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ABSTRACT

Recently there is a rapid increase in exploring the potential in renewable energy sources(RES) like solar, wind etc. Because of the abundance of solar energy, the interest in installing solar power generation systems are accelerating day by day. As a result, large number of photo-voltaic(PV) systems are getting interconnected with utility grid. Due to high penetration of PV power to grid, energy regulatory bodies are imposing strict grid codes to maintain the power quality at the PCC. This paper discusses the detailed modeling and control strategies adopted for three phase two stage photo-voltaic unified power quality conditioner (2SPV-UPQC) connected to micro grid. Besides injection of active power into the grid, the series compensator of the 2SPV-UPQC system compensates for the power quality problems in grid such as load unbalancing, voltage sags/swells, harmonics etc. The proposed system combines both the benefits of improving power quality and clean energy generation. In this paper, a 50 KW system is simulated in MATLAB/Simulink software and the proposed control is illustrated using various case studies. Different power quality issues and along with associated remedies are discussed. The results obtained demonstrate the ability of the proposed system to improve power quality in microgrids.

KEYWORDS: Distributed Generation, Renewable Energy Sources, Point of Common Coupling, Maximum Power Point Tracking, Two Stage Photovoltaic Unified Power Quality Conditioner.

1. INTRODUCTION

In recent decades, owing to the increased demand for electric power, the generation of electricity from RES like solar, wind etc has grown a lot. Global intensive efforts has been put to overcome the harmful environmental effects produced by polluting energy sources like coal, natural gas & oil which also adds the production from RES. Distributed generation system using RES have done a major contribution in bringing advanced features which aid in planning the traditional power systems[1]. Out of the RES, solar energy has arisen as a promising renewable energy source owing to its abundance in earth's surface. Using photovoltaic (PV) cells, panels and arrays, solar energy is transformed into electrical energy.

Grid-connected PV systems can be installed by means of single-stage (S-S) [2], [3], [4] or two-stage (2S) power conversion [5]. S-S PV systems typically comprise of only a grid-tied inverter which converts dc to ac. In S-S, the PV system is connected to the dc bus of the grid-tied inverter directly. But in 2S PV, a dc/dc converter is additional positioned between the PV system and the inverter. In this layout, the MPPT is accomplished by the dc/dc converter [6].

The loads connected in utility are mostly highly nonlinear power electronics loads. Additionally, the increased penetration of RES like solar PV in utility system leads to disturbances in voltage and ultimately in grid instability [7]. These factors lead to malfunction of industrial equipment, false tripping of sensitive power electronic equipment, data loss etc. The increased installation of RES and nonlinear loads result in various PQ problems both at grid side and load side.

To mitigate the power quality issues, modern power electronics has contributed custom power devices like DSTATCOM, DVR and UPQC. Grid voltage sag/swells are compensated by DVR which is connected in series with grid [8]. Power quality issues like reactive current, harmonics and load imbalance are compensated by DSTATCOM which is a shunt compensation device connected in parallel at PCC [9]. The combined functionality of DSTATCOM and DVR is provided by UPQC [10] where series and shunt inverters are back to back connected at DC side. Numerous categories of UPQCs have been narrated in the literature with respect to the topology, location of the shunt/series inverters and control strategies.

Recently the concept of active power filter integration with DG sources [11], [12] has been reported in the literature. With the increased prominence on DG and micro grids, there is a revived interest in UPQC systems [13], [14]. The integration of PV array with UPQC has been reported in [15]. In addition to the fault ride through capability of converter, PV integrated UPQC has several advantages such as mitigating PQ issues in the grid, shielding sensitive loads from grid side disturbances over traditional grid tied inverters. The integration of single stage PV array with UPQC has been reported in [16],[17], [18],[19].

In this paper, dynamic performance of two stage photovoltaic upqc integrated (2SPV-UPQC) system with adaptive voltage controller is analyzed and studied using various case studies like grid voltage fluctuations, voltage interruption, harmonics, and load unbalancing. The proposed 2SPV-UPQC system has the capability of enhancing the quality of voltage and current at PCC and will be an effective solution for most of the power quality problems. Using Matlab / Simulink software the proposed system is modeled and simulated. The results are presented using various case studies to show the ability of the proposed 2SPV-UPQC system in mitigating PQ issues.

2. MATERIALS AND METHODS

Power quality issues and solutions

2.1.1 Introduction

Power quality problems have become serious concerns as a result of increased usage of nonlinear loads such as industrial drives, IT infrastructure devices etc. In addition to these, capacitor bank switching, lightning strikes, and grid faults can cause power quality problems such as voltage unbalance, sag, swell, transients, interruption, harmonics etc. On the other-hand, pure sinusoidal wave is required for the proper functioning of sensitive loads like digital equipments, controllers etc. Compensation mechanism is needed in utility grids in-order to meet the PQ standards for end users.

2.1.2 Importance of Power Quality

Nowadays, customers are aware of the utility grid power quality issues. As end users are becoming well informed about grid power quality issues, utilities are challenged by them. Power quality concerns are increasing day by day from both utilities and end users of electric power. This is mainly due to the following factors:

- More sensitive equipments are connected to utility grid.
- Voltage disturbance is caused by some of the equipment.
- A growing need for standardization of power quality.

2.1.3 Solution for Power Quality Issues

In advanced power electronic technology custom power devices are used to mitigate PQ problems and provide good quality power as per standards. The customer power devices are basically power electronics-based devices which are used to supply valuable power to end user. The introduction of micro grid to the system helps reduce network congestion and the controller is used to alleviate grid PQ problems.

The PQ problems can be mitigated in three ways as below:

- Reducing disturbances in power supply
- Improving immunity of the load equipment to the disturbances in power supply
- Implanting compensation equipments between the utility grid and the sensitive loads

This paper focuses on the last option, as suitable compensation devices are needed to improve power quality in load side. Some of the custom power devices used to mitigate PQ problems in the load side includes:

- Solid State Transfer Switch
- Distribution Static Compensator
- Dynamic Voltage Restorer
- Unified Power Quality Conditioner

On study it was concluded that alleviation of voltage interruption and additional provision of active power supply to the network, need to be addressed. The existing compensation devices have not engrossed much on long voltage interruption problems and also the exploitation of photo-voltaic energy. The proposed 2SPV-UPQC system improves significantly the PQ based on voltage sag/swell, load unbalancing, harmonics and voltage interruptions.

