Single-phase grid-tied photovoltaic inverter to control active and reactive power with battery energy storage device

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Abstract— **This paper presents a Photovoltaic (PV) inverter along with a battery energy storage system connected in shunt with the grid. The objective of the proposed control system is to control both active and reactive power exchange between the grid and the load throughout the day, through a Voltage Source Inverter (VSI). Along with the reactive power compensation, it also provides current harmonic compensation to the connected load. A combined PV-battery arrangement is provided through a bi-directional DC-DC converter for uninterrupted power supply.**

Index Terms— ***Instantaneous Reactive power theory, Photovoltaic, Matlab/Simulink, Solar Cell, Single Diode Equivalent circuit, Active Power Filter.***

I. INTRODUCTION

Renewable energy sources, particularly solar photovoltaic power generating systems are intermittent in nature. The performance of the solar photovoltaic system depends on upon various environmental parameters, such as solar radiation, day and night time weather condition, temperature etc. Therefore, the sensitive residential loads installing solar PV system can implement combined PV-battery energy storage system. During the day time, the battery gets charged from the PV panel through a shunt connected DC-DC bi-directional buck-boost converter, apart from sharing the active and reactive power to the connected load and the utility grid. Whereas, during the night time or cloudy condition the battery discharges to the connected critical residential loads and to the grid for uninterrupted reactive power and harmonic compensation. Power theories such as instantaneous reactive power theory and instantaneous active and synchronous reference frame (DQ) theory are two powerful and popularly used methods for active and reactive power regulation and for load current harmonic solutions in a three-phase environment.

A fuzzy [1] based hybrid active power filter in conjunction with PV-battery arrangement is discussed. Variation of solar radiation is not analyzed, thus, the effectiveness of the storage system during zero solar radiation is not highlighted. Reactive power compensation only for R-L load is given [2] for a single-phase grid-connected PV system. The single-phase signal has been delayed by 120◦ and 240◦ to get the three-phase signal to implement the the-phase P-Q theory. Series resonant high pass filter is used [3] to eliminate the load current harmonics. The mathematical model analyzed is more complicated compared to the original P-q theory. Different types of reactive power injection strategies [4] have been discussed and harmonic compensation is nit analyzed.

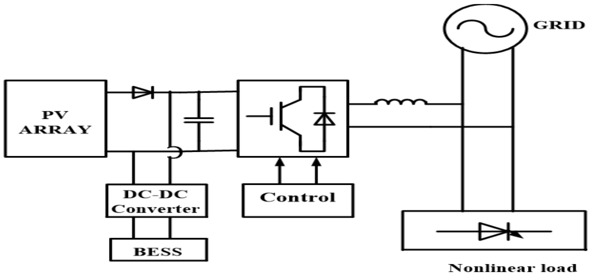

Fig.1. Grid connected photovoltaic system.

Instead of going for a diesel based PV system, battery energy storage system is proposed because of its various advantages. The charging and discharging of the storage device are carried out using a DC-DC bi-directional buck-boost converter [5] according to the availability of solar energy. A single stage single-phase shunt connected voltage source inverter-based PV system for grid integration is proposed. The control algorithm used is based upon single phase p-q theory [4], [5]. Based upon various environmental parameters (solar radiation, temperature etc.) an one-diode equivalent mathematical model [6]-[7] has been constructed to obtain the ideal solar I-V and P-V characteristics. To determine Maximum power point, Perturb and Observation method is used [8]-[9]. The organization of the paper is as follow: section II briefly describes the principle of operation of a grid-connected PV system, followed by the control algorithm in section III. The section IV describes the BESS and simulation results are given in section V, followed by the conclusion in section VI.

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II. Principle of Operation

The block diagram showing the control loop is presented in the Fig. 2. Where, U_s, I_L, V_{dc}, V_{dc*}, I_c, L_c are the grid voltage, load current, dc bus capacitor voltage, V_{dc} reference, inverter current, Point of Common Coupling (PCC) inductance respectively. Various types of linear and non-linear loads used in the simulation are presented in the Fig. 3.

