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Grid Connected Solar PV System with Power Quality Improvement

Vrinda AV [1], Sheeja V [2]

M.Tech Student, Dept. of Electrical & Electronics Engineering, LBS College of Engineering, Kasaragod, India [1]

Assistant Professor, Dept. of Electrical & Electronics Engineering, LBS College of Engineering, Kasaragod, India [2]

Abstract: Solar photovoltaic (SPV) energy is the most important energy due to its eco-friendly nature and cost-effectiveness. Nowadays, grid interfaced SPV generating systems are becoming popular than stand alone SPV power generation.This paper discusses about the design and control of a grid interfaced solar photovoltaic (SPV) system which also mitigates power quality problems in three-phase distribution system. The grid connected SPV system consists of a PV array, DC/DC converter, a three leg VSC (Voltage Source Converter), grid and linear/nonlinear loads. Along with this, a suitable control algorithm (based on Instantaneous Reactive Power Theory) is also implemented for improved power quality so as to provide zero voltage regulation (ZVR) or power factor correction (PFC) along with harmonic elimination and load balancing. Simulation results obtained using MATLAB/Simulink shows the performance of the proposed control strategy for power quality improvement under various modes of operation.

Keywords: Instantaneous Reactive Power Theory (IRPT), Solar Photo Voltaic (SPV), Zero Voltage Regulation (ZVR), Power Factor Correction (PFC), Power Quality (PQ).

I. INTRODUCTION

Photovoltaic (PV) energy has grown at an average annual rate of 60% in the last five years; surpassing one third of the cumulative wind energy installed capacity and is quickly becoming an important part of the energy in some regions and power systems. This has also triggered the evolution of classic PV power converters from conventional single phase grid-tied inverters to more complex topologies to increase efficiency, power extraction from the modules and reliability without impacting the cost. Single stage grid interfaced, two stage grid interfaced and multi level grid interfaced are the main potential configurations for SPV power generating system. By the effective control of SPV generating system, PQ problems of AC distribution system caused by nonlinear and unbalanced loads can be mitigated. Depending upon the needs and applications, grid-connected PV generation systems can be found in different sizes and power levels and are subdivided depending on their power rating: small scale from a few watts to a few tens of kilowatts, medium scale from a few tens of kilowatts to a few hundreds, and large scale from a few hundreds of kilowatts to several hundreds of megawatts. In addition, PV systems can be further classified depending on the PV module arrangement: a single module, a string of modules, and multiple strings and arrays (parallel connected strings) [1]. The two stage SPV power generating system has not considered the PQ problems in detail [2-4]. The grid interfaced SPV generating systems have used various control algorithms which have focused on PQ problems limited to itself and on the PQ improvement on converter side only. But, the PQ problems are dominant in the grid because of various non-linear loads in distributed system, and the PQ issues include poor power factor, voltage regulation and reactive power compensation at AC mains. In distributed power generation, voltage source converter (VSC) is used as a power quality conditioner for effective utilization after suppression of power quality problems. The dynamic performance of power quality conditioner depends upon the design of power circuit elements as well as control algorithm. It has been found that transferring reactive power to long distances from the grid to satisfy the load requirements is very ineffectual task. Hence, SPV generating systems should be situated near the load for reactive compensation of the load. Different conventional control schemes like SRFT (Synchronous Reference Frame Theory), IRPT(Instantaneous Reactive Power Theory)[5], ILST (Improved Linear Sinusoidal Tracer), neural network, enhanced phase locked loop (EPLL), novel adaptive DC link voltage control algorithm etc [6] are presented for the integration of SPV system with three-phase grid. Thus, there is a need for continuous development of control algorithms for the optimal switching of VSC to get a fast, flexible and reliable grid integrated SPV system.