Modeling of two stage photovoltaic upqc

2.2.1 Introduction

Now a days usage of non-linear loads in utility grids create many PQ problems. Poor power quality results in equipment tripping, malfunction of industrial equipments, loss of data, stoppage of sensitive equipments etc. Solar energy has high potential to provide power supply with minimal environmental impact, since it is clean and pollution free. When the power supply crisis started in the recent past, PV generation became a very popular alternative for fossil fuel in-order to generate electrical power.

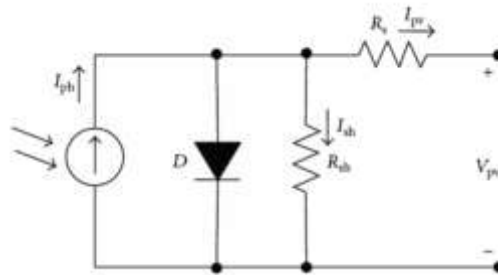


Fig.1. Solar Cell - Equivalent circuit

A PV/Solar cell convert direct sunlight to electrical energy which is the basic building block of solar panel. The equivalent circuit of a typical solar cell is shown in figure 1. A number of solar cells are interconnected to form a panel/module as shown in figure 2. A solar array is formed by interconnecting a large number of solar modules in series and parallel forms.

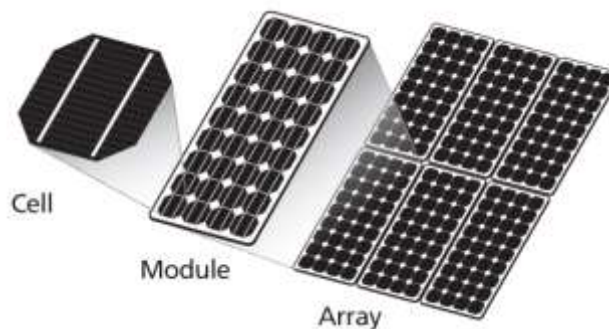


Fig.2. Arrangement of Solar Cell, Module and Array

Two stage PV system consists of multiple solar arrays and DC-DC converter which are connected in parallel to obtain the sufficient power. In below sections the design and development of the proposed 2SPV-UPQC system

to mitigate PQ issues in AC micro grid is discussed.

2.2.2 Two Stage Photovoltaic UPQC Power Circuit

2SPV-UPQC is a multitasking power conditioner which is an integration of both series and shunt compensator. The power circuit structure of 2SPV-UPQC is shown in figure 3.

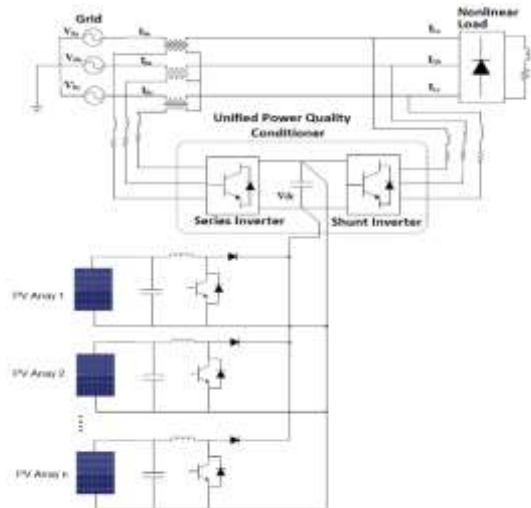


Fig.3. Two Stage PV-UPQC system

2SPV-UPQC system consists of major components such as PV Arrays, DC-DC Converters, DC link capacitor, shunt and series inverters, inverter controllers, filters and coupling transformer. In 2SPV-UPQC system, one DC-DC boost converter is integrated with each PV array. The MPPT is done by DC-DC boost converter and shunt inverter maintains the DC link voltage. The shunt and series inverters are back to back connected to common DC bus. Control scheme employed for compensation in 2SPV-UPQC system includes controllers for series inverter and shunt inverter.

The series part of the 2SPV-UPQC mainly includes a series inverter which is connected in series with the feeder. AC side of the series inverter consists of Low Pass Filter (LPF) and coupling transformer whereas the dc side is connected to the common DC link capacitor along with DC-DC boost converter and PV arrays. The switching harmonics generated by series inverter is prevented by LPF. The primary function of the series coupling transformer includes voltage matching and isolation between the series inverter and the network.

The shunt part of the 2SPV-UPQC mainly includes a shunt inverter which is connected in parallel with load at PCC. AC side of the shunt inverter consists of shunt coupling inductor whereas the dc side is connected to the common DC link capacitor along with DC-DC boost converter and PV arrays. The switching harmonics generated by the shunt inverter is filtered out by shunt interface inductor.

The main purpose of series inverter is the compensation of grid voltage sags and swell. It inject series compensation voltage, in such a manner that load voltage is balanced and undistorted. By comparing the load and supply voltage, the series controller trigger firing pulses for series inverter switches. Series LPF filter out the harmonics due to switching action of series VSI.

The main purpose of shunt inverter is to compensate load current harmonics, reactive power and regulate the DC-link voltage at common DC bus. Current is injected at the PCC by shunt inverter such that the reactive along with the harmonic components of the load currents are canceled and a balanced load current is supplied. The DC link capacitor provides the injection current. Based on the supply voltage, supply current, PV voltage, PV current and load current the shunt controller generates firing pulses for shunt inverter switches.

2.2.3 Design of PV Array Parameters

The 2SPV system is used to provide a DC source for UPQC which will inject active power into micro grid. The rating should be such that, the 2SPV system supply the active power to the load and also feed power into the grid under nominal conditions.

2.2.3.1 PV Array & DC-DC Converter

PV array acts as DC source for UPQC. It injects active power into the distribution system. It includes inductors, capacitors and diodes. A large capacitor is connected between DC links to achieve continuous voltage from converter. Parallel capacitor limit voltage from PV panel. The output voltage V_o of the DC-DC boost converter is regulated by varying duty cycle(D).

$$V_o = V_{pv} * \left(\frac{1}{1-D}\right) \tag{1}$$

Where,

V_o - output voltage of DC converter

V_{pv} - photovoltaic array voltage

When duty cycle D is 0, the output voltage equals source voltage. When the converter switch is closed, the current through inductor rises and inductor stores energy. The inductor voltage is given by

$$V_L = L * \left(\frac{di}{dt}\right) \tag{2}$$

When the device (IGBT) is switched off, the inductor current falls and the stored energy from inductor is transferred to the capacitor.