In this paper, the PV and the grid are connected together in one stage. It can be seen from the system configuration, in between PV array and the voltage source inverter there is a single capacitor. Controlling the capacitor voltage is vital for accommodating the change in the PV cell parameters and for unity power operation of the system. Each instant the DC bus voltage becomes equal to the reference voltage the control loop delivers a pulse to the inverter. The transfer of the reactive power depends upon the voltage difference between the grid and the inverter. Similarly, the PV active power transfer is a function of the phase difference between these two.

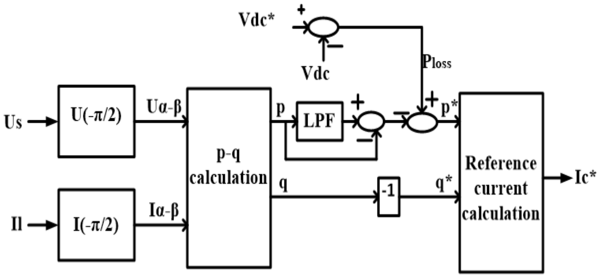

Fig. 2. Block diagram representation of the control algorithm.

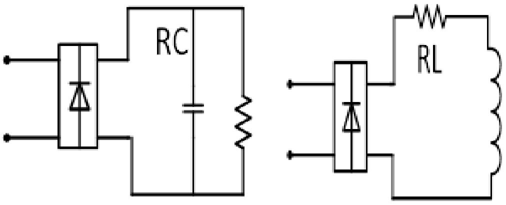

Fig. 3. Various linear and non-linear loads used for simulation.

III. Control of The Grid Integrated PV System

The instantaneous p-q theory has been successfully employed in multi-phase systems. But for single-phase power systems, only single voltage and single current signals are available, as a result, it becomes difficult to evaluate the instantaneous power. To overcome this difficulty we can lag or delay the available single phase signal by 120° and 240° [2] to obtain three different signals.

Otherwise, a much simpler approach is to delay the existing signal phase by 90° to get a two-phase reference system [3], as explained in Table 1. These two signals can be treated as α-β reference system signals, according to equation (1) and (2). They can further be used to evaluate the instantaneous active and reactive powers, similar to three phase system. The advantages associated with the second method of single phase p-q theory are (i) it is devoid of a-b-c to α-β transformation [10]-[11] (ii) simpler than three phase system as it is an essentially a two- phase analysis, thus (iii) the number of components and the time delay loss compared to ±120° delay is less.

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = \begin{bmatrix} U_s(wt) \\ U_s\left(wt - \frac{\pi}{2}\right) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} I_l(wt) \\ I_l\left(wt - \frac{\pi}{2}\right) \end{bmatrix} \tag{2}$$

TABLE 1 CONTROL ALGORITHM FOR THREE-PHASE AND SINGLE-PHASE SYSTEM

Events	**Three-phase**	**Single-phase**
Clark's transformation or α-β transformation	$V_{s\alpha\beta} = MV_{sabc}$, $I_{l\alpha\beta} = MI_{labc}$ Where, $M = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$	$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = \begin{bmatrix} U_s(wt) \\ U_s\left(wt - \frac{\pi}{2}\right) \end{bmatrix}$ $\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} I_l(wt) \\ I_l\left(wt - \frac{\pi}{2}\right) \end{bmatrix}$
p-q calculation	$p = U_\alpha I_\alpha + U_\beta I_\beta$ $q = U_\alpha I_\beta - U_\beta I_\alpha$	$p = U_\alpha I_\alpha + U_\beta I_\beta$ $q = U_\alpha I_\beta - U_\beta I_\alpha$
Selection of power for compensation	p^* and q^*	p^* and q^*
Reference current evaluations	$\begin{bmatrix} I_{c*\alpha} \\ I_{c*\beta} \end{bmatrix} = \frac{1}{V_{s\alpha}^2 + V_{s\beta}^2} \cdot \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ V_{s\beta} & -V_{s\alpha} \end{bmatrix} \begin{bmatrix} p^* \\ -q \end{bmatrix}$	$I_c^* = \frac{U_\propto p^* - U_\beta q}{U_\propto^2 + U_\beta^2}$
Inverse Clark's transformation	$\begin{bmatrix} I_{c*a} \\ I_{c*b} \\ I_{c*c} \end{bmatrix} = M^{-1} \begin{bmatrix} I_{c*\alpha} \\ I_{c*\beta} \end{bmatrix}$	I_c^*

