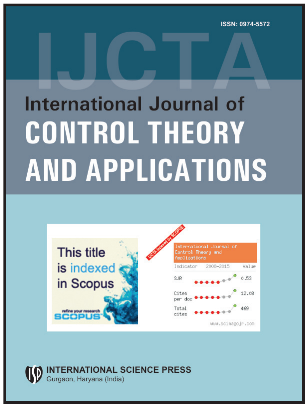

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Realization of a Single Stage Control Strategy for Three-Phase Grid-Connected Photovoltaic System with Linear and Non-Linear Loads

D. Sudheerkumar[a], P.V.R.L. Narasimham[b], N. Gouthamkumar[c] and D. Udaykiran[d]

[a-d]Department of Electrical and Electronics Engineering, Velagapudi Ramakrishna Siddhartha Engineering College, Vijayawada, India.
Email: [a]sudhir.darsi@gmail.com; [b]drpvrln@gmail.com; [c]gowthamkumar218@gmail.com; [d]udaykiran.dokala@gmail.com

Abstract: This paper realizes the design of three phase grid connected photovoltaic system with a single stage inverter control strategy for obtaining the maximum power point tracking. The control strategy is adopted based on p-q theory for better utilization of grid connected photovoltaic system with linear & nonlinear loads. Based on this theory, during day time PV system compensates active power (completely/partially) and the reactive power required by the load. When the irradiance is weak (during night time), the PV system compensates the reactive power required by the load, and the active power is supplied by grid. The significance of the presented control strategy is that the photovoltaic system can be operated throughout the day. Further, harmonic compensation is also supplied to mitigate the harmonics in order to enhance the power quality issues at grid side. Finally, the single stage control strategy is demonstrated on three phase grid connected system with linear balanced, linear unbalanced and non-linear loads and thus obtained simulation results are validated the effectiveness of the control strategy for effectively minimizing the total harmonic distortion and greater reduction of harmonic content.

Keywords: Grid-connected photovoltaic system; harmonic compensation; maximum power point tracking; nonlinear loads.

1. INTRODUCTION

The load demand is increasing day to day activities and present generating units are already loaded up to their maximum limits, which are not possible to load them further in the present scenario. In addition to the constraint posed by the capacity of generating units, another limitation is imposed by the capacity of the transmission lines which cannot be loaded beyond their rated limits. As a result, the focus has been shifted to generate more electric power using available alternative energy sources such as photovoltaic (PV), fuel cell, wind, etc. Now-a-days, the usage of solar photovoltaic systems is increasing due to awareness about the importance of a clean environment while concerning the global warming, pollution effects, etc. For effective utilization of solar power, there is a need to track maximum power obtain from the PV panel by means of maximum power point tracking (MPPT). However, MPPT may not always be generous to operate PV panel at maximum power point in case of standalone systems, because the load could not be absorb all the generated power until unless a provision for energy storage systems. Besides, a grid connected PV system can make full use of MPPT because the grid can absorb any amount of power generated by the PV source and due to this reason battery backup is not required [1].

Usually, there are two stages of operation for a grid-connected PV system. The first stage is MPPT along with boosting the voltage by using DC-DC converter and the other stage is having an inverter to convert DC power into AC power and then feed to grid. But these two stages may result in more switching losses, high cost and more complexity of the system. Numerous researchers have developed a concept of single stage grid-connected PV system with one power conversion stage in which all the functionalities of two stage conversion i.e. MPPT, inversion and boosting are achieved by the inverter in single stage itself [2]. A modified incremental conductance MPPT method has been presented and applied through a single stage grid-connected PV system to improve the stability of a system during rapid changes in environmental circumstances [3]. Many concepts have been proposed to achieve the active and reactive power with their mathematical models. For controlling active and reactive powers, active and reactive components of the currents are controlled by using SRF control theory. The system is having a DC–DC converter for MPPT, two PI controllers and one phase locked loops (PLL) [4]. Input voltage clamping technique is used for MPPT and for controlling active and reactive power by synchronous reference frame control theory is used. In order to obtain the reference current, passive filters are used and these filters had introduced the errors in phase angle and amplitude of the reference current [5]. A detailed mathematical model of PV array and how the I-V and P-V curves effects with change in irradiation, temperature and other parameters has been presented in the reference [6]. A modest control strategy has been proposed in [7] for a grid integration of distributed generation units. In their contributions, the regulation circuit was used to control the active power and p-q theory for reactive power. The instantaneous value concept was used in [8] to frame the instantaneous reactive power in three-phase circuits for arbitrary current and voltage waveforms with transient states. The concept of instantaneous p-q theory was used in the control strategy addressed in [9] for single stage conversion by voltage source inverter when the integration of photovoltaic system with grid for linear loads. However, the realizations of p-q theory used in single stage conversion of grid-connected PV system are not yet been demonstrated with unbalance linear and nonlinear loads.

This paper realizes the design of single stage inverter control strategy demonstrated on a three phase grid connected photovoltaic system. The instantaneous p–q theory is adopted to solve the system with linear and nonlinear loads. This concept offers a simple algebraic calculations to enhance the overall system speed and the absence of PLL. Also, a modified incremental conductance (INC) method is embedded for good performance under wide variations of atmospheric conditions for obtaining the maximum power point. In order to validate the effectiveness of the control strategy, it has been verified on a three-phase grid with linear balanced, linear unbalanced and nonlinear loads. Thus, the obtained simulation results reveal that the proposed control strategy effectively controlled the active and reactive power and also improved the power quality of the system.

The remaining paper is organized as follows: Section 2 explains the description of single stage control strategy for three phase grid connected system. Section 3 provides the simulation studies with linear and nonlinear loads connected to the system followed by conclusions.

2. SINGLE STAGE CONTROL STRATEGY FOR GRID-CONNECTED PHOTOVOLTAIC SYSTEM

The proposed system consists of a PV array connected to grid with the help of voltage source inverter and coupling capacitor as shown in Figure 1.

