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Power Quality Enhancement in Solar PV and Battery Integrated UPQC Grid Connected System

Shravani Chapala[1], Dr. Narasimham R. L.[2] and Dr. Tulasi Ram Das[3]
[1]*Department of EEE, CVR College of Engineering, Hyderabad, India, shravanic2@gmail.com*
[2]*Dept. of EEE, Rtd. Professor, Andhra University, Vishakhapatnam, India, rlnarasimhamrl@gmail.com*
[3]*Professor Emeritus. Dept. of EEE, JNTUH College of Engineering, Hyderabad, India, das_tulasiram@yahoo.co.in*

***Correspondence:** shravanic2@gmail.com

ABSTRACT- This paper discusses a distributed generation system consisting of grid-connected solar PV and a battery-integrated Unified Power Quality Conditioner (UPQC). Embedded in the PV array, the UPQC consists of a series and shunt converter connected back through a common DC link. In this system, power quality problems of clean energy, such as harmonics, voltage drops, ripples, are compensated by injecting active energy into the power grid. The shunt converter is controlled to maintain a constant DC link voltage and harmonic compensation of the load current. The main voltage problem is compensated by a series converter that injects the voltage during sag and swell. The advantages of integrating renewable energy sources and enhancing power quality are brought together in this system. The performance of the system is analyzed during voltage sag, swell condition and under unbalance condition for nonlinear load along with power flow analysis through the enhancement of dc bus voltage. Finally, the simulation results are shown for the estimation of dynamic performance of PV, battery integrated UPQC system during unbalanced condition.

Keywords: Battery management system, Grid integration, MPPT, Power quality, Solar PV, UPQC.

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1. INTRODUCTION

The distribution system experienced power outages due to a rapid surge in non-linear demands. Harmonics are produced when non-linear loads (NLLs) are used or when renewable energy sources (RES) are integrated into power grids. End customers often experience a decline in power quality due to harmonics produced by power electronics [1][2]. RES at the distribution level, also known as distributed generation (DG), has seen a surge in voltage and current quality issues, posing a major challenge to the scientific community. Power failures in distributed systems are often brought on by systems built on cutting-edge semiconductor technology. Furthermore, this nonlinear load behaves abnormally when there is a voltage disturbance. Non-conventional energy sources such as WES, PVS and geothermal, hydroelectric cogeneration systems are used to meet the energy needs required for population growth and industrialization, as well as being environmentally friendly according to environmental safety regulations. Conventional energy sources such as coal, gasoline, natural gas, and fossil fuels produce radial and extreme effects on the environment, which can cause global warming and the greenhouse effect in the atmosphere. The integration of non-conventional energy sources such as wind into existing renewable energy systems can reduce the atmospheric effects of conventional energy systems [3].

In addition, the increasing number of renewable energy systems such as solar and wind have become a major problem in the distribution system due to their intermittent nature. Several topologies of grid-connected PV systems have been presented in active filter solutions to maintain current quality in the distribution system [4]. Photovoltaic grid integration provides an advantage over conventional systems, but voltage disturbances occur at the common connection point (PCC) due to non-linear loads. Therefore, the future power system should achieve better power quality through proper network integration topology and cost-effective solutions.

Therefore, power quality improvement devices and power conditioners are attracting attention as power quality improvement applications [5], [6]. DSATCOM integration of PV system is used for power quality improvement along with the various evaluator algorithms for battery modelling [7],[8]. Among the various types of inverters, unified power quality regulators (UPQC) have attracted great interest due to their high performance in reducing voltage and power disturbances in distribution systems [9], [10]. The use of UPQC in PV system integration has improved the performance of traditional his UPQC by providing the desired solution to power quality issues and critical load protection against voltage fluctuations [11], [10].

In [12], [13], it is discussed how PV panels and UPQC may work together. Compared to traditional grid-tied inverters, integrated photovoltaic UPQC offers many benefits, including improved grid power quality, protection of critical loads from grid failures, and increased tolerance to transient inverter failures. In [14], [15], it discusses PV modelling under various weather conditions.

Both series and shunt active power filters are compatible with the UPQC (SAPF). In [16], [17], you may find a variety of improvements to UPQC, such as a lower number of switches, higher intermediate circuit voltage, and cleaner power production. The harmonic impacts of individual transformers may be mitigated, and harmonic sources can be cancelled out thanks to a system that employs an inductive power filter (IPF) presented in the literature. Various researchers have proposed an analogy band-pass filter to eliminate harmonics with a very simple structure [18], [19].