II. SYSTEM CONFIGURATION

The block diagram of the grid-connected SPV generating system is shown in Fig.1. Under standard operating conditions, photovoltaic array is designed to generate 1.5 kW as a peak power. A DC-DC boost converter boosts the generated voltage. A DC bus voltage PI controller of VSC regulates the common DC link voltage. A VSC provides reactive power compensation for unity power factor operation and zero voltage regulation, harmonic elimination and load balancing at PCC. The VSC consists of six IGBTs (Insulated Gate Bipolar Junction Transistors), interfacing inductors and DC bus capacitor. The 1.5kW SPV power is injected at PCC which helps in reducing the overall losses in the system.

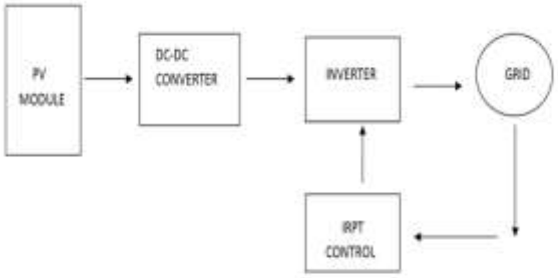

Fig.1. Block diagram of the grid connected SPV system

III. DESIGN OF THE GRID CONNECTED SPV SYSTEM

The configuration of proposed SPV system is shown in Fig.2. The system consists of PV string, DC-DC converter, VSC, interfacing inductors and a ripple filter. A PV panel consists of series and parallel combination of small photovoltaic modules to match the required power rating. The PV panel is connected in parallel to dc bus of VSC. The SPV energy conversion system is interfaced to a three-phase distribution system. Connected loads may be linear or nonlinear in nature which may be compensated by VSC of SPV system. The VSC performs the functions of harmonics elimination, balancing of grid currents and power factor correction at the same time with the proper control. The interfacing inductors and ripple filter are used to filter switching harmonics.

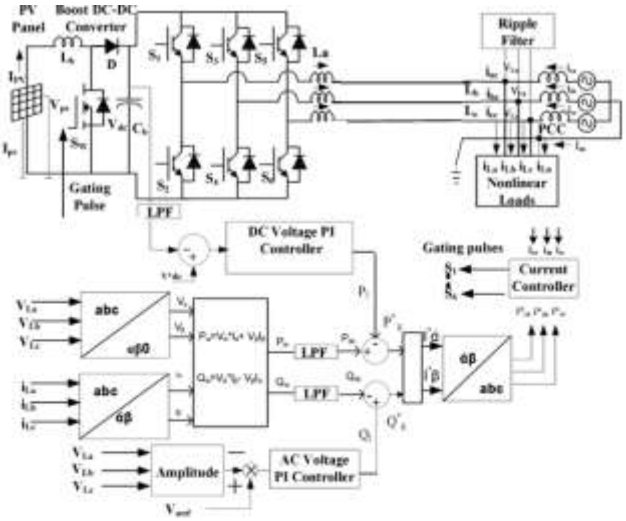

Fig.2.Schematic Configuration of the Grid connected SPV System

3.1 Solar Photovoltaic Array

The PV panel is designed for a 1.5 kW peak power capacity. A solar PV module is formed by connecting solar cells in series. Each module has an open circuit voltage of 64.2 V [7] and short circuit current (I_{sc}) of 5.96A. The generalized equation for an active power for SPV array is given as,

$$P_{mppM} = V_{mppM} * I_{mppM} \qquad (1)$$

Maximum power occurs generally at P_{mppM} = (85% of V_{oc} * 85% of I_{sc}) thus I_{mppM} is 5.58A and V_{mppM} is 54.7V of each cell. 5 modules (each module consisting of 96 cells) are connected in series to achieve a maximum voltage of 273.5V as V_{mpp} of SPV for proposed system. The total calculated maximum power is given as,

$$P_{max} = V_{mppM} * I_{mppM} = 1.5kW \qquad (2)$$

To achieve a 1.5kW peak power capacity, the required value of maximum current (I_{mpp}) is 5.48A, to achieve this current, a single string (consisting of 5series connected modules per string) is connected.