The instantaneous active and reactive power using IPR p-q theory can be calculated as follows:

$$p = U_\alpha I_\alpha + U_\beta I_\beta \tag{3}$$

$$q = U_\alpha I_\beta - U_\beta I_\alpha \tag{4}$$

The above power expressions have DC component as well as AC component, as expressed in equation (5) and (6).

$$p = \bar{p} + \tilde{p} \tag{5}$$

$$q = \bar{q} + \tilde{q} \tag{6}$$

To compensate the load harmonic and the reactive power, only the AC component ($\tilde{p}$) of active power and total reactive power (q) are used for reference power calculation. Due to switching of the inverter circuit there will be always some loss called as inverter switching loss. This loss component (P_{loss}), can be extracted by controlling the DC bus capacitor voltage, as shown in the Fig. 1. The loss component and the reference power added together to find out the reference currents as per the following equation [5], [8].

$$I_c^* = \frac{U_\alpha p^* - U_\beta q}{U_\alpha^2 + U_\beta^2} \tag{7}$$

Where, $p^* = p_{loss} + \tilde{p}$.

The hysteresis band current control scheme, used for the control of inverter output current, is shown in Fig. 4. The error signal of the reference current and the inverter current is fed to the relay switch, to get the switching pulse for the voltage source inverter.

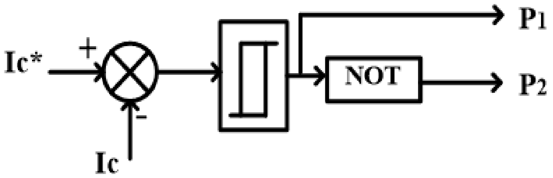

Fig. 4. Block diagram of the hysteresis control.

IV. BATTERY ENERGY STORAGE SYSTEM

The objective of a combined PV-battery arrangement is to maintain the DC bus capacitor voltage always at a steady state level, irrespective of the solar irradiation. For example, at night time the battery steps in and whole battery is connected across the DC bus capacitor of the three-phase VSC to provide uninterrupted compensation. Whereas during strong sunlight the PV provides continuous compensation apart from sharing the load requirement, so the excess energy from the PV is utilized for charging the battery.

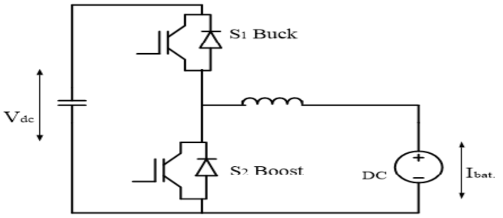

Fig. 5. DC-DC buck-boost converter

The battery energy system consists of a bi-directional DC-DC buck-boost converter called as a battery charger aided by a closed loop controller, as shown in Figure 5. It operates in two different modes: charging and discharging mode. During strong sunlight the battery get charged from the PV array and during low light or at night time the battery get discharged by delivering the power to the outside, through a bi-directional charge controller as shown in Figure 6.

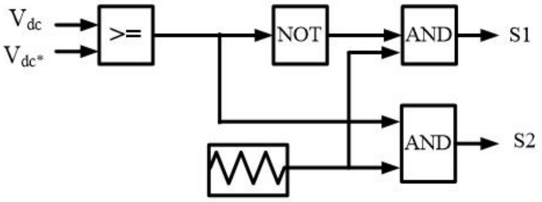

Fig. 6. The control circuit of the DC-DC converter.