PV module specification is given in Table 1.

Solar PV Module Specification	
Max. Power- Pm	295.124 W
Open circuit Voltage	44.3 V
Short circuit current	8.74 A
MPP Voltage	35.6V
MPP Current	8.29 A

2.2.3.2 DC-DC Converter Controller

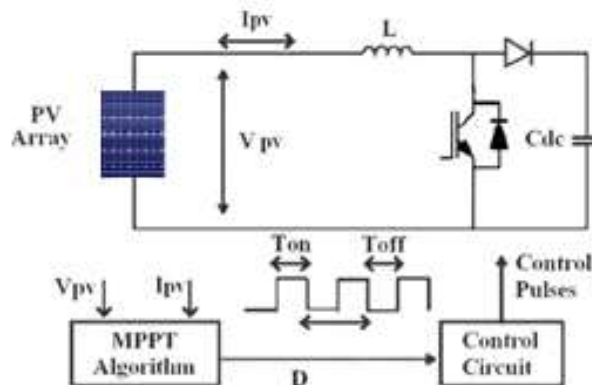


Fig.4. Arrangement of Solar Cell, Module and Array

The photovoltaic array output voltage is low in magnitude and varies. Hence a boost converter is need to step up and generate regulated higher DC voltage. The low voltage input from the PV array is fed to the DC bus after boosting by DC-DC boost converter.

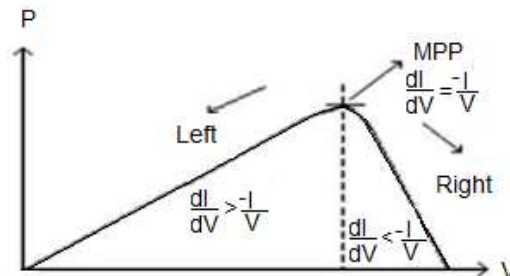


Fig.5. Solar Cell PV Curve

Maximum Power Point (MPP) traverse in the P-V curve, which relay on factors like temperature and irradiance. In this paper, the maximum power from the PV arrays are extracted using incremental conductance algorithm. The relation between $-1/V$ and dI/dV is used to calculate MPP. According to incremental conductance algorithm, if dI/dV is less than $-1/V$ then MPP lies on the right side of current position and if the dI/dV is greater than $-1/V$ then MPP is on left side.

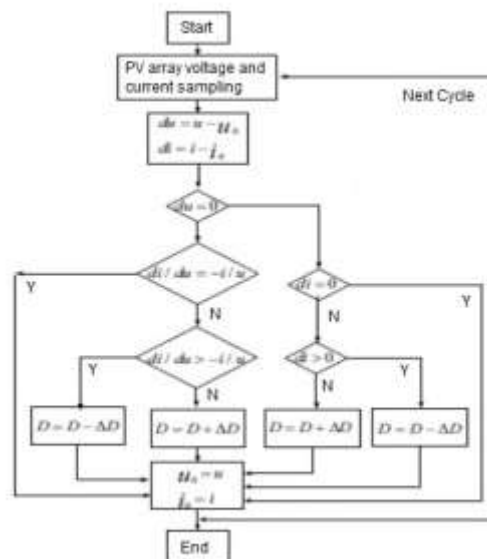


Fig.6. Incremental Conductance Algorithm

2.2.3.3 DC Link Voltage

The dc-link capacitor connected to the DC bus is common for PV array, shunt inverter and series inverter. So, the magnitude of the DC link voltage should be such that its value must be greater than twice the value of peak of phase voltage of the three phase system.

V_{dc} is given as

$$V_{dc} = \frac{2\sqrt{2}V_L}{\sqrt{3}V_m} \tag{3}$$

$$= \frac{2\sqrt{2} \cdot 415}{\sqrt{3} \cdot 1} = 677.7 \text{ V}$$

Here,

Depth of modulation(m) is assumed as 1, line voltage VL as 415 V. Minimum Vdc should be 677.7 and hence DC link voltage is taken as 700 V.

2.2.3.4 DC Link Capacitor Rating

The DC-link capacitor size is selected based upon DC-bus voltage level as well as power requirement. The DC-link capacitor energy balance equation is

$$C_{dcLink} = \frac{3aKI_{sha}V_{ph}t}{0.5(V_{dc}^2 - V_{dc1}^2)} \quad (4)$$

$$= \frac{3*1.5*0.1*34.5*239.6*0.03}{0.5*(700^2 - 677.79^2)} = 9.3 \text{ mF}$$

where,

Vdc - DC link voltage

Vdc1 - lowest required DC bus voltage

a - Loading factor

Vph - Phase voltage

t - min time to attain steady state after a disturbance

Iph - Phase current

k - constant, considering variation in energy due to dynamics

2.2.3.5 Interfacing Inductor for Shunt Compensator

The shunt inductor depends on the switching frequency(fsh), dclink voltage(Vdc) and the ripple current(Iripl). The equation for shunt inductor is

$$L_f = \frac{\sqrt{3}V_{dc}m}{12af_{sh}I_{ripl}} \quad (5)$$

$$= \frac{\sqrt{3} \times 700 \times 1}{12 \times 1.2 \times 10000 \times 6.9} \sim 1 \text{ mH}$$

where,

m - depth of modulation

Vdc - DC bus voltage

fsh - switching frequency

Iripl - ripple current of inductor is assumed as 20% of the phase current

2.2.3.6 Interfacing Inductor of Series Compensator

The series inductor rating depends on switching frequency(fse), dclink voltage(Vdc) and ripple current(Iripl). Equation for series inductor is

$$L_r = \frac{\sqrt{3}V_{dc}K_{SE}}{12af_{se}I_{ripl}} \quad (6)$$

$$= \frac{\sqrt{3} \times 1 \times 700 \times 3}{12 \times 1.2 \times 10000 \times 7.1} \sim 3.6 \text{ mH}$$

where,

m - depth of modulation

Vdc - DC bus voltage

KSE - Turns ratio of series transformer

fsh - switching frequency

Iripl - ripple current of inductor is assumed as 20% of the grid current

2.2.3.7 Shunt Compensator Controller

In order to perform load compensation, the active fundamental component(d-q) of load current(ILabc) is extracted using the synchronous reference frame(SRF) technique. Clarke's transformation is used for transformation of load current in abc frame to d-q-0 coordinates.

