass filters with an extremely low cutoff frequency are used to eliminate the double harmonic component. This leads to inadequate dynamic performance [24]. This study utilizes a moving average filter (MAF) to effectively filter the d-axis current and extract the basic load active current. This achieves maximum attenuation while maintaining the controller's bandwidth intact [25]. MAF has recently been used to enhance the performance of DC-link controllers and to achieve grid synchronization via the use of phase locked loop (PLL). The references [26] and [27] are provided.

This work presents the design and performance analysis of a three-phase PV-UPQC. A control system based on MAF (Moving Average Filter) and d-q theory is used to enhance the dynamic performance while extracting active current during load operation. The primary benefits of the suggested system are as follows:

- Integration of clean energy generation and power quality improvement.
- Simultaneous voltage and current quality improvement.
- Improved load current compensation due to use of MAF in d-q control of PV-UPQC.
- Stable under various dynamic conditions of voltage sags/swells, load unbalance and irradiation variation.

The performance of the proposed system is analysed extensively under both dynamic and steady state conditions using MATLAB-Simulink software. The performance is then experimentally verified using a scaled down laboratory prototype under various conditions experienced in the distribution system such as voltage sags/swells, load unbalance and irradiation variation.

II. UNIFIED POWER QUALITY CONDITIONER (UPQC)

The Unified Power Quality Conditioner (UPQC) is a versatile power conditioner that may be used to compensate for various voltage disturbances and changes in the power source, as well as to block the entry of harmonic load current into the power system [28]. This is a specialized power device designed to mitigate the impact of disruptions on the functioning of delicate equipment. The Unified Power Quality Conditioner (UPQC) consists of two voltage-source inverters connected by a shared direct current (dc) connection. The dc connection may be configured as single-phase, three-phase three-wire, or three-phase four-wire [29]. In the active power filter (APF) series, one inverter is regulated as a variable voltage source, while another inverter is regulated as a variable current source in the shunt active power filter (APF). The series Active Filter compensates for power supply anomalies such as harmonics, imbalances, sag, swell, flickers, negative and zero sequence components. The shunt filter is designed to compensate for load current distortions, such as those caused by harmonics or imbalances, as well as to regulate reactive power and manage the dc link voltage [30].

III. System Configuration and Design of UPQC

Figure 1 depicts the PV-UPQC design. The topology is specifically developed for a three-phase system. The system layout included a set of series converters and shunt converters connected in a back-to-back arrangement, with a DC-bus located between them. Typically, the shunt converters are linked during the load end. The Solar Photovoltaic array will be linked directly to the UPQC's common DC-link capacitor using a diode that may impede reverse current flow. The series converter typically operates in voltage control mode and is designed to mitigate grid voltage sags and swells. Inductors are used to link a shunt converter and a series converter to a network or electrical grid. A series-connected injection transformer may be used to inject a voltage signal, created by a series-connected compensator, into an electrical grid system. Ripple filters are designed to eliminate the harmonics that are produced as a result of the rapid switching of the converters. A nonlinear load is used, consisting of a bridge rectifier linked to a voltage-fed load.