V. SIMULATION RESULTS

The simulation results presented in this paper were obtained using MATLAB/Simulink software, for a single phase power systems with a shunt connected PV inverter. The performance of the PV inverter was evaluated for the ideal source voltage; change in load and for change in solar radiation level.

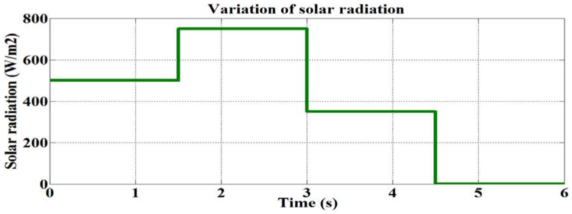

Fig. 7. Variation of solar radiation.

Fig. 7 shows the variation of solar radiation (S) at various instants as input to the PV array. Fig. 8 represents the variation of active power due to change in solar radiation. For example, at t =1.5 s, when the solar input is increased, the inverter output power is increased and simultaneously there is a decrease in active power delivered by the grid as the power consumed by the load remains constant. Fig. 10 presents the compensation of grid reactive power throughout the observation. The inverter supplies the total reactive power required by the load and relieves the grid from the reactive power burden. Even when PV active power is zero (at t = 4.5 s), the inverter is able to supply the whole reactive power demand by the load. Therefore, irrespective of the solar radiation, as shown in the Fig. 8, the grid voltage and currents are always in phase with each other as all the reactive power of the load has been compensated.

The Total Harmonic Distortion (THD) diagram for both the inductive and the capacitive load at an initial solar radiation of 500 W/m^2 is shown in the Fig. 11 and Fig. 12. When compensation is applied, the load current, injecting inverter current and the compensated grid current is presented in the Fig. 13 and Fig. 14, for inductive and capacitive load respectively. The grid current is always sinusoidal and is in phase with the grid voltage, as evident from Fig. 15. The THD level is reduced from 25.79% to 2.46% for the inductive load (Fig. 16). Table 2 lists the THD level of the source current for different types of loads at various solar irradiation levels.

TABLE 2 SIMULATION PARAMETERS

Description	**Parameter**
Two PV modules connected in cascade	Open circuit voltage = 260V (V_{max} = 236.3V), short circuit current = 25.44A (I_{max} = 24.9A) and P_{max} = 5891W at standard test condition.
Inductive Coupling	5.12 mH
DC capacitor	0.1 mF
Load	R_l =5Ω, L_l = 15 mH, C = 650 µF
Grid	Vs = 230V rms, 50 HZ.

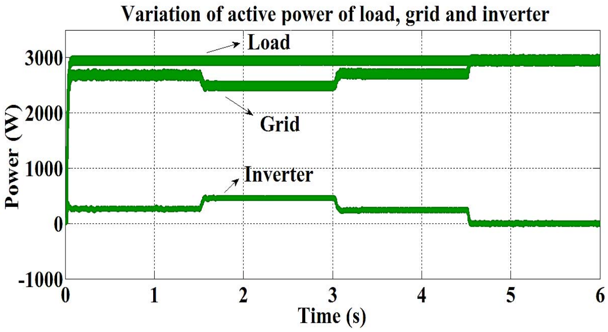

Fig. 8. Active power of grid, inverter and load without storage device.

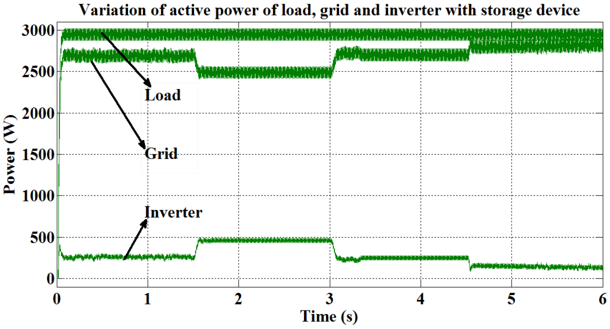

Fig. 9. Active power of grid, inverter and load with storage device.