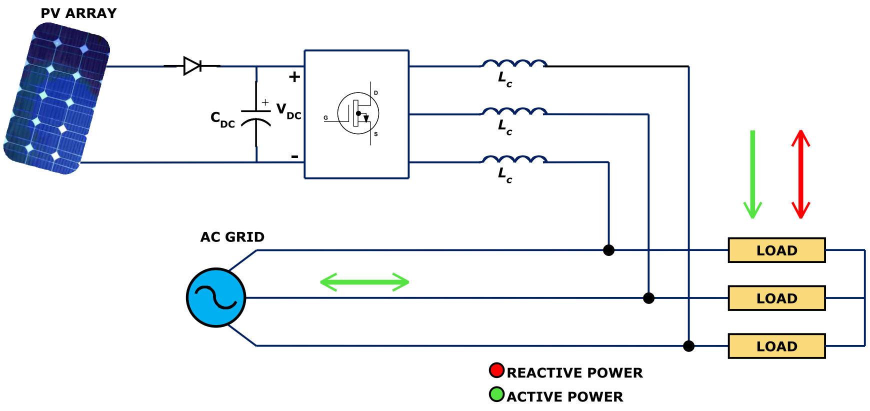

Figure 1:Grid-connected Photovoltaic System

The load in the system is a three phase linear or non-linear type. During day time, active power and reactive power required by the load will be supplied by PV system. Any excess active power supplied by PV system may be fed to grid. The reactive power required by the load will be supplied by the charged capacitor along with inverter and active power will be supplied by the grid during night time. The PV system is well designed to meet the requirement of reactive power during night time.

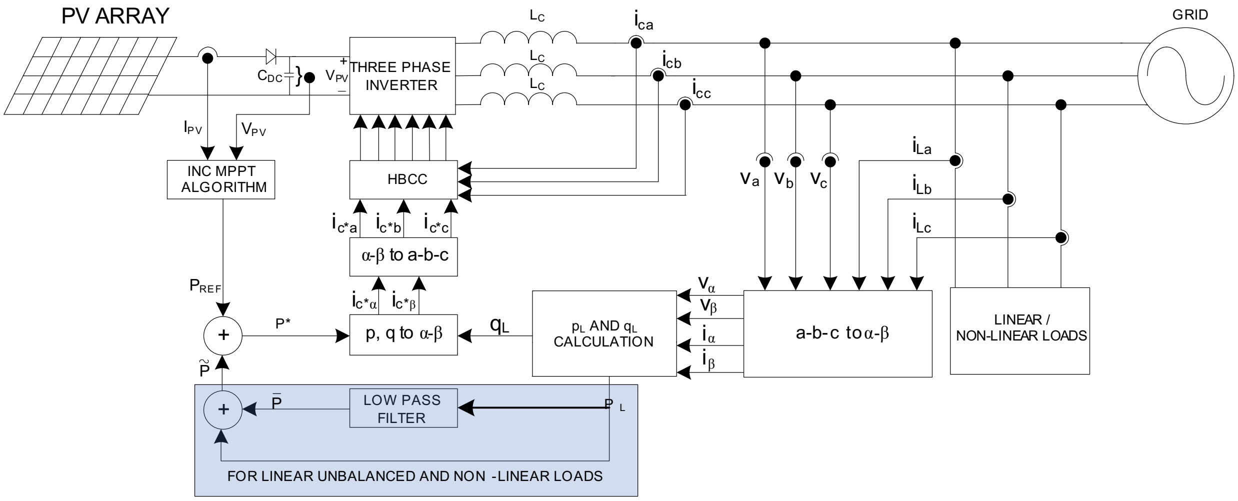

Figure 2: Proposed Single Stage Control Strategy for Grid-connected PV System

The control strategy adopted for active and reactive power control in a single stage grid connected photovoltaic system with MPPT is shown in Figure 2. The measuring variables in this scheme are the PV output voltage V_{pv}, output current I_{pv}, the grid voltages v_a, v_b, v_c inverter's output currents i_{ca}, i_{cb}, i_{cc} and load currents i_{La}, i_{Lb}, i_{Lc}. For the computation of real and reactive powers of the load p_L and q_L, the three phase voltages and load currents must be transformed to the stationary two axis $\alpha - \beta$ co-ordinates by using Clarke transformation [9], and the corresponding relations are present in equations are shown in (1) and (2).

$$v_{\alpha\beta} = cv_{abc} \tag{1}$$

$$i_{\alpha\beta} = ci_{Labc} \tag{2}$$

where, $v_{\alpha\beta} = [v_\alpha \quad v_\beta]^T$, $v_{abc} = [v_a \quad v_b \quad v_c]^T$ and C is the Clark transformation matrix. The real and reactive power p_L and q_L instantaneous values are calculated using the equations mentioned in (3) and (4). Similarly, $i_{\alpha\beta} = [i_\alpha \quad i_\beta]^T$ and $i_{abc} = [i_{La} \quad i_{Lb} \quad i_{Lc}]^T$

$$p_{\mathrm{L}} = v_\alpha i_\alpha + v_\beta i_\beta \tag{3}$$

$$q_{\mathrm{L}} = v_\alpha i_\beta - v_\beta i_\alpha \tag{4}$$

The grid inverter exchanges the active power based on the delta angle δ, which is between grid voltage and inverter output voltage. The inverter active and reactive powers are given in equations (5) and (6).

$$p_{inv} = \frac{3\mathrm{V}_s \mathrm{V}_{inv} \sin \delta}{\mathrm{X}_{\mathrm{LC}}} \tag{5}$$

$$q_{inv} = \frac{3\mathrm{V}_s (\mathrm{V}_{inv} - \mathrm{V}_s)}{\mathrm{X}_{\mathrm{LC}}} \tag{6}$$

where, V_s and V_{inv} are the voltages of grid and inverter and X_{LC} is the smoothing inductor which is connected between the grid and inverter. $\mathrm{P}_{\mathrm{REF}}$ value is the maximum power available at the solar panel which is derived from MPPT algorithm whose value decides the load angle δ. The adjustable $\mathrm{P}_{\mathrm{REF}}$ adjusts the angle delta δ which in turn decides the value P_{inv}.