3.2. DC Capacitor Voltage

The minimum dc bus voltage of VSC should be greater than twice the peak of the phase voltage of the system. The dc bus voltage is calculated as

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \qquad (3)$$

where m is the modulation index and is taken as 1, and V_{LL} is the ac line output voltage of the VSC which is 239.6V. For V_{LL} of 415 V, V_{dc} is obtained as 391.87 V and is selected as 400 V.

3.3. DC-DC Boost Converter

The DC-DC boost converter is used to boost the input of SPV array which used to feed the active power at the DC bus of the VSC. The ripple current for the boost converter is given as,

$$\Delta i_1 = \frac{V_{dc}\, D(1-D)}{2L_b f_s} \qquad (4)$$

where D is Duty cycle, Δi_1 is input current ripple and for this design the value of Δi_1 is considered 5% of boost converter inductor current (0.27A). Thus the calculated value of Δi_1 is 8.25A. f_s is switching frequency and the value of f_s is considered as 10 kHz, where V_{dc}, L_b and f_s are fixed value.

The condition of maximum value of the ripple current given as

$$\left(\frac{d\Delta i_1}{dD}\right)=0 \qquad (5)$$

The value of D corresponding to maximum ripple current obtained is 0.5. The value of inductance (L_b) is obtained as 18.5 mH.

3.4. DC Link Capacitor

The value of dc capacitor (C_{dc}) of VSC depends
on the instantaneous energy available to the VSC during transients. Using the principle of energy conservation,

$$\frac{1}{2}C_{dc}[V_{dc}^2 - V_{dc1}^2] = 3V(aI)t \qquad (6)$$

where V_{dc} is the reference dc voltage and V_{dc1} is the minimum voltage level of dc bus, a is the overloading factor, V is the phase voltage, I is the phase current, and t is the time by which the dc bus voltage is to be recovered. Considering the minimum voltage level of the dc bus, V_{dc1} = 380 V, V_{dc} = 400 V, V = 138.560 V, I = 120.28A, t = 250 µs, a = 1.2, the value of C_{dc} is 4522.28 µF and is selected as 5000 µF.

3.5. AC Inductor

The value of the ac inductance (L_f) of VSC depends on the current ripple $i_{cr,pp}$ switching frequencyf_s, dc bus voltage (V_{dc}) and L_f is given as

$$L_f = \frac{\sqrt{3}mV_{dc}}{12af_s i_{cr,pp}} \qquad (7)$$

where m is the modulation index and a is the overload factor. Considering, $i_{cr,pp}$ = 3%, f_s = 10 kHz, m = 1, V_{dc} = 400 V, a = 1.2, the value of L_f is calculated to be 2.16 mH and a round-off value of 2.5 mH is selected.

3.6. Ripple Filter

A low-pass first-order filter tuned at half the switching frequency is used to filter the high-frequency noise from the voltage at the PCC. Considering a low impedance of 8 Ω for the harmonic voltage at a frequency of 5 kHz, the ripple filter capacitor is designed as C_f=10µF.

A resistance R_f of 5 Ω is included in series with the capacitor (C_f). The impedance is found to be 391 Ω at fundamental frequency, which is sufficiently large and hence, the ripple filter draws negligible fundamental current.

3.7. Voltage Source Converter

The VSC consists of six switching devices and it allows bidirectional power flow and is realized using devices such as insulated gate bipolar transistors (IGBT) with anti-parallel diodes. The rating of the switches is based on the voltage and current rating of the compensation system.

IV. CONTROL ALGORITHM FOR SWITCHING OF VSC

The control algorithm of VSC focusses on generating gating signals for the appropriate switching of the VSC and includes control functions such as load balancing, harmonics elimination, regulating the PCC voltage, balancing grid currents and PFC. The control technique used here is based on instantaneous reactive power theory (IRPT).