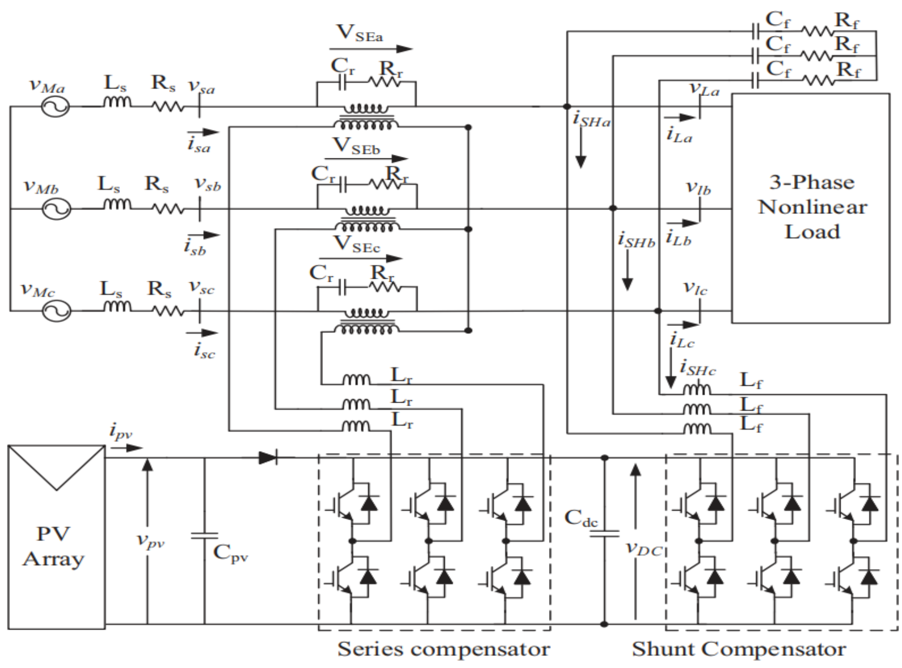

Figure1: System Configuration of PV-UPQC

A. *Basics of design configuration of PV-UPQC*

The design process of the PV-UPQC begins with accurately determining the size of the solar photovoltaic array, the voltage level of the DC-Link, and the capacitor for the DC-Link. The selection of the shunt converter's size is crucial to effectively handle the highest power output generated by the solar

Photovoltaic array, while also compensating for reactive power and current harmonics. The photovoltaic solar array must be coupled with the system via a common DC link of the Unified Power Quality Conditioner (UPQC). Therefore, while determining the size of the PV array, it is important to verify that the maximum power point (MPP) voltage meets the needed voltage at the DC link. When choosing the power rating, it is crucial to note that a solar array should be able to provide the active power required by the load under typical circumstances, while also being able to feed excess power back into the energy grid. The additional components include an interface inductor linked in series, as well as shunt compensators. There is also a series injecting transformer connected to a series connected compensator.

IV. SIMULATION RESULTS ANDDISCUSSION

Figure 2 shows the MATLAB Model of PV Integrated UPQC system. By performing simulation study in MATLAB software, a steady state as well as dynamic system behavior of Solar PV-UPQC can be examined. A load having nonlinear nature is used which comprises of 3Ph diode bridge connected rectifier connected with R-L load. A stepping size for simulation study is taken as 1e-6s. There are different dynamic conditions occurring in the system which may be voltage sag and voltage swells at PCC end and variation in the Photovoltaic irradiation.