The above proposed theory is applied to various types of loads like linear (balanced & unbalanced), non-linear loads for its verification. For linear balanced loads reference currents generation based up on the values of $\mathrm{P}_{\mathrm{REF}}$, and q_{L}. The reference currents are obtained through below equation (7).

$$\begin{bmatrix} i_{c^*\alpha} \\ i_{c^*\beta} \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\alpha & v_\beta \end{bmatrix} \begin{bmatrix} \mathrm{P}_{\mathrm{REF}} \\ q_{\mathrm{L}} \end{bmatrix} \tag{7}$$

With linear unbalanced and nonlinear loads, load power having oscillating component in addition with DC component. For eliminating oscillating component of power at grid side and/or harmonics presented in the grid current, reference currents are generated based up on the $\mathrm{P}_{\mathrm{REF}} + \tilde{p}$ and q_{L} by using instantaneous active and reactive power $(p - q)$ theory. $\tilde{p}$ is the oscillating component of load active power. The corresponding reference currents are generated as per equation (8) mentioned below.

$$\begin{bmatrix} i_{c^*\alpha} \\ i_{c^*\beta} \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\alpha & v_\beta \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \tag{8}$$

where, $p^* = \mathrm{P}_{\mathrm{REF}} + \tilde{p}$ and $q^* = q_{\mathrm{L}} = \bar{q} + \tilde{q}$. In above two cases reference currents generation in the $\alpha - \beta$ coordinates and these currents are again converted into three phase quantities by using inverse clock transformation. The equation (9) shows the reference currents in three phase quantities.

$$\begin{bmatrix} i_{c^*a} \\ i_{c^*b} \\ i_{c^*c} \end{bmatrix} = [c]^{-1} \begin{bmatrix} i_{c^*\alpha} \\ i_{c^*\beta} \end{bmatrix} \tag{9}$$

3. SIMULATION STUDIES

A grid interfaced PV system is simulated on the MATLAB/Simulink and performed on personal computer Dell-core i5, 2.67 GHz, 4GB RAM. The parameters of the electrical power system quantities and PV array are given in Table 1 & Table 2, respectively.

3.1. Results for Balanced Linear Loads

Figure 3 shows the changes in solar irradiance at specific times. At time $t = 2$ sec its value is equal to zero, represents night time. Figure 4 represents the amount of active and reactive power demanded by the load.

Table 1
Input Parameter Values of PV Array

Description	*Parameter value*
Number of series modules per string	22
Number of strings in parallel	2
Number of cells per module	36
Complete array open circuit voltage at STC	868V
Complete array short circuit current at STC	6.9A
Maximum power output at STC	3830W

Table 2
Power System Parameters

Description	*Parameter value*
Inductive coupling per phase	35mH (For linear loads) 2mH (For Non-Linear load)
DC link capacitor	1000μF
Load parameters	R_L = 50ohm, X_L = 20mH (For linear loads) 3-φ Full bridge rectifier with R_L = 30ohm (For Non-Linear load)
Grid voltage per phase	230V(R.M.S)
Grid frequency	50Hz

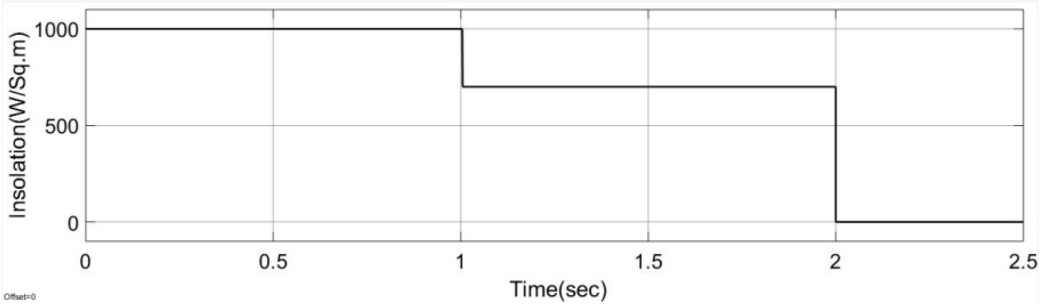

Figure 3: Change of Irradiance with respect to Time

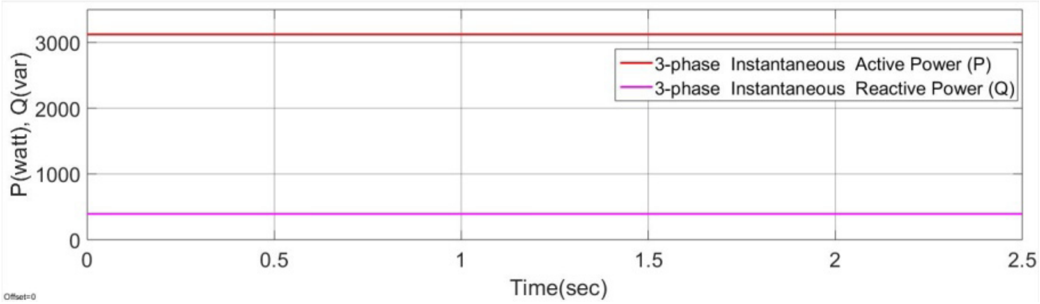

Figure 4: Load Active and Reactive Powers

Figure 5 shows the changes in active power of PV system corresponding to the changes in the irradiance at different time intervals and the reactive power supplied by the PV inverter, according to the control strategy it is evident that PV inverter completely compensates the reactive power demanded by the load irrespective of the irradiance value, i.e. even when the irradiance value is zero (during night time) the inverter will provide reactive power continuously that has been demanded by the load.