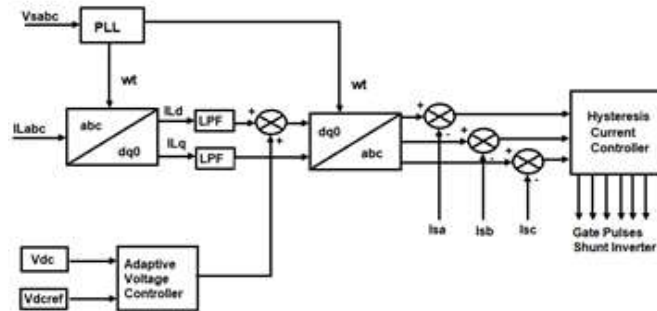


Fig.7. Shunt Compensator Controller

The control scheme is shown in figure 7. Source voltage at PCC is fed into PLL to extract phase and frequency which is used to convert load current from abc to d-q-0 domain using Clarke’s transformation. The DC link voltage is maintained by means of an adaptive voltage controller. Using SRF theory, the active fundamental component (ILd) of the load current is extracted by the shunt compensator. The d-component (ILd) is filtered to extract the dc component (ILdf) which represents the fundamental component in the abc frame. DC quantities in the d-q axes is extracted using low pass filters (LPF). The reference source current is obtained by taking the difference of DC component and output of DC link controller and is then converted from d-q-0 to abc. The reference source currents obtained is then compared with the sensed source current using a hysteresis current controller and switching pulses for shunt converter are generated.

2.2.3.8 Series Compensator Controller

Series compensator control strategy is primarily employed for voltage compensation. Voltage is injected in phase as that of grid voltage by the series compensator, which aids in minimum injection voltage.

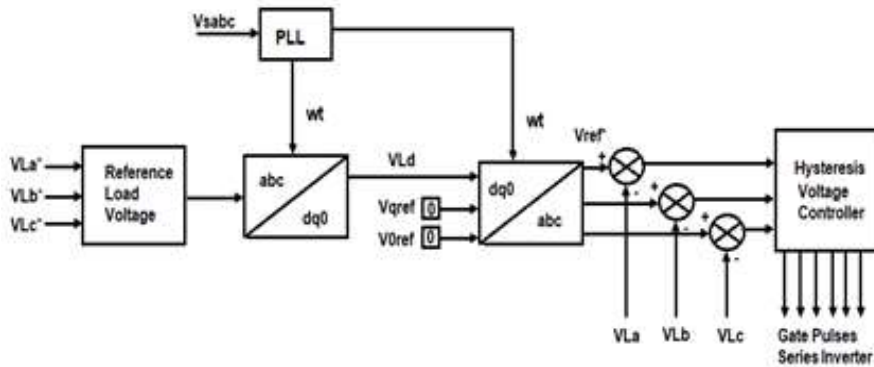


Fig.8. Series Compensator Controller

The control strategy used in series compensator is depicted in Fig. 8. Source voltage at PCC is fed into PLL to extract phase and frequency which is used to convert load voltage from abc to d-q-0 domain using Clarke’s transformation. The reference load voltage is generated using the frequency and phase angle obtained from PLL. The reference load voltage and PCC voltage should be in phase, so the d-axis component value of load reference voltage is set as the peak load reference voltage. The q-axis component is kept at zero. This reference signal is then converted from d-q-0 to abc frame. The difference between the PCC voltage and load reference voltage gives the reference voltage for the series compensator. This series compensator voltage is passed through hysteresis voltage controllers to generate appropriate switching pulses for series inverter.

3. RESULTS AND DISCUSSION

3.1 Introduction

The performance of 2SPV-UPQC is assessed in terms of load balancing and mitigation of voltage swell, sag and interruption conditions. The simulation results of the Simulink model are represented in figures 10 to 17, which indicate the acceptable performance of the proposed system with four different case studies.

In case 1, three-phase balanced grid voltage sag results in 20% decrease from the nominal value from 0.2sec<t<0.3sec and grid voltage swell result in 25% increase from the nominal value from 0.6sec<t<0.7sec. In case 2, three-phase balanced grid voltage sag and swell is studied with fifth and seventh harmonics in grid voltage from 0.2sec<t<0.3sec and 0.6sec<t<0.7sec respectively. In case 3, upstream feeder fault is simulated from 0.4sec<t<0.5sec. In case 4, non-linear load is varied from 0.4sec<t<0.5sec in the load side.

3.2 Simulation Parameters

Simulation parameters used for 2SPV-UPQC system are given below:

Table 2: UPQC-PV System Parameters

Parameter	Value	Parameter	Value
Input voltage of DC-DC Converter	356 V	Maximum Power(P)	50 KW
No of series modules, Ns	5	DC-DC Converter Inductance	1 mH
No of parallel modules, Np	34	DC Link Capacitance	10 mF
DC Link Voltage Vdc	700 V	Series Transformer	5KVA Linear
System frequency(f)	50Hz	Non-Linear Load	2 Diode rectifiers with load of R=20Ω, L=20mH and R=30Ω, L=20mH resp.
System Voltage	415 V		

3.3 2SPV-UPQC System Simulation Models

2SPV-UPQC System simulink model is shown in figure 9 which includes the below mentioned subsystems:

- Micro Grid
- Load
- Two Stage PV
- Shunt Compensator Controller
- Series Compensator Controller

Grid Voltage is taken as 415V and the specifications of non linear load connected in Load subsystem is mentioned in table 2.