This paper proposes the control and operation of a three-phase three-wire PV-B-UPQC system in a distributed network with significant non-stationary loads requiring uninterrupted power supply to the loads. This document primarily focuses on mitigating PQ issues in RES systems due to voltage/current, sag, swell, noise, non-linear load, unbalanced load, and THD reduction issues. The controller with UPQC-PQ device which is used to alleviate these issues. The main contribution of the document is presented as follows: (1) the combined function of generating renewable energy and improving the quality of downstream and downstream electricity in one system. Therefore, this system has better utilization than the traditional grid-connected inverter system. (2) RES is connected to grid system and PCC can be connected to non-linear load, unbalanced load, or both. Embedded system can introduce harmonics and unbalance under distorted supply voltage (3) this system controls the load voltages by keeping the mains current as sinusoidal and the power factor near to the unity. The proposed control strategy is designed and validated by connecting nonlinear loads and unbalanced loads to the PCC. (4) This also provides constant power during disturbances in PV power generation and voltage fluctuations to the grid, thus improving the stability of the distribution grid.

2. PV-BATTERY-UPQC SYSTEM CONFIGURATION

The configuration of UPQC integrated with a photovoltaic array is shown in *figure 1*. The system mainly consists of UPQC series and shunt converters, boost converters, bi-directional converters, and regulators. At the common connection point, the system is integrated into the UPQC fixed connection. Solar photovoltaic panels and batteries are directly integrated into the power line. Voltage regulation is achieved by the series converter and compensates for dips and swells of the line voltage, while the shunt converter compensates for load harmonics generated by the non-linear load and connected on the open side. The serial and shunt converters are connected via an interface inductor. The load is a bridge rectifier, which is a non-linear load. The transformer in series is used to supply the generated voltage by the compensator in series with the network.

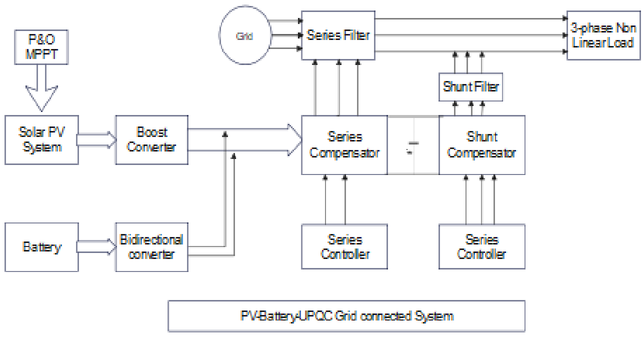

Figure 1: PV-Battery integrated UPQC System

2.1 Solar PV and Battery Design

With proper selection of size of PV array, dc link voltage and dc link capacitor, the PV-Battery-UPQC system is designed. Due to the PV system's DC link integration with the UPQC grid, an MPPT based boost converter was required for the system's architecture. The boost converter is controlled to extract the PV system maximum power and to maintain constant DC link voltage. *Figure 2* shows the battery integrated PV system model. The following are the parameters used for designing the system.

DC link voltage

$$V_{dc} = \frac{2\sqrt{2}VLL}{\sqrt{3}\,m}$$

DC link capacitor

$$C_{dc} = \frac{3ka\,Vph\,Ish\,t}{0.5\,X\,(V^2dc - V^2dc1)}$$

Shunt converter inductance

$$Lf = \frac{\sqrt{3}mVdc}{12afsh\,I}$$

Reference grid current

$$Iref = ILd + Iloss + Ipv$$

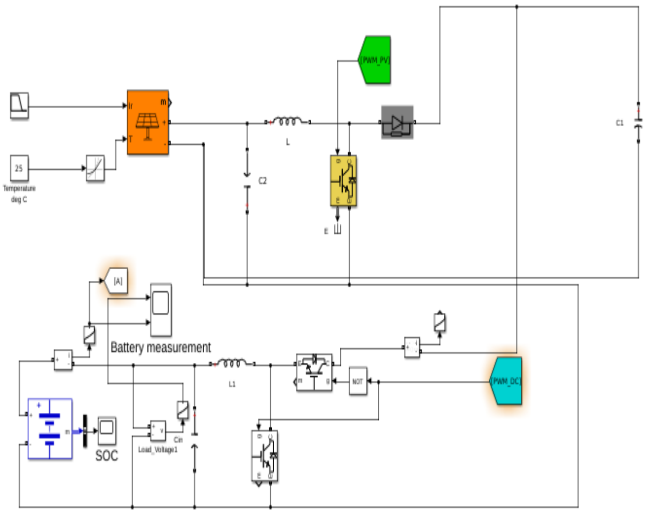

Figure 2: Solar-PV system

2.2 UPQC

The shunt converter is designed in such a way that it must compensate for load current, to mitigate current harmonics apart from the handling of PV power output. To deal with voltage changes on the load side, the series converter is built. In a typical operation, PV provides electricity to the load and injects power into the grid. The configuration of UPQC is shown in *figure 3*.