The instantaneous reactive power theory was initially published in English in the Proceedings of the International Power Electronics Conference in 1983 [8]. However, it was in 1984, after its publication in an IEEE TRANSACTIONS, when this theory became well known worldwide [9]. Since then, the instantaneous reactive power theory has been the most used compensation strategy. Indeed, the proposed strategy obtains sinusoidal and balanced currents, constant instantaneous power, and unity power factor in the source side when the voltage applied is balanced and sinusoidal [9]. In any other case, i.e., when the voltage is unbalanced and/or non-sinusoidal, the instantaneous power is constant after compensation in the source side, but the current is not balanced and sinusoidal, and the power factor is not the unity [10], [11]. Thus, from the point of view of research, the publication of this theory caused a great impact in compensation techniques.

The conventional reactive power in three-phase circuits has been defined on the basis of the average value concept for sinusoidal voltage and current waveforms in steady states. The instantaneous reactive power in three-phase circuits is the concept defined on the basis of the instantaneous value for arbitrary voltage and current waveforms, including transient states. The basic block diagram of IRP Theory is shown in Fig.3.

The grid feeds active power to connected consumer loads at PCC. It is also supplemented by SPV power generation through DC link voltage controller of VSC. During the availability of sun, the DC link PI voltage controller of VSC takes care of the injection of SPV power.

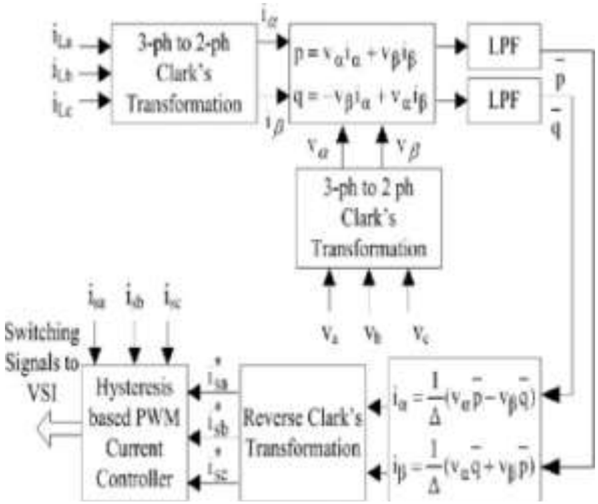

Fig.3. Basic Block- diagram of IRP Theory

4.1 IRPT Control Algorithm

In the instantaneous reactive power theory (IRPT), the estimation of instantaneous active and reactive powers of the loads is made after converting sensed voltages (v_{La}, v_{Lb}, v_{Lc}) and load currents (i_{La}, i_{Lb}, i_{Lc}) to α-β reference frame using the following equations

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} \qquad (8)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (9)$$

These voltages and currents in the α and β reference frame are used to estimate instantaneous active and reactive powers of the loads. The active power taken by the loads is given by,

$$P_w = (v_\alpha i_\alpha + v_\beta i_\beta) = P_{dc} + P_{ac} \qquad (10)$$

Here the active power consists of two components a DC component (P_{dc}) and an oscillating component.(P_{ac}) (which is due to harmonics, to be fed by VSC) This instantaneous power P_w is passed through a low pass filter (LPF) to extract its DC component P_{dc}, which is the fundamental active power of the loads used in estimation of reference AC mains currents. Also, instantaneous reactive power of the loads is estimated as,

$$Q_w = (v_\alpha i_\beta - v_\beta i_\alpha) = Q_{dc} + Q_{ac} \qquad (11)$$

This reactive power of the loads consists of DC (Q_{dc}) component as well as AC component (Q_{ac}) and after passing through LPF, it is Q_{dc}.