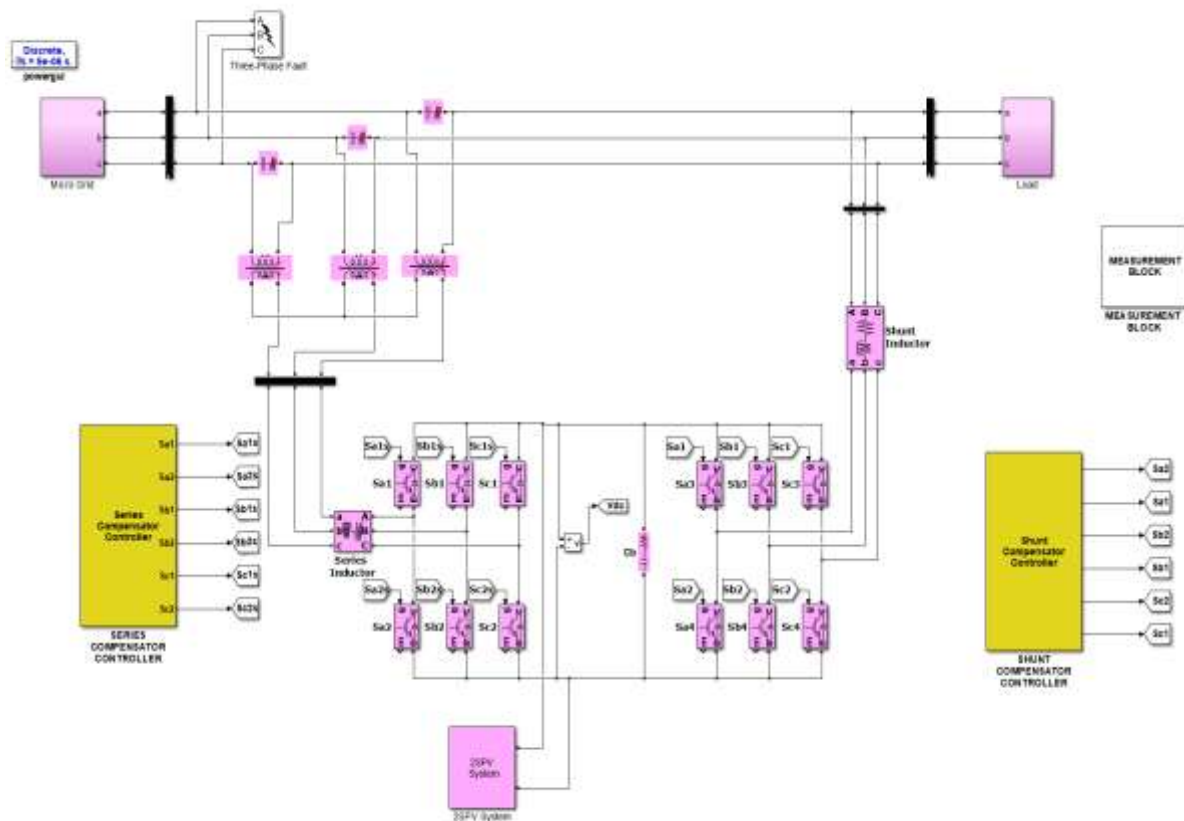


Fig.9. 2SPV-UPQC System

3.4 Results

Four case studies were conducted and the simulation results obtained for different case studies are given below.

Case 1: Balanced Voltage Sag and Swell

The 2SPV-UPQC is integrated with grid and applied 20% sag in grid voltage between $0.2\text{sec} < t < 0.3\text{sec}$ and 25% swell in grid voltage between $0.6\text{sec} < t < 0.7\text{sec}$. The grid voltage, load voltage and series compensation voltage injected are shown in Fig.10 and corresponding current wave forms are shown in Fig 11. Load voltage is taken from PCC. From the simulation results, a good dynamic response is observed as the distorted source voltage is compensated at PCC satisfactorily.