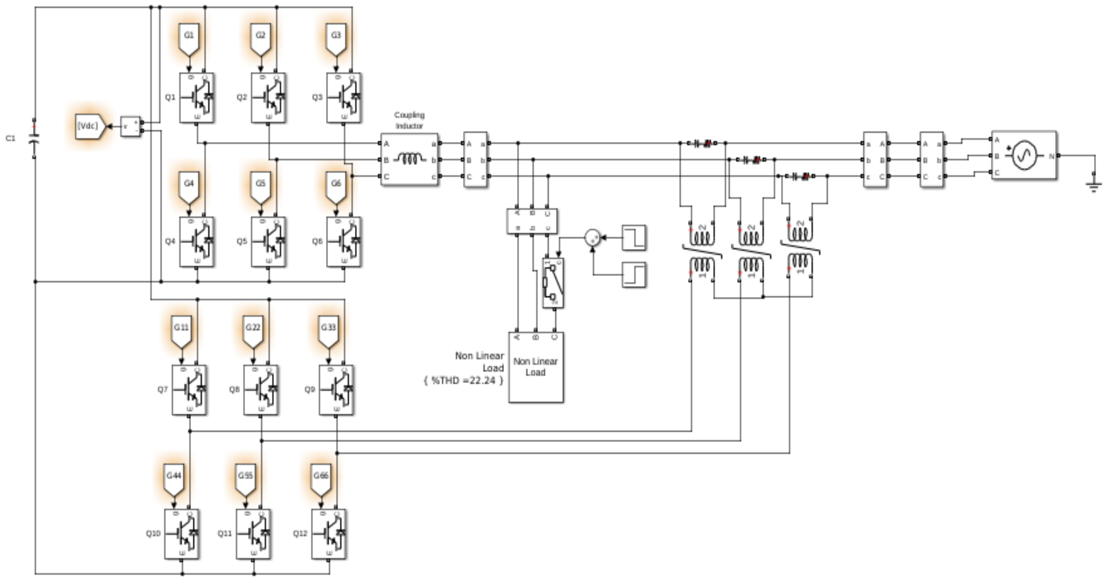

Figure 3: Configuration of UPQC

3. SYSTEM PERFORMANCE AND CONTROL

In this system which is given in *fig.4*, the compensation scheme utilized is of dual compensation approach, which has advantages over traditional compensation scheme with one grid connected inverter. The series converter is controlled to compensate voltage and in contrast shunt converter is controlled for grid current compensation.

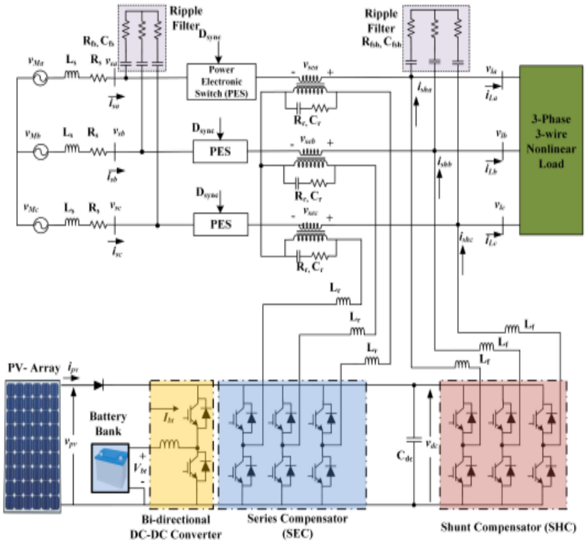

Figure 4: Schematic diagram of the system

The transformer links the system to the series converter. This can be controlled to mitigate the voltage sag and swell problems at source, by injecting the compensating voltage. In this method, the source and the load voltages can be compared, and the generated error is compared with reference voltage after the conversions of *abc* to *dq0* and then converter back to the initial system PWM signals can be generated through voltage-controlled signals. *Figure 5* shows the block diagram of series converter control structure.