4.1.1 Voltage Regulation and Load Balancing

The quadrature or reactive power components of grid currents takes care of the voltage drop in the grid (source) impedance by injecting a small reactive power current into the grid through VSC. A PI voltage controller is used to regulate PCC voltage. The output of the PI voltage controller is the reactive power component supplied by VSC for voltage control. These quadrature or reactive power components are estimated through following basic equations. For PCC voltage regulation, an error voltage of the amplitude of AC terminal voltage at the point of common coupling (PCC) is regulated by a PI AC voltage regulator. The amplitude of voltage at PCC is given by

$$V_S = \sqrt{\left(\left(\frac{2}{3}\right)(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)\right)} \qquad (12)$$

V_S is filtered and the voltage error between the reference voltage and this estimated voltage is fed to a PI controller which in turn regulates the PCC voltage. The output of the PI controller is reactive power component and it is obtained by,

$$Q_{l,n} = i_{l,(n-1)} + K_{pq}(v_{ae\ n} - v_{ae\ n-1}) + K_{iq} v_{ae\ n} \quad (13)$$

where $v_{ae\ n} = v_{mr} - v_{m\ n}$ and K_{pq} and K_{iq} are the proportional and integral gain of the AC voltage PI controller, $v_{ae\ n}$ and $v_{ae\ n-1}$are the voltage errors at the n^{th} and $(n-1)^{th}$ sampling instant, $Q_{l,n}$ and $Q_{l,(n-1)}$are the are the output of the AC PI voltage controller at the n^{th} and $(n-1)^{th}$ sampling instant,
The reference reactive power is given as,

$$Q_g^* = Q_l - Q_{dc} \qquad (14)$$

To estimate the active power components of grid currents, the active power of consumer loads and output of the DC link voltage controller have to be estimated. The DC link PI voltage controller of VSC takes care the injection of SPV power generation, during the availability of sun. The basic equations for estimating active power components at nth instant is given as,

$$P_{l,n} = P_{l,(n-1)} + K_{pD}(v_{de\ n} - v_{de\ n-1}) + K_{id} v_{de\ n} \quad (15)$$

where $v_{de\ n} = v_{dcr} - v_{dca\ ,n}$ is the error between sensed and reference DC bus voltage of VSC and K_{pd} and K_{id} are the proportional and integral gain of the DC voltage PI controller, $v_{de\ n}$ and $v_{de\ n-1}$are the voltage errors at the nth and (n-1)th sampling instant, $P_{l,n}$ and $P_{l,(n-1)}$ are the are the output of the PI DC bus voltage controller at the n^{th} and $(n-1)^{th}$ sampling instant,
The reference active power $P_g^*$of the grid is obtained using ,

$$P_g^* = P_l - P_{dc} \qquad (16)$$

The estimated reference active and reactive powers of the grid are utilized to obtain reference grid currents in α,β frame are given as,

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \left(\frac{1}{(v_\alpha^2 + v_\beta^2)}\right) \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} P_g^* \\ Q_g^* \end{bmatrix} \qquad (17)$$

In order to produce reference grid currents, these reference grid currents in α,β reference frame are transformed in to a,b,c reference frame by inverse Clark transform as,

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} \qquad (18)$$

4.1.2 Power Factor Correction and Load Balancing

The quadrature or reactive power components of grid currents must be zero for power factor correction (PFC) to unity at PCC. Power factor correction can be achieved by putting the value of reactive power component (Q_g^*) zero [12].

4.1.3 Current Controlled Pulse Width Modulated (PWM) Generator

In a current controller, the sensed and reference grid currents are compared and a proportional controller is used for amplifying current error in each phase before comparing with a triangular carrier signal to generate the gating signals for six switches for VSC of the SPV power generating system.

V. MATLAB MODELING

The three phase SPV power generating system integrated with the grid is modeled and simulated in MATLAB/Simulink with the help of sim-power system toolbox. The light intensity of SPV array is set as 1000W/m^2. The algorithm used for controlling the VSC is realized in Simulink. The reference grid currents are derived from the sensed load voltages (v_{La}, v_{Lb}, v_{Lc}) load currents (i_{La}, i_{Lb}, i_{Lc}) and the DC bus voltage of VSC (Vdc). A current controller based on pulse width modulation is used for comparing reference grid currents (i_{sa}^*, i_{sb}^*, i_{sc}^*), and sensed grid currents (i_{sa}, i_{sb}, i_{sc}) to generate the switching pulses for the IGBTs of the VSC. The control algorithm proposed here serves in improving the power quality parameters of the distribution network. To demonstrate these functions of the proposed system, its behaviour is observed and studied under different load conditions (linear and nonlinear loads).