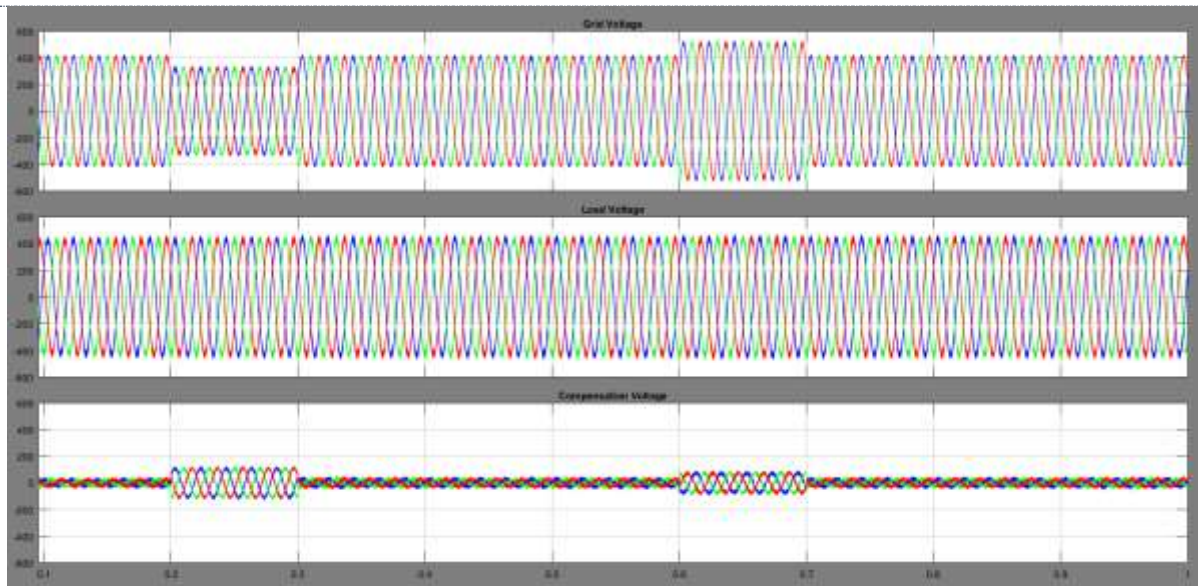


Fig.10. Case 1: Source, load & compensating voltages

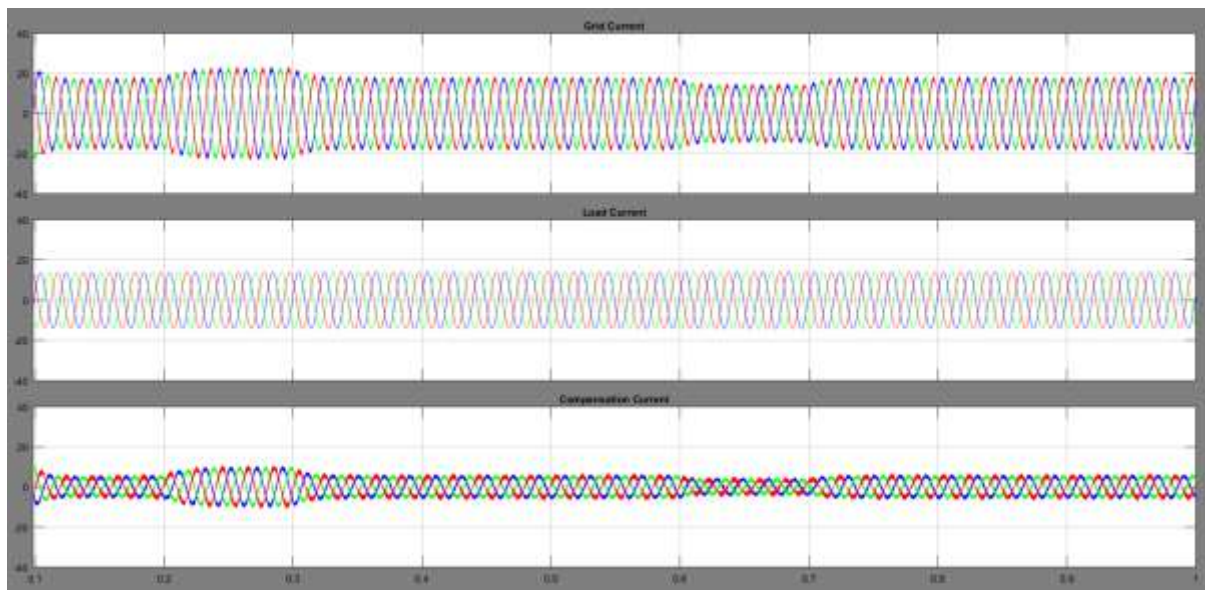


Fig.11. Case 1: Source, load & compensating currents

Case 2: Balanced Voltage Sag and Swell with Harmonics

The 2SPV-UPQC is integrated with grid and fifth and seventh order harmonics are present in grid voltage. Grid voltage contains 20% sag between $0.2\text{sec} < t < 0.3\text{sec}$ and 25% swell between $0.6\text{sec} < t < 0.7\text{sec}$. The grid voltage, load voltage and series compensation voltage injected are shown in Fig.12 and corresponding current wave forms are shown in Fig 13. From the simulation results, a good dynamic response is observed as the distorted source voltage is compensated at PCC satisfactorily.