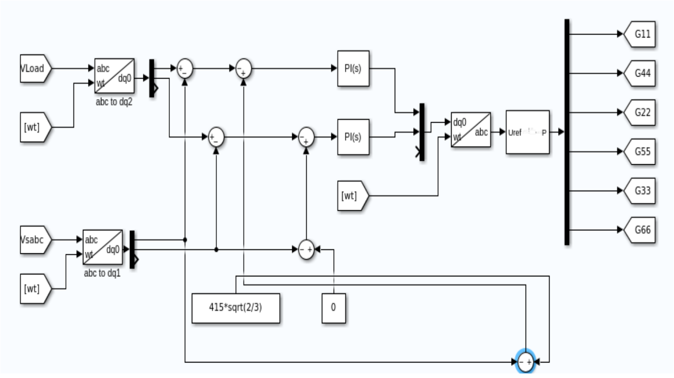

Figure 5: Maximum power Series converter control structure

Figure 6 shows the sunt converter controller. This can be controlled to compensate for the current related power quality problems along with that constant DC link voltage is maintained. A PV system with P&O algorithm produces reference voltage for shunt converter. Shunt converter controlled to mitigate unbalanced nonlinear load conditions. *Figure 7* and *8* show the PWM generator for generating the control signals for boost converter which is fed to PV system and nonlinear load which is bridge rectifier respectively.

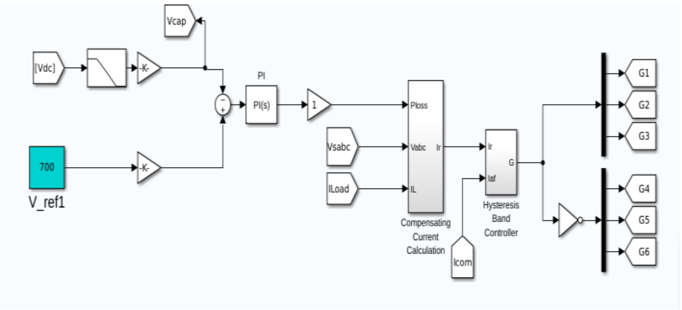

Figure 6: Control structure of Shunt converter

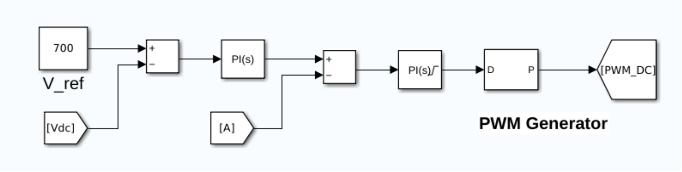

Figure 7: Boost converter PWM generator

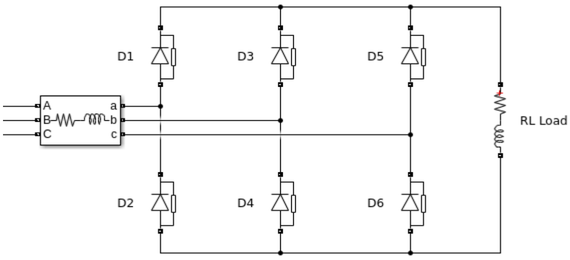

Figure 8: Nonlinear load

4. SIMULATION RESULTS

We use system simulation in MATLAB/Simulink to examine both the static and dynamic properties of the PV-Battery-UPQC. System load, here meaning nonlinear load, is provided by a three-phase diode bridge rectifier connected to an RL load. A few dynamic situations, including voltage dips, over voltages, imbalance, and changes in solar radiation, are included in the analysis. In this simulation, the solver step size is set to 1e6s.

Simulation parameters: Utility grid voltage: 400V (Phase to phase), frequency: 50Hz; Dc link capacitance: 6668 μF; DC link voltage: 700V, Coupling inductor 1.39mH; three-phase full bridge rectifier with R = 30 Ω, L =0.15mH; switching frequency: 10 kHz; PV array parameters: Isc=7.84 A, Imp= 7.35A, Voc =36.3V, Vmp = 29V, Ppv = 10kW; Battery nominal voltage = 480V, rated capacity=48Ah. The parameters of the PV-Battery integrated UPQC System are shown in *table 1*.

Table 1: PV-Battery integrated UPQC System parameters

Parameter	Values
System Voltage	400V
Frequency	50Hz
DC link C	6668 μF
DC link voltage	700V
Coupling L	1.39mH
Rect. Resistance	30 Ω
Rectifier Inductor	0.15mH
fsw	10kHz
Isc	7.84 A
Battery	480V 48Ah Lithium Ion
PV array	Ppv = 10kW Isc=7.84 A Imp= 7.35A Voc =36.3V Vmp = 29V
M	1
A	1.5
Ripple current	20%

4.1 Performance of the System During Voltage Fluctuations

In this sub session the performance of the system during voltage fluctuations is analysed. Voltage sag and swell condition is compensated by using UPQC. PCC voltage sag and swell, and their effects on the system, are considered. The irradiance of the PV system is kept constant that to at 1000 W/m2. The PV system specifications like irradiance, voltage, current and temperature are shown in *figure 9*. Generated PV power is shown in *figure 10* which is constant. Initial %SOC of battery is considered as 50 and the battery %SOC is shown in *figure 11* for a period of 1 sec.