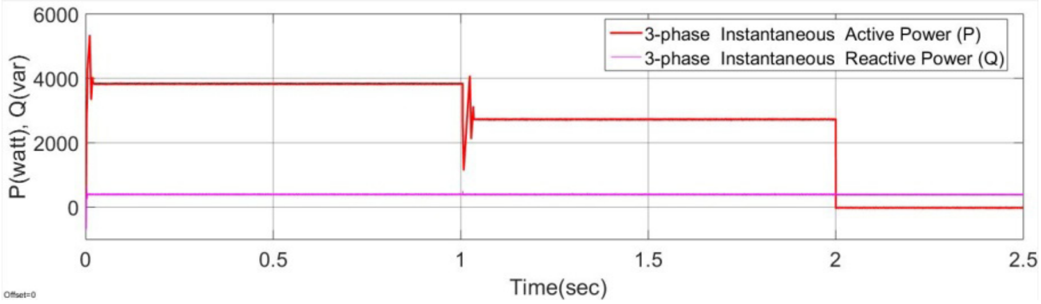

Figure 5: Active and Reactive Power Supplied with PV System

From Figure 5, it is observed that up to 1sec the active power supplied by PV system is 3830W, but the active power needed by the linear balanced load is only 3124W, the remaining 706W of power is fed to grid. After 1sec, the active power of 2720W is supplied by the PV system alone and active power of 404W is taken from the grid to meet the load demand. After 2sec the active power required by the load is taken from the grid alone, here in this time (considering as a night time) PV system does not supply any active power. At any time reactive power demanded by load is 393VAR, which is always supplied with the PV system. Figure 6 shows the active and reactive power supplied by grid for the same load conditions. Until 1sec, the active power generated by the PV system is more than the active power needed by the load, so the rest of solar power is fed to the grid. During 1-2sec, the active power generated with PV system is lesser than the load demand, so the required load power is drawn from the grid. After 2sec, the total active power of load is supplied only by the grid due to zero irradiance value and reactive power supplied by the grid is always zero.

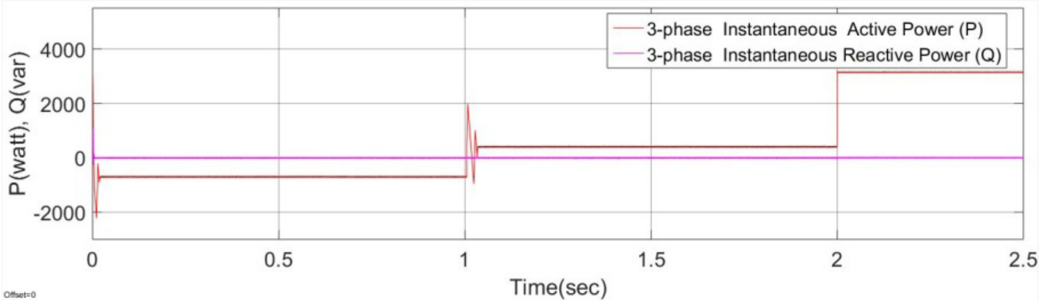

Figure 6: Active and Reactive Power Supplied with Grid

Figure 7 shows the details of active power required by the load P_L, active power supplied by the PV system P_{REF} and active power supplied by the grid P_{Grid} at various irradiances, which is mathematically expressed as $P_L = P_{Grid} + P_{REF}$.

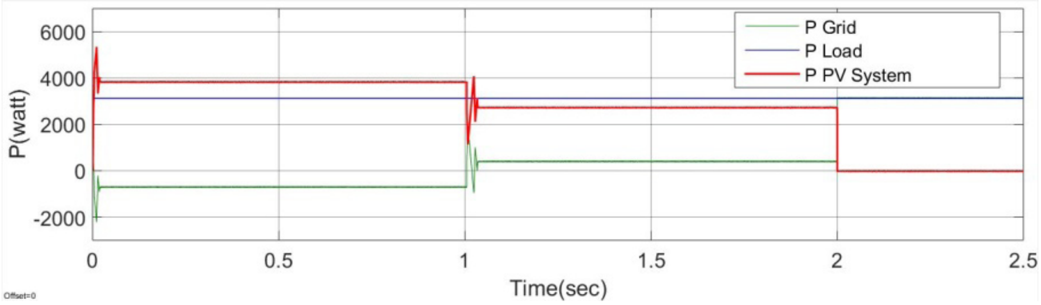

Figure 7: Grid, PV System and Load Active Powers

The phase ‘a’ current waveforms for the load i_{La}, the inverter i_{ca} and the grid i_{sa} are shown in Figure 8. Load current is the sum of the inverter current and grid current, which is expressed as $i_{La} = i_{ca} + i_{sa}$. Figure 9 shows the phase ‘a’ voltage and currents of grid at irradiance values of 700 W/m^2 (1.9-2 sec) and zero (2-2.1 sec). At any irradiance the voltage and current are in phase because total reactive power of the load is supplied by PV system, which reduces the burden of the grid.