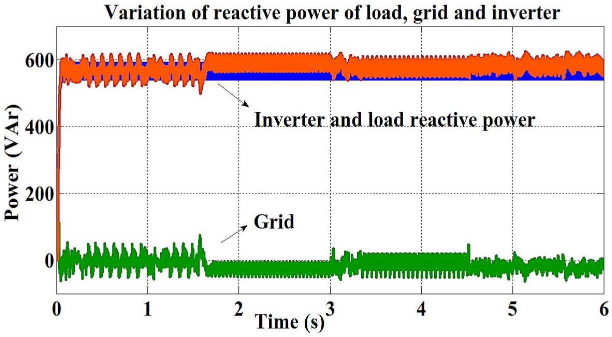

Fig. 9. Reactive power of grid, load and inverter.

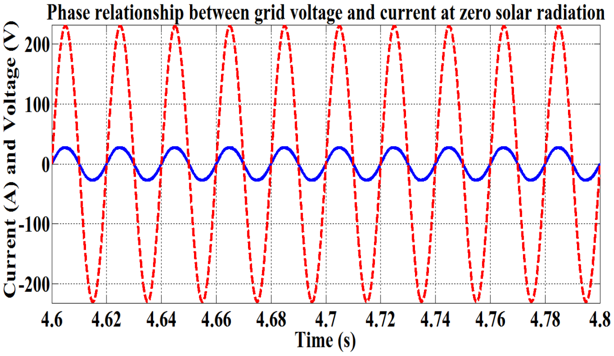

Fig. 10. Voltage and current of the grid.

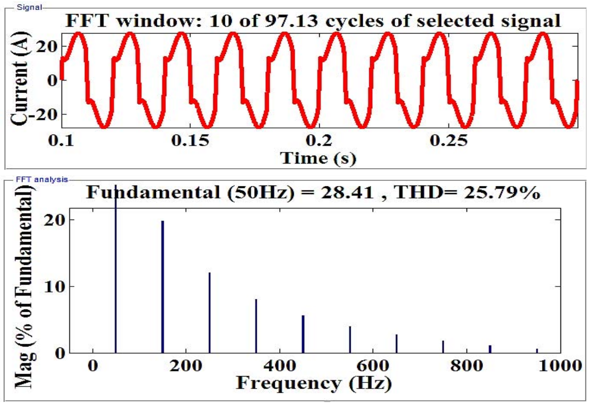

Fig. 11. The THD diagram of the non-linear inductive load.

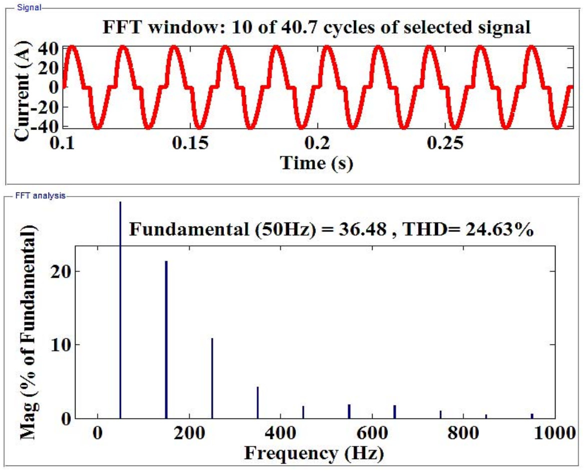

Fig. 12. The THD diagram of the non-linear capacitive load.