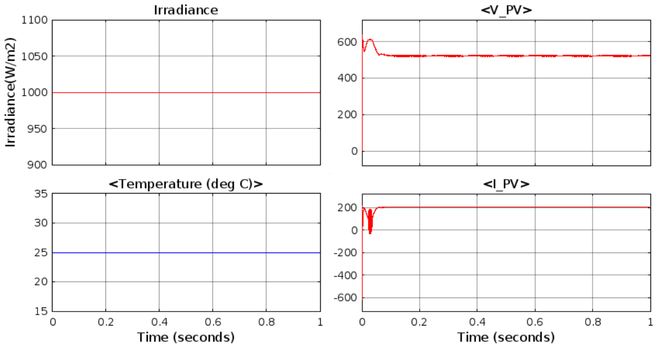

Figure 9: PV system parameters

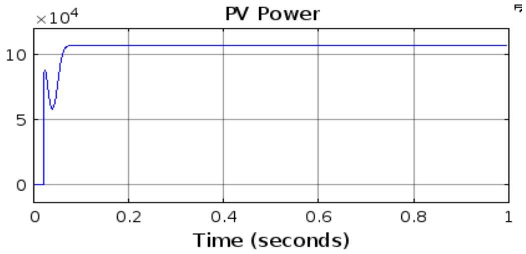

Figure 10: PV power

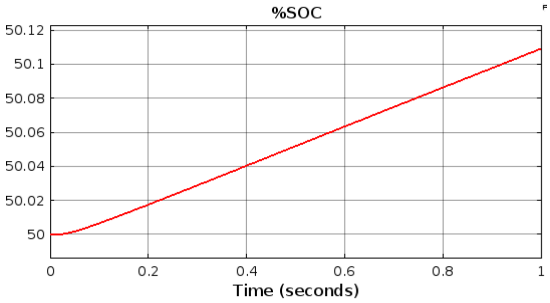

Figure 11: Battery %SOC

The grid is considered as constant power source and the load is also considered as constant. There is a voltage sag between 0.1 to 0.2s and from 0.3 to 0.4s there is voltage swell as shown in *figure 12*. The series converter is controlled based on voltage. During sag and swell condition series converter injects voltage in phase and in phase opposition respectively, so the grid voltage is maintained constant.

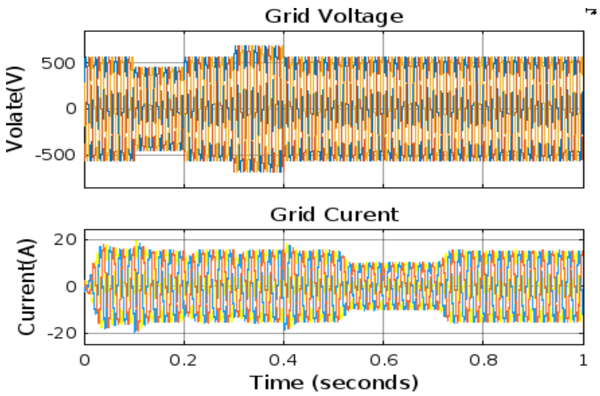

Figure 12: Grid voltage and current

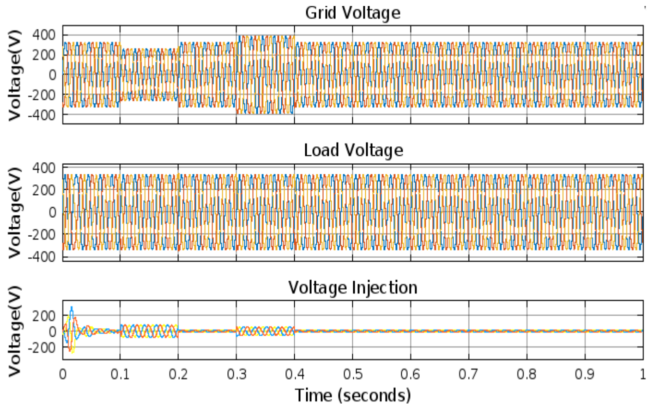

Figure 13: Grid voltage, Load voltage and Series converter injected voltage

The supply voltage, load voltage and injection voltage of the series converter are shown in *figure 13* and *14*. The drop and overvoltage on the open side is compensated for by the voltage injected from the serial converter. The serial converter injects a compensation voltage to reduce voltage quality problems.