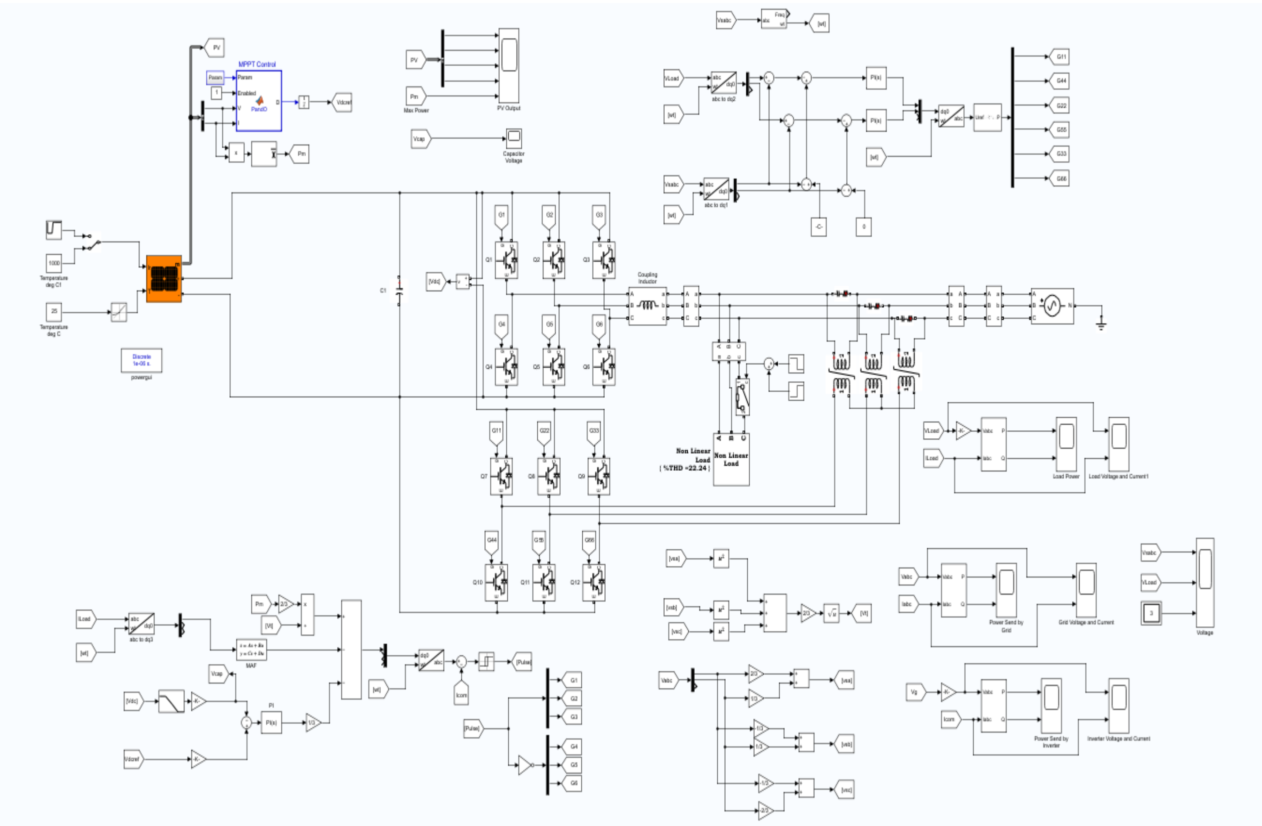

Figure 2:MATLAB Model of PV Integrated UPQC system

TABLE I: SIMULATION PARAMETERS

Simulation Parameters	Values
Maximum Power (W)	213.15
Cells per module (Ncell)	60
Open circuit voltage Voc (V)	36.3
Short-circuit current Isc (A)	7.84
Voltage at maximum power point Vmp (V)	29
Current at maximum power point Imp (A)	7.35
Parallel Strings	18
Series-connected modules per string	25

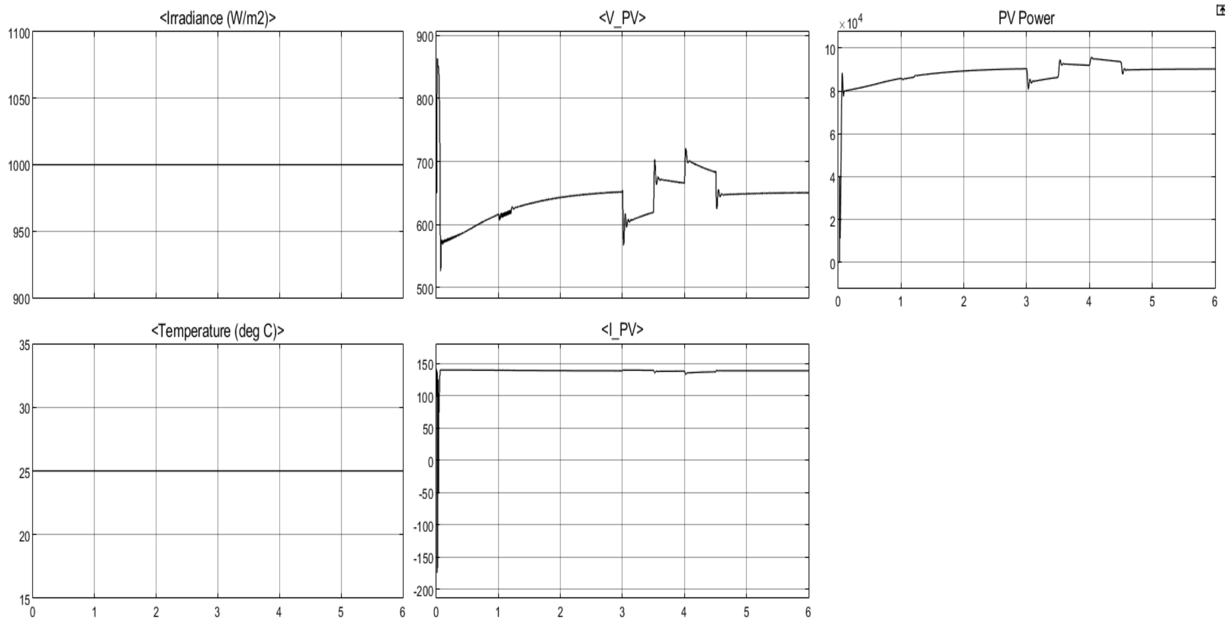

Figure 3: Irradiance, Temperature, Voltage-PV, Current-PV & Power-PV V/s Time in (S)