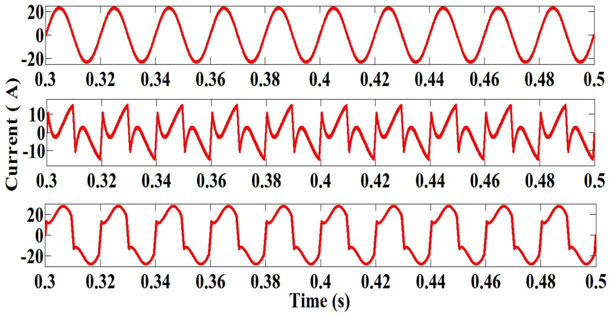

Fig. 13. Grid current (top), injected inverter current (middle) and non-linear inductive load current (bottom) during the compensation.

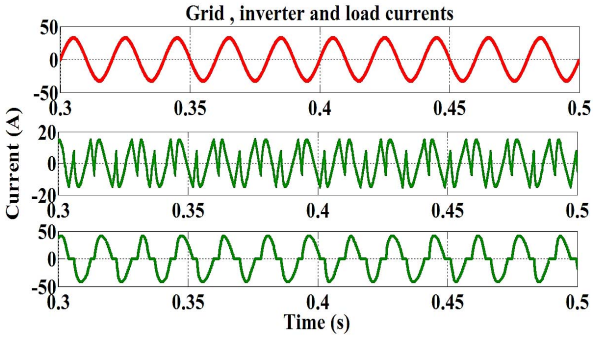

Fig.14. Grid current (top), injected inverter current (middle) and non-linear capacitive load current (bottom) during the compensation.

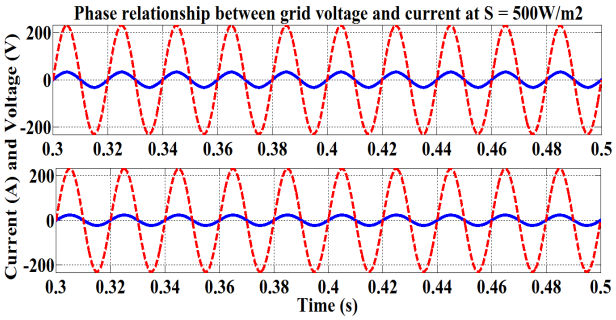

Fig. 15. Phase relationship between the grid voltage and current for non-linear inductive (top) and capacitive (bottom) load.

TABLE 2 THD FINDINGS

Solar Radiation (W/m2)	THD (in %) of grid current (for inductive load)	THD (in %) of grid current (for capacitive load)
500	2.46	2.28
750	3.59	2.86
350	2.21	2.36
0	2.91	3.15

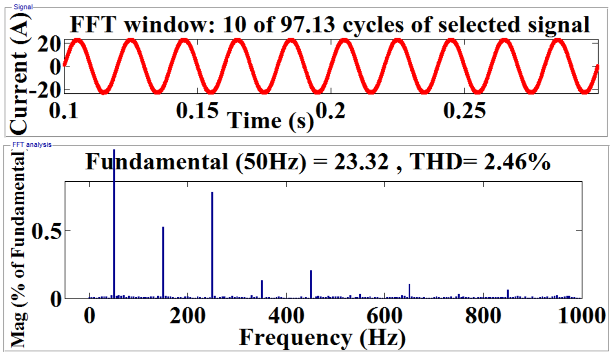

Fig. 16. THD diagram of compensated grid current for non-linear inductive load..

VI. CONCLUSION

In this paper, the investigation has been carried out for a single phase single stage grid-connected PV system, for change in solar radiation level and variation of load using the instantaneous single phase reactive power p-q theorem. The advantages associated with this operation is it does not require passive filter so that it can be suitable for varying electrical and weather conditions. It does not contain a boost converter to transmit the PV output and any Phase Lock Loop (PLL) circuit, which reduces cost and complexity of the system. Simple mathematical equations are involved in calculating the active, reactive power and reference currents. Therefore, it requires less calculating power and thus system dynamics can be improved. Finally, it can concluded that this arrangement of the PV-battery hybrid system is able to deliver the active power to the grid and at the same time compensates the load harmonics and reactive power of the load throughout the day, thereby improving the power factor of the power systems and utilization of PV system during low sunlight.

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