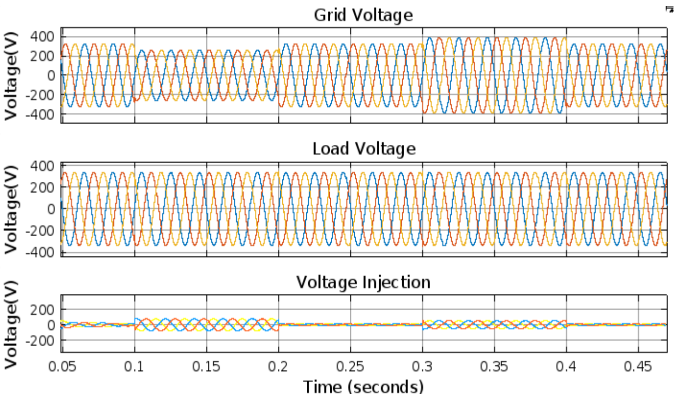

Figure 14: Grid voltage, Load voltage and Series injected voltage during sag and swell condition

4.2 Performance of the System during Nonlinear Load Condition

Three phase bridge rectifier is considered as a load which is a nonlinear load. Load power and grid power are shown in *figure 15 and 16*.

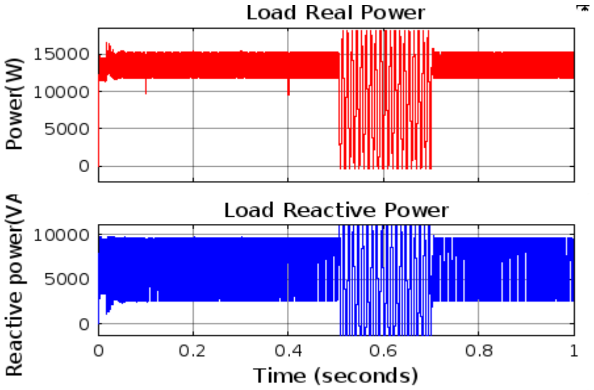

Figure 15: Load power

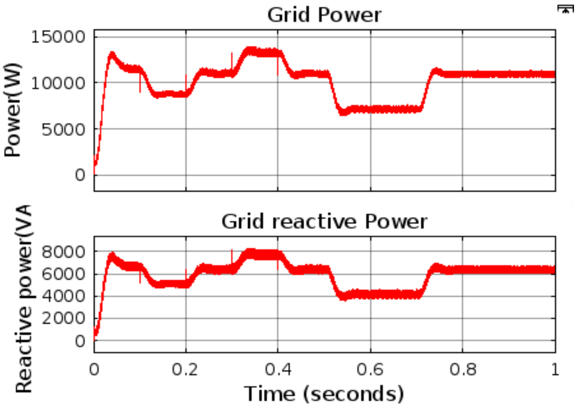

Figure 16: Grid power

Shunt converter voltage and current are shown in *figure 17* below. Shunt converter is controlled to maintain sinusoidal source current during nonlinear and unbalance load conditions. Non sinusoidal load current due to non-linearity load condition and sinusoidal grid current after compensation are shown in *figure 18*.