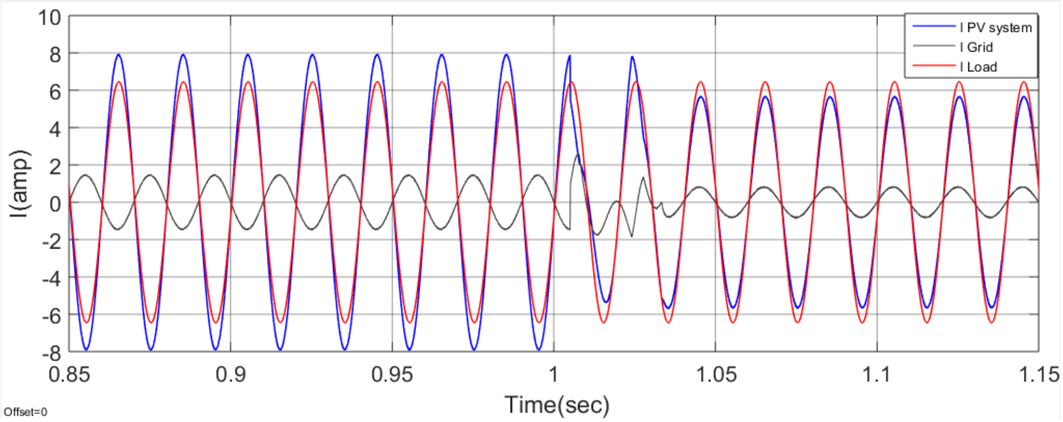

Figure 8: Grid, Load and Inverter Currents

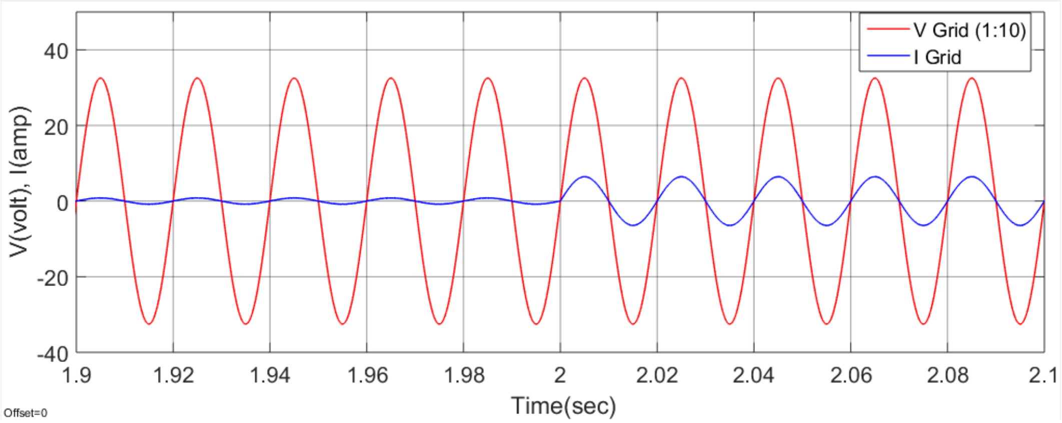

Figure 9: Grid Voltage and Current Waveforms of Phase ‘a’

3.2. Results for Unbalanced Linear Loads

For linear unbalanced load, the active and reactive powers are oscillating in nature as shown in Figure 10.

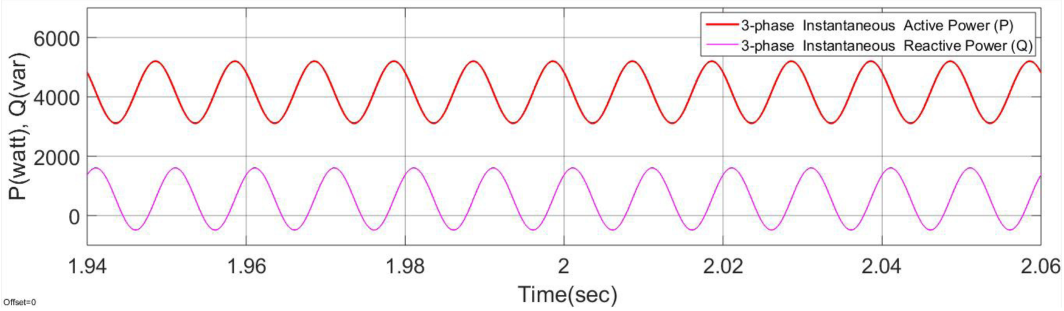

Figure 10: Active and Reactive Powers of Unbalance Load

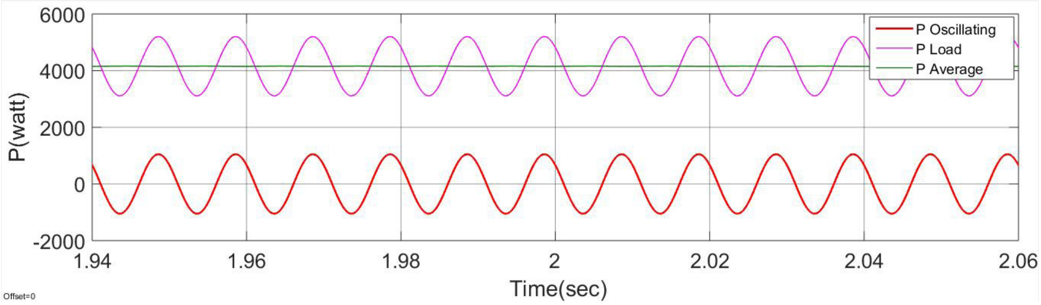

Figure 11: Oscillating and Average Components of Active power

The oscillating component from load active power is separated by using low-pass butter worth filter. The oscillating and average components of load active powers are shown in Figure 11, and is mathematically expressed as $\widetilde{P} = P_L - \overline{P}$. Here, the oscillating component of active power, average active power (either full or partial power depending on irradiance), and reactive power of load are supplied by PV system. The remaining average active power is being supplied/absorbed by the grid, which are shown in Figure 12 and 13, respectively.