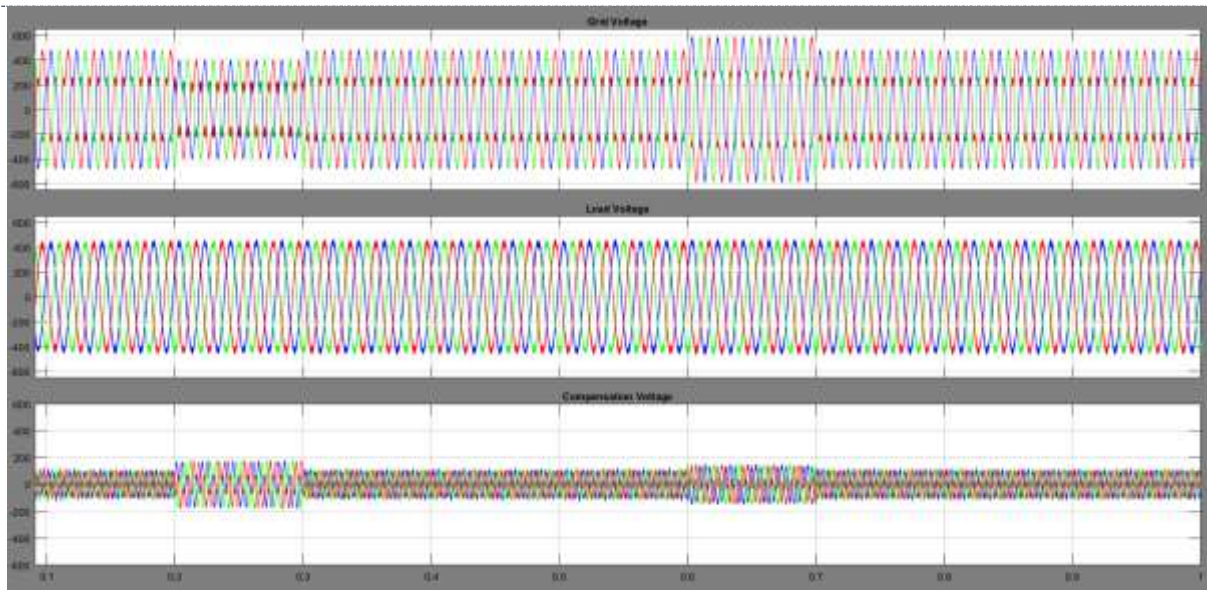


Fig.12. Case 2: Source, load & compensating voltages

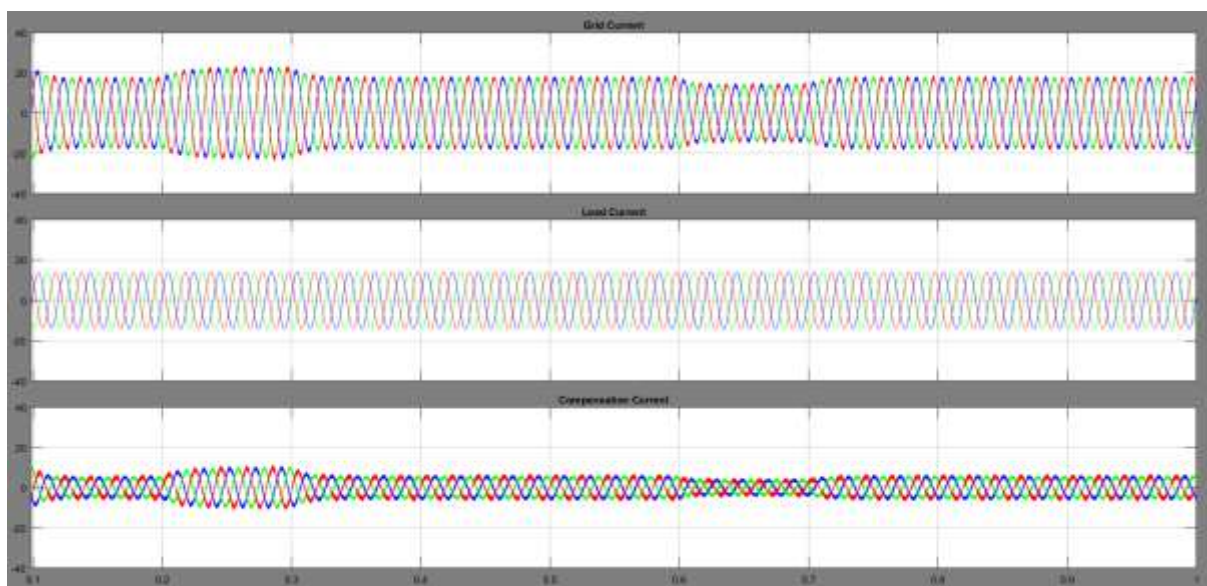


Fig.13. Case 2: Source, load & compensating currents

Case 3: Upstream Feeder Fault

When fault such as LG, LLG, and LLLG occurs in Feeder, there will be sag/swell or interruption in voltage across the critical/nonlinear sensitive loads. 2SPV-UPQC compensates this voltage imperfection. A LLLG fault was simulated to study the performance of the 2SPV-UPQC between $0.4\text{sec} < t < 0.5\text{sec}$. A satisfactory response obtained from the simulation is shown in Fig 14 and Fig 15.



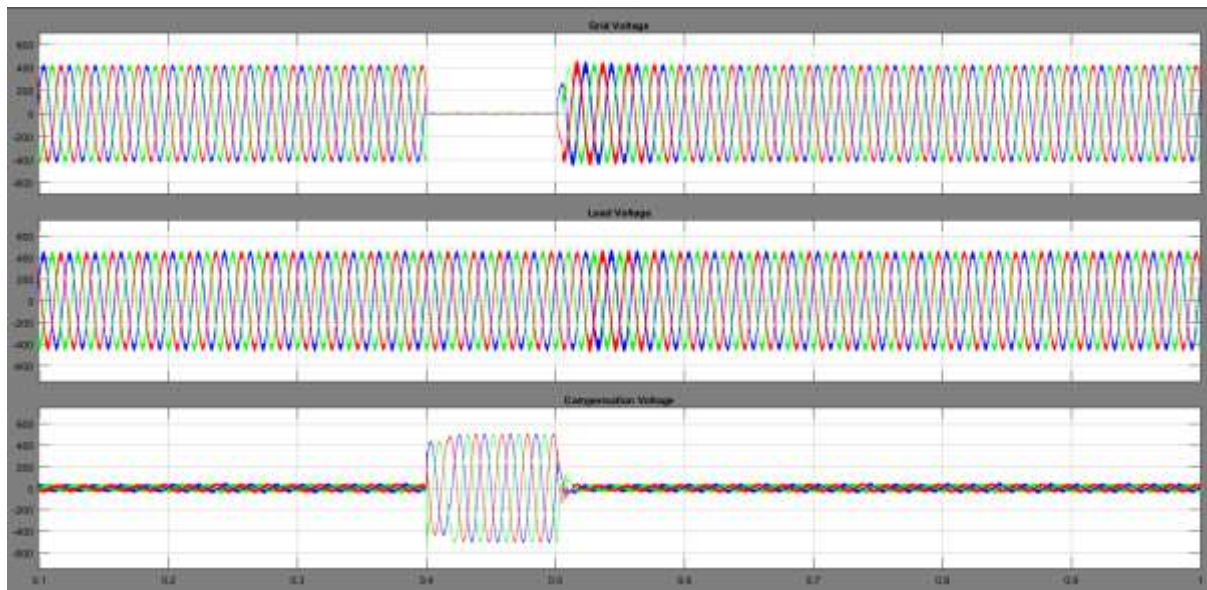


Fig.14. Case 3: Source, load & compensating voltages

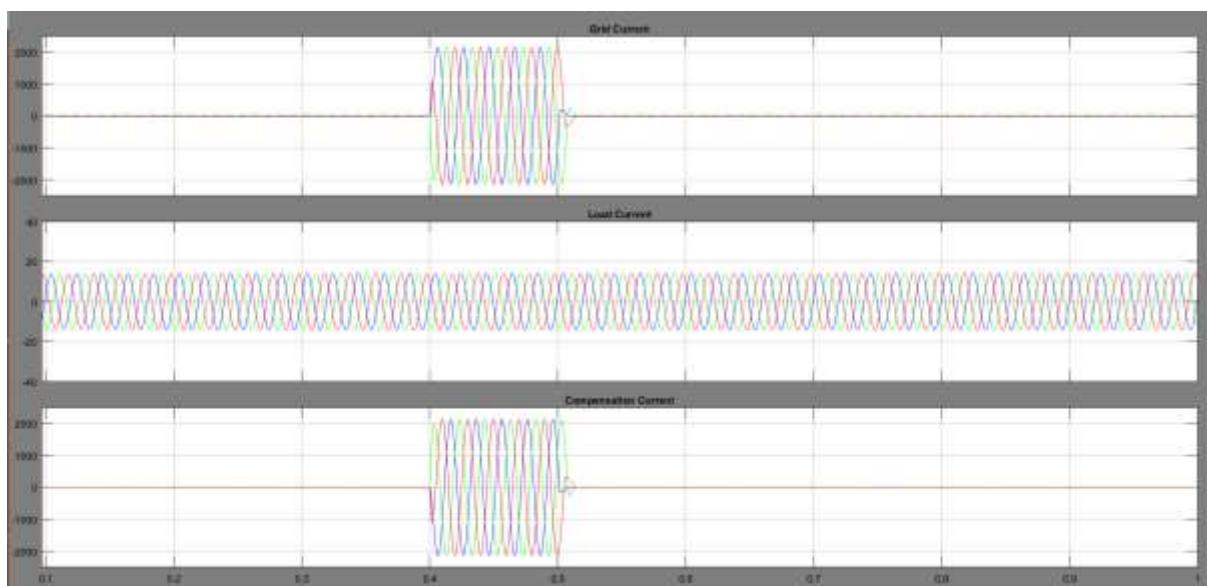


Fig.15. Case 3: Source, load & compensating currents

Case 4: Change in Load

To study 2SPV-UPQC system performance during load changes, a change in load is simulated at $t=0.4$ sec. Switching of nonlinear load was performed at $t=0.4$ sec. The system response obtained is depicted in Fig 16 and Fig 17. From the waveforms, it can be observed that even if there is a load change at PCC and the load voltage remains undisturbed and the nonlinear load current is compensated.