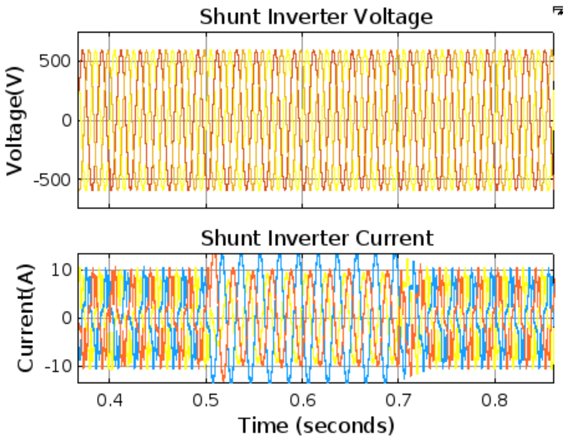

Figure 17: Shunt inverter voltage and current during nonlinear load condition

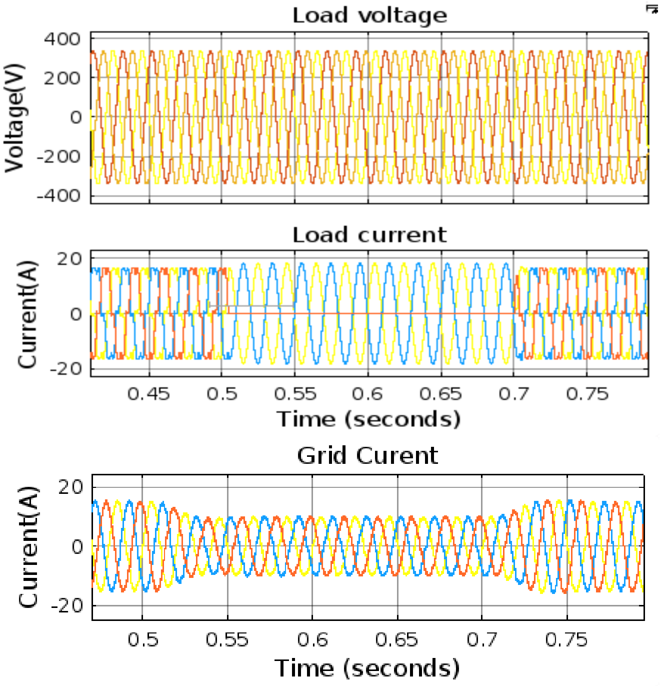

Figure 18: Non sinusoidal current due to nonlinear load condition and Sinusoidal grid current after compensation

4.3 Performance of the System at Unbalancing Load Condition

Figure 19 displays the time-varying behavior of the imbalanced condition under stress. As of t = 0.5 s, the load's phase "c" has been turned off and the same is continued up to 0.7s. It can be observed that the load current is non sinusoidal in shape and unbalanced one. The effect of unbalanced non sinusoidal load current is compensated for and is shown in *figure 20*. The electric grid current has a sinusoidal form, and the power factor is 1 as can be observed. The rise in network current supply is a result of a fall in total effective load. The intermediate circuit voltage also remains stable and close to the regulated value of 700 V.

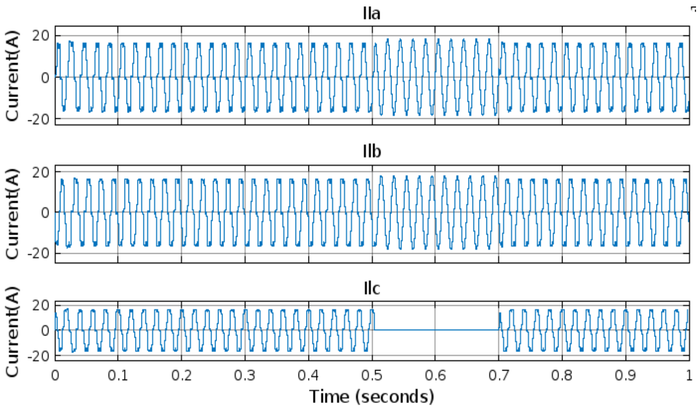

Figure 19: Non sinusoidal load currents during unbalance

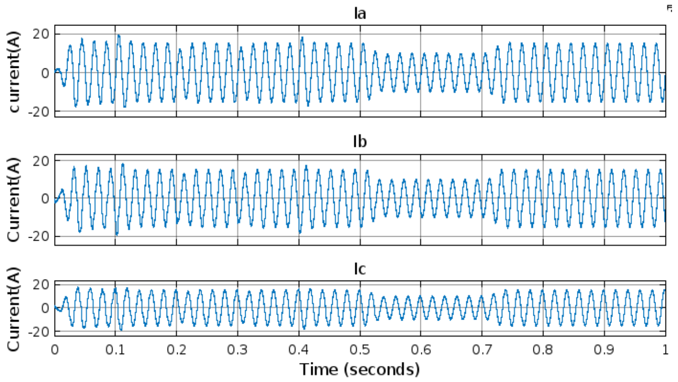

Figure 20: Grid current after compensation

4.4 Performance of the System under Varying Irradiation

The dynamic characteristics of the system with changes in solar radiation are shown in *figure 21*. Solar radiation goes from 1000 W/m2 in 0.4 s to 0 W/m2 in 0.8 s. The irradiance changes, the output power of the photovoltaic generator, and therefore the grid current, also changes when the photovoltaic generator feeds into the grid. The shunt compensator monitors the MPPT as well as the harmonic compensation caused by the load current. *Figure 22* shows the battery %SOC during irradiance by considering initial value of 80. The grid, load, PV, and inverter power with changes in solar radiation are shown in *figure 23*. The PV power is maximum during initial conditions for radiation of 1000 W/m2 and when solar radiation goes from 1000 W/m2 in 0.4 s to 0 W/m2 in 0.8 s, the load power is going to meet from the inverter.