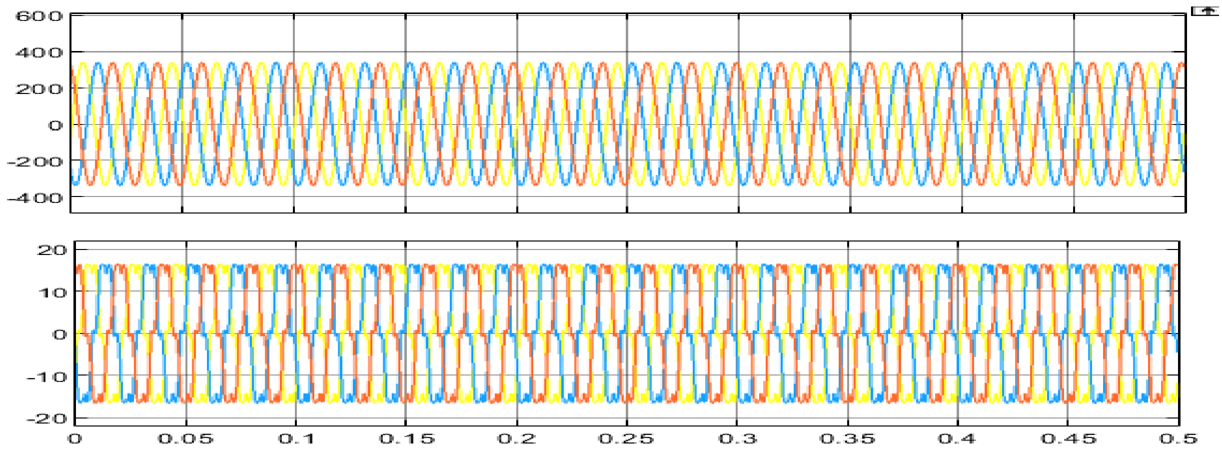

Figure 4: Load Voltage and Current V/s Time in (S)

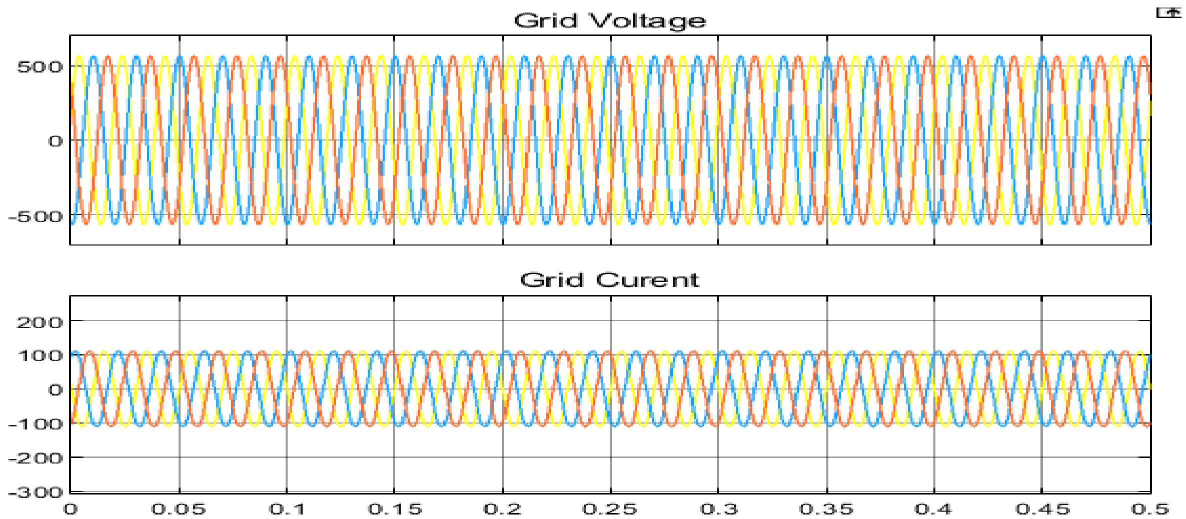

Figure 5: Grid Voltage and Grid Current V/s Time in (S)