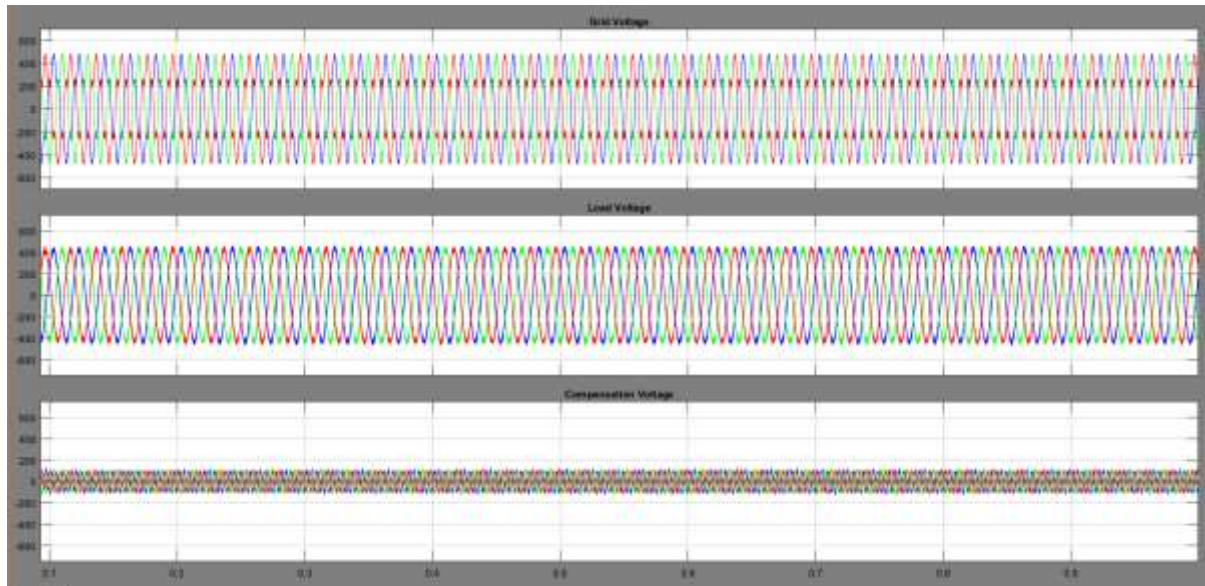


Fig.16. Case 4: Source, load & compensating voltages

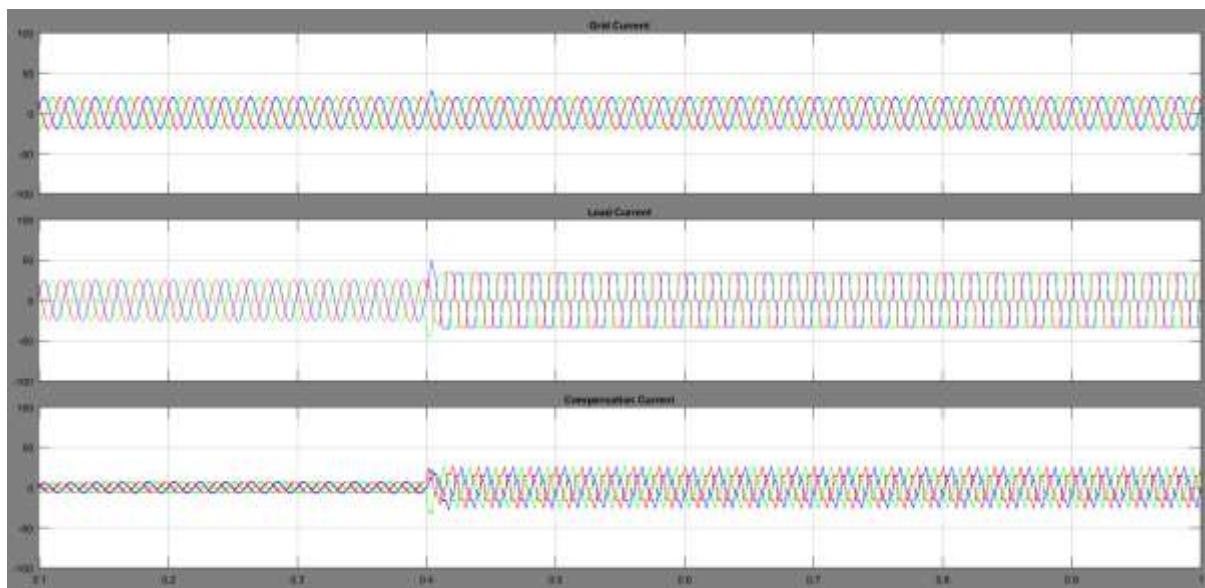


Fig.17. Case 4: Source, load & compensating current

4. CONCLUSION

Design and detailed analysis of proposed 2SPV-UPQC system was conducted and the system behavior was studied. When compared to a conventional UPQC system, the proposed system is capable to protect the sensitive and critical loads in utility against sag, swell, distortions and interruptions. The 2SPV-UPQC system performance was evaluated using multiple case studies and it offers the following benefits:

- Protection of nonlinear/sensitive loads by regulating the load voltage at PCC against sag/swell and disturbances.
- Reactive and harmonic components was compensated for the nonlinear load.
- Protection of nonlinear/sensitive loads by transferring active power during voltage interruption.

The proposed 2SPV-UPQC system is a promising solution for micro grid with power quality improvement.



5. ACKNOWLEDGEMENTS

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