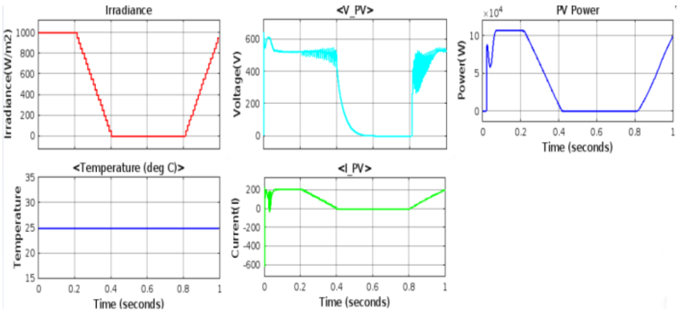

Figure 21: PV during variable irradiance

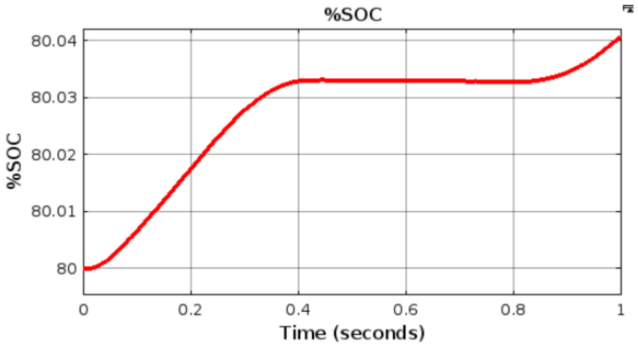

Figure 22: Battery SOC during variable irradiance

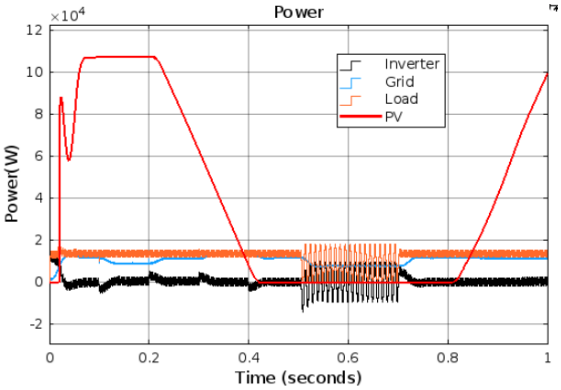

Figure 23: Power contribution during variable irradiance

Table 2: Comparison of features of existing methodology and this paper

Ref.	Methodology	Grid Integration	VS THD (%)	IL THD (%)	Response	Grid pf
[18]	UPQC with PI Controller	With Grid	Greater	High	Slow	Less than Unity
[17]	PV - UPQC with PI Controller	Without Grid	Greater	High	Slow	Less than Unity
[15]	PV - UPQC - Microgrid	Without Grid	Greater	High	Slow	Less than Unity
This paper	PV-Battery integrated UPQC	With Grid	Lower	Low	Fast	Approx. equal to Unity

Table 3: THD Comparison

Parameter	Existing System [18]	PV-battery- UPQC system
Load current	24.1%	8.64%
Grid Voltage	11.65%	2.24%

Table 3 shows the average THD values of the grid voltage and load current for the PV – Battery integrated UPQC system with respect to the existing system. The present system compensates for the voltage variations in the source voltage and the effect of nonlinear load. It can be observed that the UPQC based load current compensation system reduces the load current THD from 24.1% to 8.64%. It indicates that the system compensates for the voltage sag and swell problems and better performance with respect to THD.

Table 4: THD values load current

Harmonic order	%THD With out PV-battery integrated UPQC	%THD With PV-battery integrated UPQC
3rd harmonic	24.1%	8.64%
5th harmonic	24.1%	8.64%
7th harmonic	24.1%	8.48%

Table 5: THD values load voltage

Harmonic order	%THD With out PV-battery integrated UPQC	%THD With PV-battery integrated UPQC
3rd harmonic	15.2%	3.54%
5th harmonic	15.2%	3.64%
7th harmonic	15.2%	3.48%

Table 4 and *5* show the THD comparison of the load current and load voltage respectively during unbalancing load condition for different harmonic order without any compensation and with the PV-battery integrated UPQC system respectively. The proposed method has PQ issues improvement along with real power management to the grid. *Table 2* presented the comparison of presented work with the existing methodology.

5. CONCLUSION

This paper describes the design and performance of a UPQC grid connection system integrated with a PV array is analyzed. The performance of the system during the static and dynamic conditions is evaluated. The UPQC system built into the PV array reduces voltage sag and surge and harmonic problems generated by nonlinear chargers. It was found that the network current remains sinusoidal under nonlinear and unbalanced conditions. To improve the power quality of the distributed generation system, this system is a good solution. UPQC series and shunt converters are controlled to reduce voltage and associated power quality issues. Besides power quality issues, power management between loads, grids and PV systems has been achieved. The system response is satisfactory during various conditions of sag/swell, imbalance, non-linear load, and varying irradiance. In this grid-tied system, it is possible to depend maximum on the power of the PV system and the minimum in the grid. The system can be extended by considering another renewable source like wind along with PV. The way the controller is constructed could also be changed by replacing the conventional UPQC controller with optimization techniques.

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