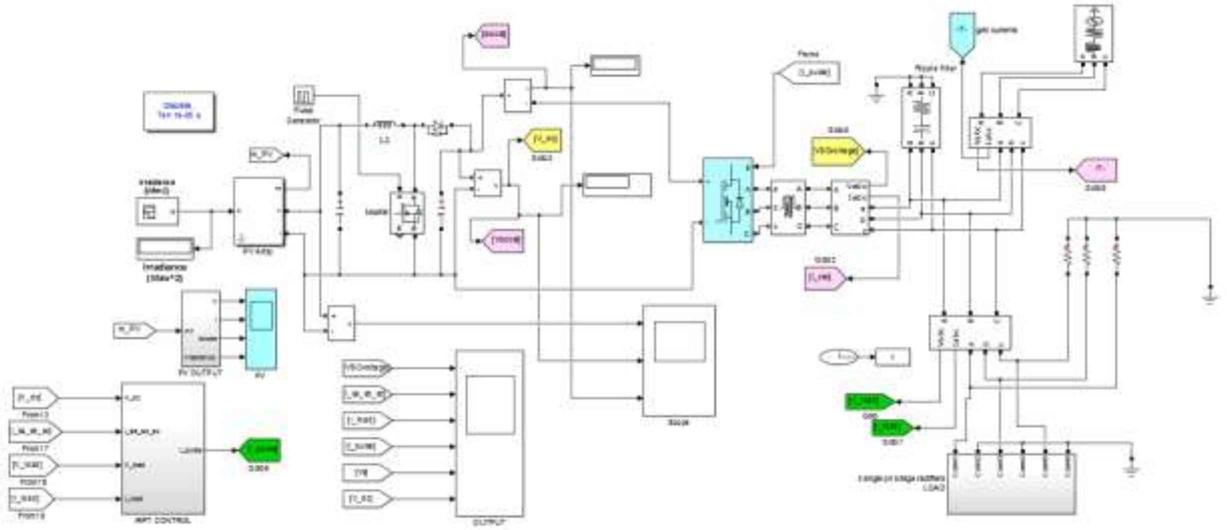

Fig.4. MATLAB model of the Grid Connected PV System

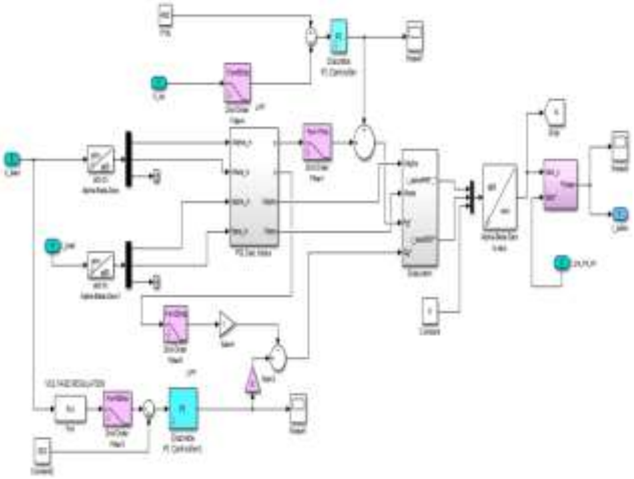

Fig.5.MATLAB based model of the IRPT control scheme for VSC

VI. SIMULATION RESULTS

The model of SPV grid connected system is implemented in MATLAB/Simulink with UPF and ZVR modes of operation under different conditions. For assessing the behavior of the proposed system, results involve significant signals such as SPV array DC current (I_{pv}), SPV array DC voltage (V_{pv}), grid voltages, grid currents, load currents and

VSC-DC link voltage (V_{dc}) From the simulation results, it is found that PCC voltage is regulated to rated value in spite of the changes in loads and grid currents are sinusoidal and almost balanced. Also the grid voltage and grid currents are in phase.