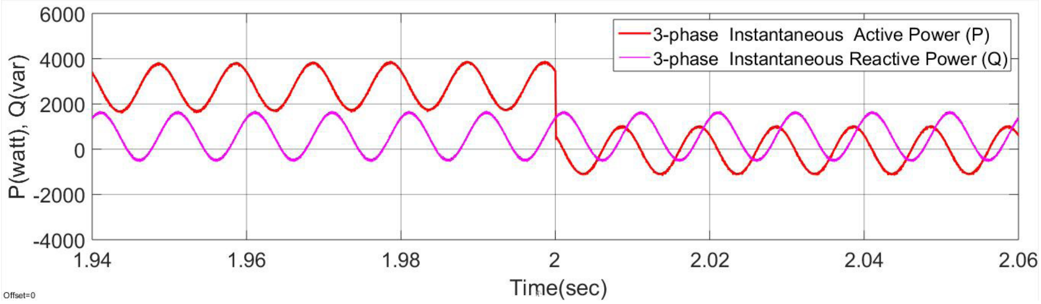

Figure 12: Active and Reactive Power Supplied by PV System

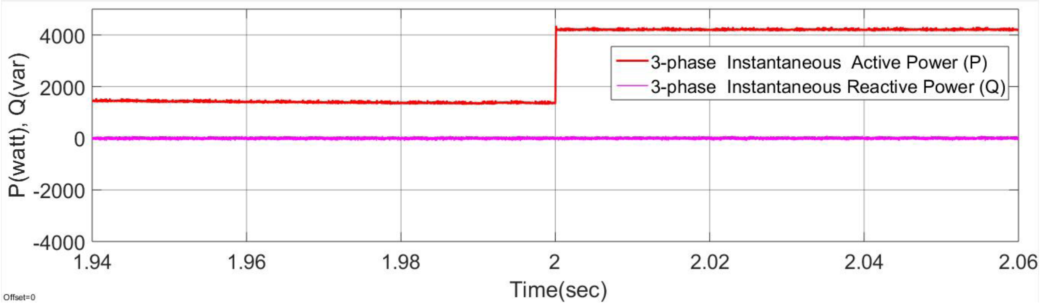

Figure 13: Active and Reactive Power Supplied by the Grid

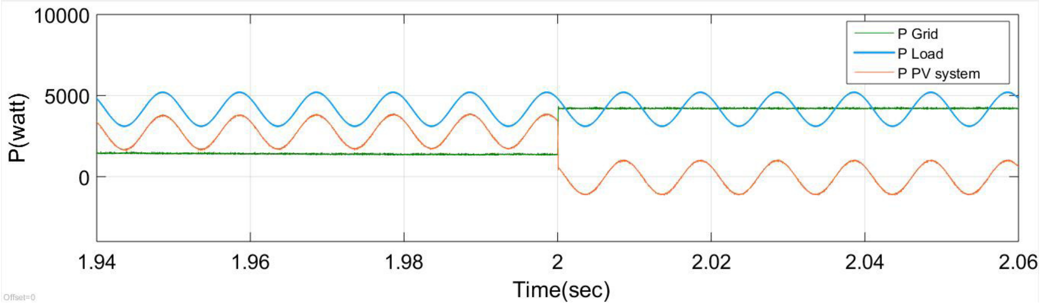

Figure 14: Grid, PV System and Load Active Powers

Figure 14 represents the active power supplied by grid and PV system to the load for different irradiance values of 700 W/m^2 (1.94-2 sec) and zero (2-2.06 sec). Also it satisfies the instantaneous active power $p_L = p_{Grid} + p_{REF}$. The voltage and current wave forms of phase 'a' at grid side are in phase for any irradiance value as depicted in Figure 15.

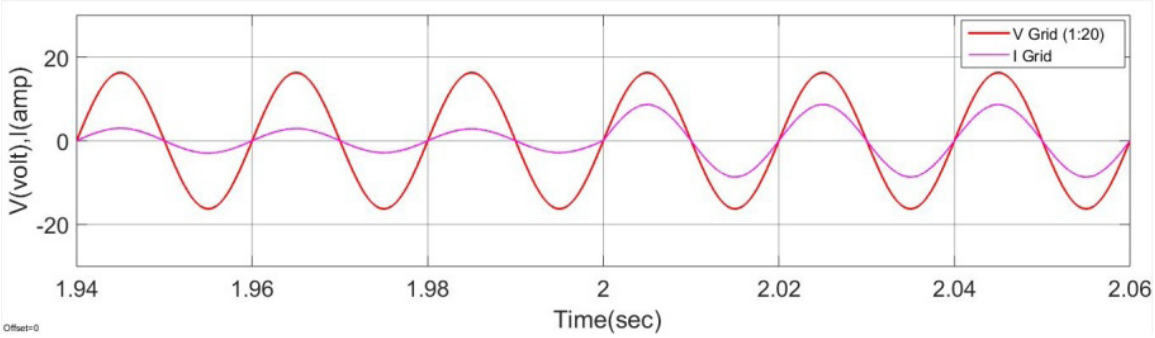

Figure 15: Grid Voltage and Current Waveforms of Phase 'a'

4. RESULTS FOR NON-LINEAR LOADS

In case of non-linear load, the load current is non-sinusoidal and the active and reactive powers of the load are oscillating in nature. Figure 16 shows the non-linear load current having a total harmonic distortion (THD) of 27.62%. The active and reactive powers drawn by the non-linear load are shown in Figure 17. Active power has two components one is DC (average) component and other one is oscillating component, whose average value is zero. These two components are separated by using low pass Butterworth filter. Figure 18 shows the average and oscillating components of load active power separately. The average value of active power is 9471W and the average value of oscillating component is zero.