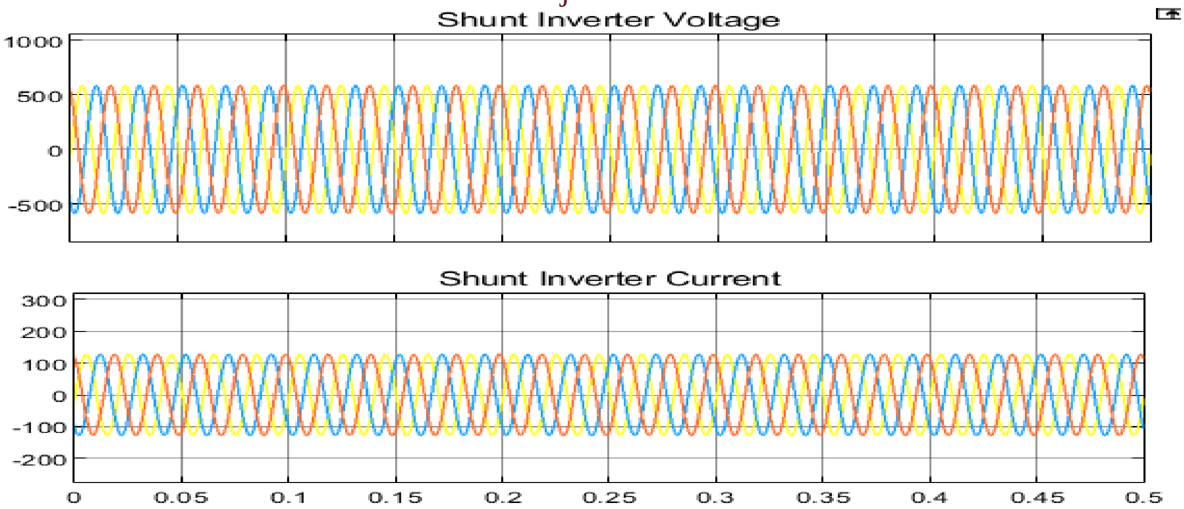

Figure 6: Shunt Inverter Voltage and Shunt Inverter Current V/s Time in (S)

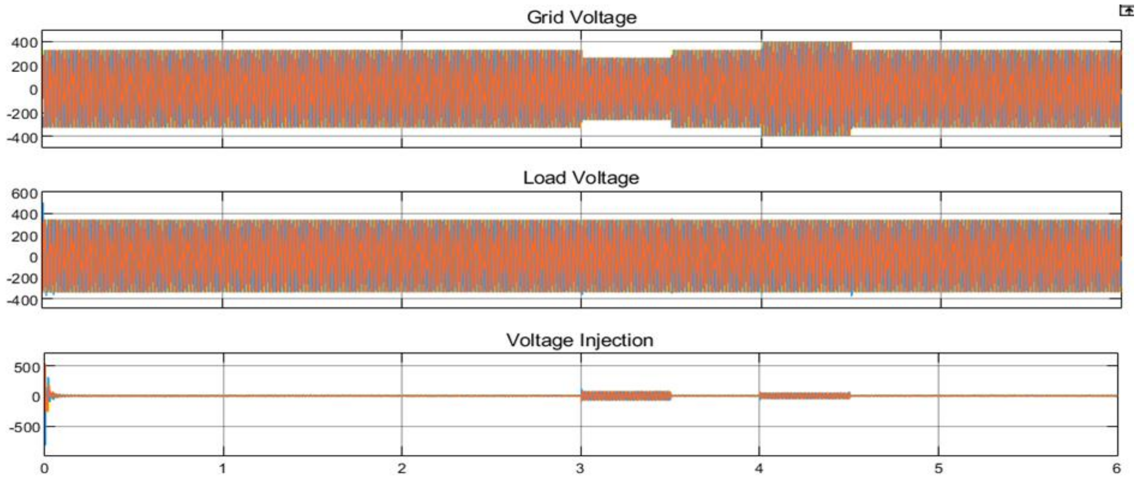

Figure 7: Grid Voltage, Load Voltage and Voltage Injection V/s Time in (S)

CONCLUSION

An analysis has been conducted on the design and dynamic performance of a three-phase PV-UPQC, including changing irradiation and grid voltage sags/swells. The system's performance has been verified by conducting experiments on a reduced-scale laboratory prototype. PV-UPQC has been shown to effectively reduce the harmonics generated by nonlinear loads and ensure that the total harmonic distortion (THD) of the grid current remains within the limitations specified by the IEEE-519 standard. The system demonstrates stability when exposed to changes in irradiation, voltage sags/swell, and load imbalance. The use of a moving average filter has enhanced the effectiveness of d-q control, especially in situations when the load is uneven. PV-UPQC is an effective option for current distribution systems as it combines distributed generating with power quality enhancement.

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