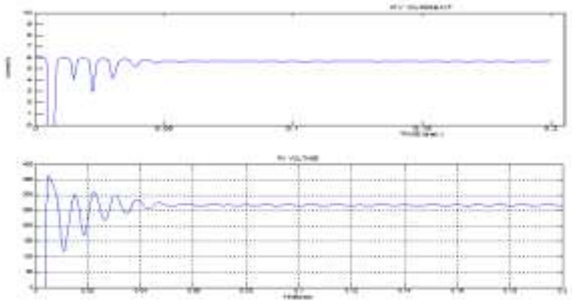

Fig.6. PV Voltage and Current Waveform

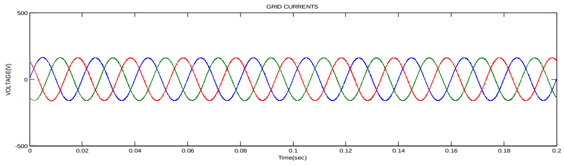

Fig.7. Grid Current

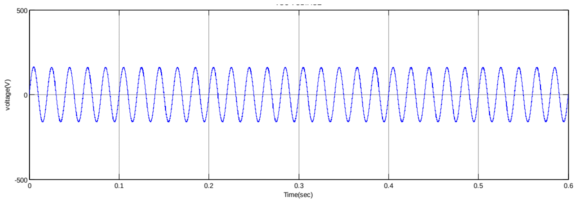

Fig.8. Grid Voltage

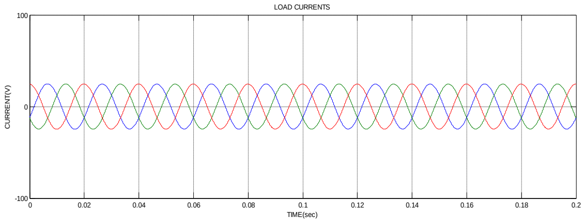

Fig.9. Load Current

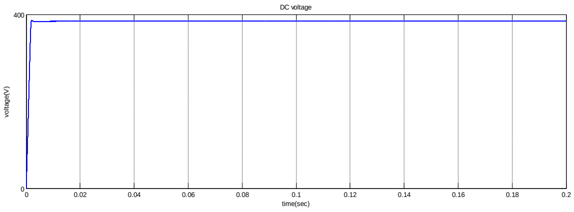

Fig.10. DC bus Voltage

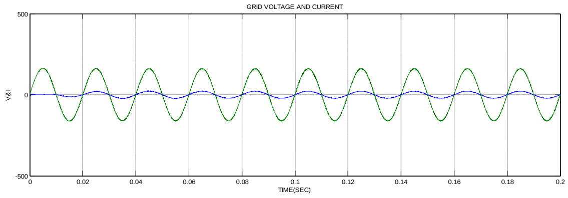

Fig.11. Source Voltage and Current (UPF Operation)

VII. CONCLUSION

The performance of grid connected PV system has been demonstrated for reactive power compensation. The dc bus voltage has been regulated to the reference dc bus voltage under all varying loads. It is also found that the grid voltages and currents are in phase, which demonstrates the upf mode of operation.

Comparison with the four-leg converter shows that the number of switches is reduced in the proposed configuration, thus reducing the complexity and cost of the system. Thus the control approach based on the instantaneous reactive power theory has compensated the reactive power and the dc bus voltage is almost maintained to the reference value under all disturbances. Hence the proposed grid interfaced SPV power generating system is capable to inject active power into the grid and able to compensate for load reactive power and load current harmonics.

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