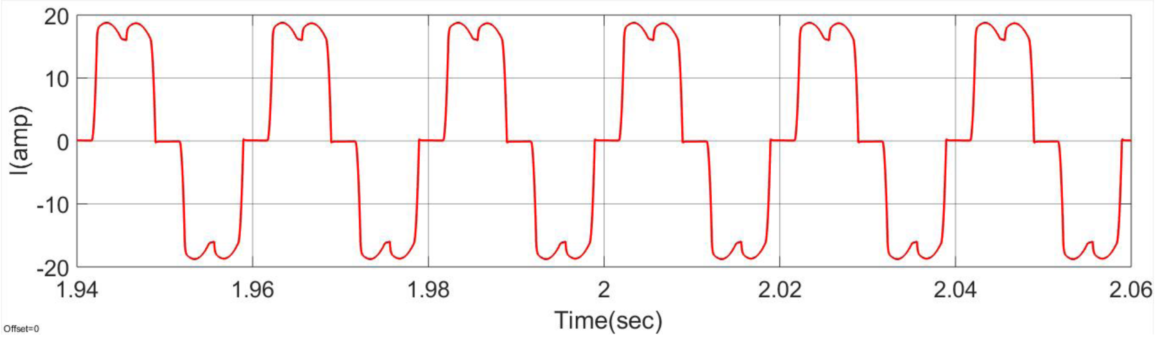

Figure 16: Load Current Wave Form

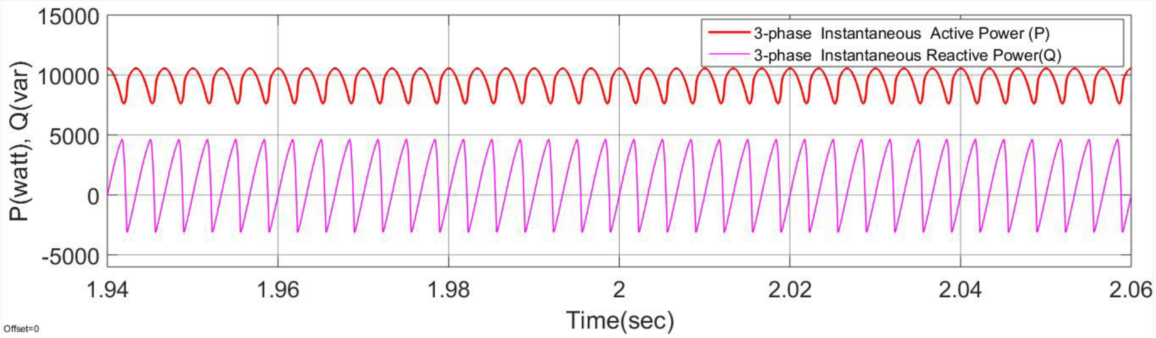

Figure 17: Active and Reactive Powers drawn by the Non-linear Load

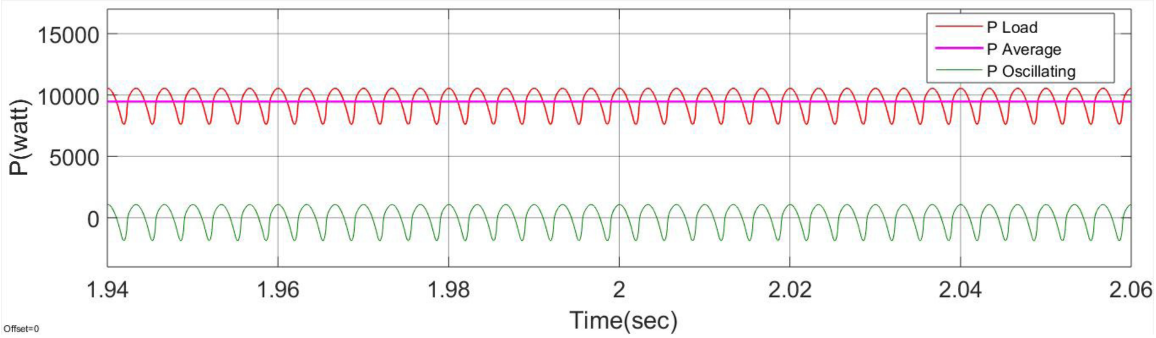

Figure 18: Separation of oscillating component of power from load active power

In order to eliminate the harmonic component in current on grid side and to make the grid power factor as unity, the oscillating component of active power and total reactive power of the load is compensated by the inverter. Figure 19 shows the active power supplied by the PV inverter in which it has observed that up to 2 sec, the active power supplied with the PV inverter is sum of the maximum power available at panel (2720W) and oscillating component. After 2 sec, the inverter compensates only oscillating component of active power because the power output at the PV panel is zero. The reactive power supplied by the PV inverter to the load is depicted in Figure 20. So, the inverter supplies the total reactive power demanded by the load for all irradiance conditions due to which the grid current and voltage are in phase and is shown in Figure 21. The active and reactive powers supplied by the grid is shown in Figure 22 and observed that it has zero reactive power and no oscillating component present in active power. However, the grid is supplying average active power of 6751W to the load up to 2 sec, thereafter it is supplying the complete average active power of 9471W. The total THD of load current and grid currents are represented in Figure 23 and 24, respectively. Here, the load current of THD is observed as 27.62% and limited to 1.12% in the grid current.

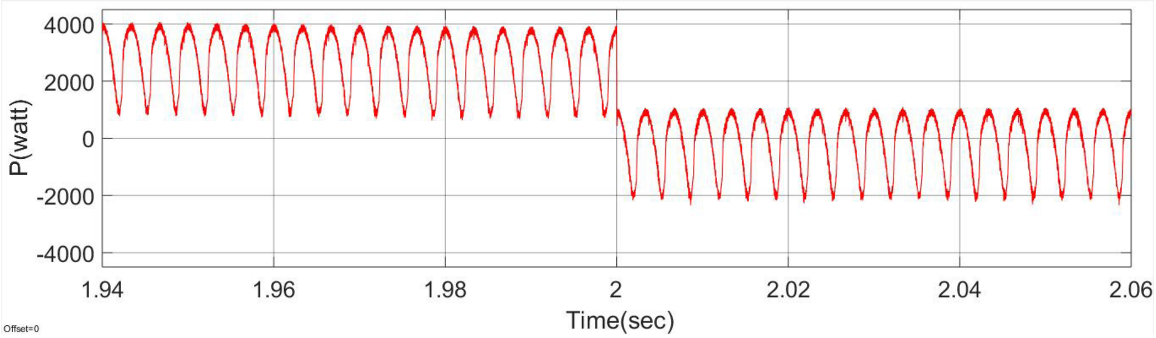

Figure 19: Active Power Supplied by PV Inverter

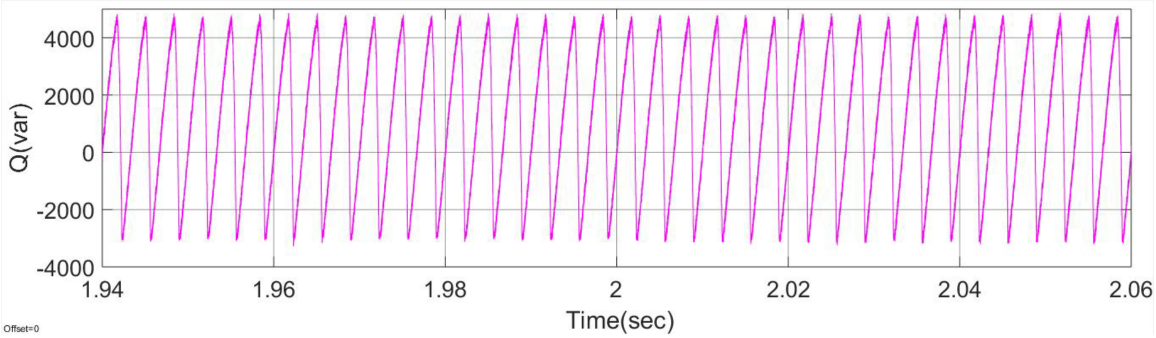

Figure 20: Reactive Power Supplied by PV Inverter

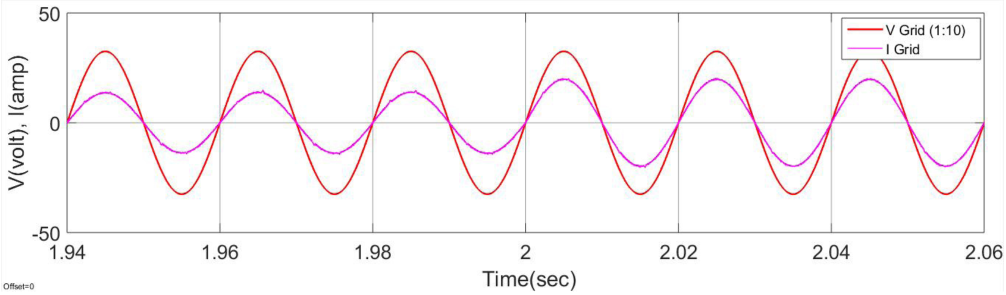

Figure 21: Voltage and Current Waveforms of Grid

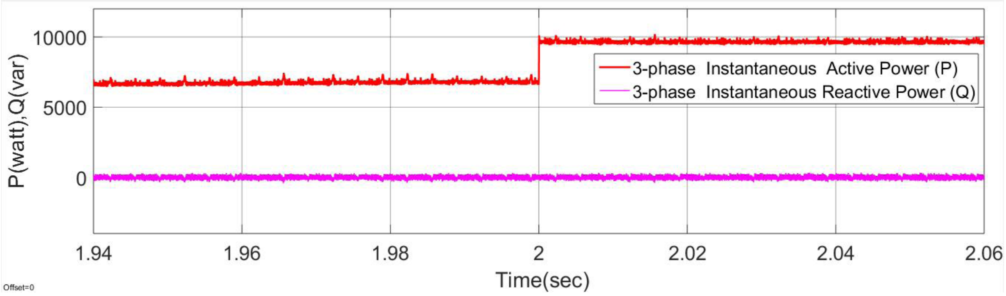

Figure 22: Active and Reactive Power Supplied by Grid

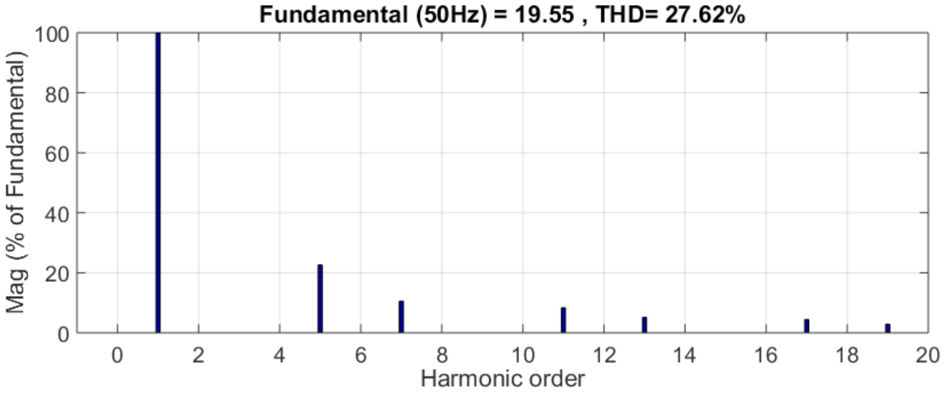

Figure 23: THD of Load Current

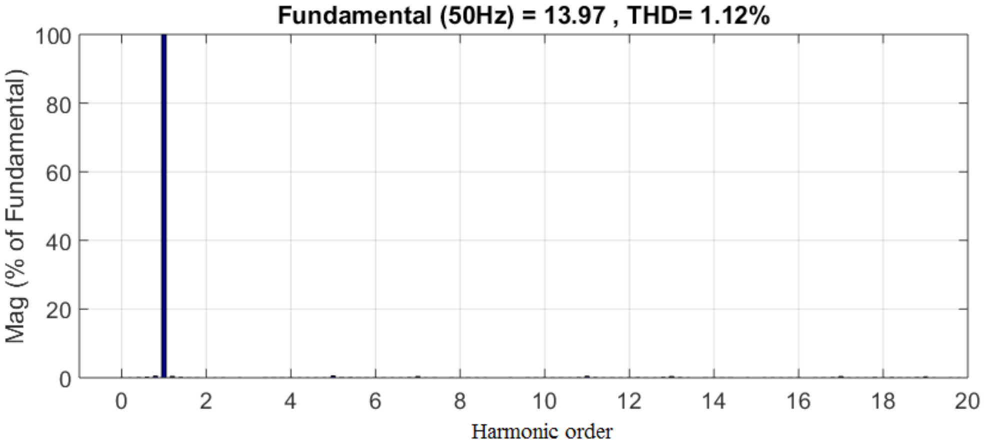

Figure 24: THD of Grid Current

5. CONCLUSIONS

In this paper, the investigations are made on a single stage three phase grid connected photovoltaic system with modified MPPT and active and reactive power control is realized by using P-Q theory. The proposed technology is verified with balanced, unbalanced linear & non-linear loads. For balanced loads, the active power 3124W required by the load is supplied by the PV system with 3830W and balance power of 706W is fed into the grid at an irradiance level of 1000W/m^2. When irradiance level is changed to 700W/m^2, the PV system is supplying active power of 2720W whereas the grid is supplying the remaining power of 404W. During zero irradiance level, the grid system only supplying a power of 3124W as required by the load. The reactive power required by the load is always supplied by PV system. The unbalanced linear load possess the oscillating components with average value in active power and zero average value in reactive power. The oscillating component of active power and reactive power are completely supplied by the PV system whereas the average active power is met by PV system and grid based on the different level of irradiance. In nonlinear loads, the load current is non-sinusoidal possessing harmonics leading to total harmonic distortion of 27.62%. Since P-Q theory is adopted in this proposed system, the harmonic content in grid current is reduced to 1.12% due to effectively minimization of harmonics. Hence, the proposed system does not required any complex mathematical expressions and costly PLL. Therefore, the advantage of the proposed system implies a simple mathematical model for realizations.

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