A Grid-Connected PV Inverter with Compensation of Load Active and Reactive Power Imbalance for Distribution Networks

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Abstract: Load balancing is an important issue in distributed systems. In addition, using distributed generation sources such as photovoltaic is increasing. Power electronic converters are main interfaces between the sources and the grid. In this paper, a method has been proposed to reduce the load imbalance in distribution networks using PV Grid Interface Converter. Two DC/DC and DC/AC converters have been utilized for connecting PV to the grid. A control strategy is presented which enables the converter to compensate the load imbalance by injecting power of solar cells to the load and grid. Simulation results by MATLAB/SIMULINK software indicate the ability of the proposed control method to reduce the load imbalance.

Keywords: Load Imbalance, PV, Grid-Connected Inverters, Distribution Network.

1 Introduction

Load imbalance is one of the distribution networks problems. Imbalance Load in distribution networks is because of random behavior of single-phase consumers and their non-uniform distribution among different phases. Unbalanced and nonlinear loads in three-phase four-wire systems results the large neutral current. Different studies have reported various approaches to compensate neutral currents. Among these methods, passive solutions such as zero sequence harmonic filters [1, 2], synchronous machine [3], hybrid filters [4] and active power filters for three-phase four-wire systems [5-7] can be mentioned. Among the methods, three-phase four-wire filters, which are designed to compensate neutral current, is more appropriate [8].

On the other hand, the growth of electrical energy consumption increased in the recent decade and thus the sensitive load that need to high power quality increased [9]. In addition, the continued use of fossil fuels will cause energy crisis and increase environmental pollution [10]. In dealing with these problems, distributed generation systems are increasingly used [11]. Numerous studies show that distributed generation sources (DGs) not only can connect renewable energy sources to the power grid, but also can improve the stability of power systems in some respects.

In DGs systems, grid-connected inverters are the main interfaces to connect renewable energy sources and energy storage devices to the power grid [12]. In order to optimum the cost of grid-connected inverters to DGs, multi-functional grid-connected inverters (MFGCI) are proposed [13]. Power electronic converters not only can inject the power to the electrical grid, but also they can increase the power quality. Auxiliary functions such as active filter, voltage imbalance compensator, grid feeding and control in voltage drop have been studied [13]. In the three-phase four-wire distribution systems, the neutral current causes an important power quality problem [11]. According to the conducted studies, the neutral current of 22.6% of systems is greater than 100 percent of phase current [11]. Thus, it seems that the compensation of neutral current is more important compare to the other power quality problems in three-phase four-wire distribution systems. Different structures are provided using power filters in three-phase four-wire distribution systems. These structures cannot fix the DC link voltage at high unbalance loads conditions. To deal with larger voltage drops in the grid, severe load imbalance or even interruption, DC capacitor should be replaced by an energy storage system [14].

In this paper, MFGCI is used to reduce load imbalance in a three-phase four-wire distribution network. Therefore, to fulfill this objective, the inverter structure is introduced. The presented structure is capable to reduce load imbalance. The inverter

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performance is dependent on the control strategy. For this purpose, an improved control strategy is presented in order to reduce load imbalance in three-phase four-wire distribution networks. In this structure, the costs reduce by discarding the battery. Also the batteries have high maintenance cost and short life. In section 2, characteristics of the utilized structure are expressed. The improved control strategy proposed to compensate the load imbalance, discussed in section 3. Simulation results are given in section 4. Finally, the section 5 is conclusion.

2 Structure of the Proposed System

Fig. 1(a) shows structure of the proposed system. In this structure, the solar cells are connected the grid in parallel with an unbalanced load through two DC/DC and DC/AC converters. DC/DC converter is responsible for maximum power point tracking (MPPT) in grid-connected mode. Moreover, the use of DC/DC converter provides the possibility of increasing the low voltage of solar cells in order to meet the need of DC/AC converter. For this purpose, the boost converter is used. The boost converter is shown in Fig. 1(b). DC/AC converter is responsible for injecting power to the grid as well as balancing load. As shown in Fig. 1(c), three single-phase voltage source inverters (VSI) have been used in the structure of this converter which control hysteresis band. Using three single-phase VSI is for load balancing.

The advantage of using single-phase VSI is that the control method can be performed as a single three-phase unit or three separate single-phase units and the maximum voltage of each H bridge is phase voltage. Thus the DC link voltage decrease (divided by √3) and the inverter capacity reduce. Each VSI is connected to the grid by a single-phase transformer and the grid is isolated from the inverter. A passive filter is used in series with DC/AC converter in order to filter the high frequency harmonics of the current.

3 Introduction of the Proposed Control System

To control DC/DC and DC/AC converters, grid-connected mode is considered. The load and inverter are connected in parallel to the grid. The objective of controller of the DC/DC converter is maximum power point tracking for solar cell and the objective of controller of the DC/AC converters is compensation for load imbalance along with power transmission of solar cell to the grid and the load. The maximum power generated by the solar cells inject to the grid and the load imbalance reduce. If generated power by the solar cells is greater than load capacitance, the additional power is injected to the grid.

3.1 Control of DC/DC Converter

In this paper, the Perturb and Observe method is used to track the maximum power point. The P&O method operates periodically incrementing or decrementing the output terminal voltage of the PV and comparing the power obtained in the current cycle with the power of the previous cycle. If the voltage varies and the power increases, the control system changes the operating point in that direction, otherwise change

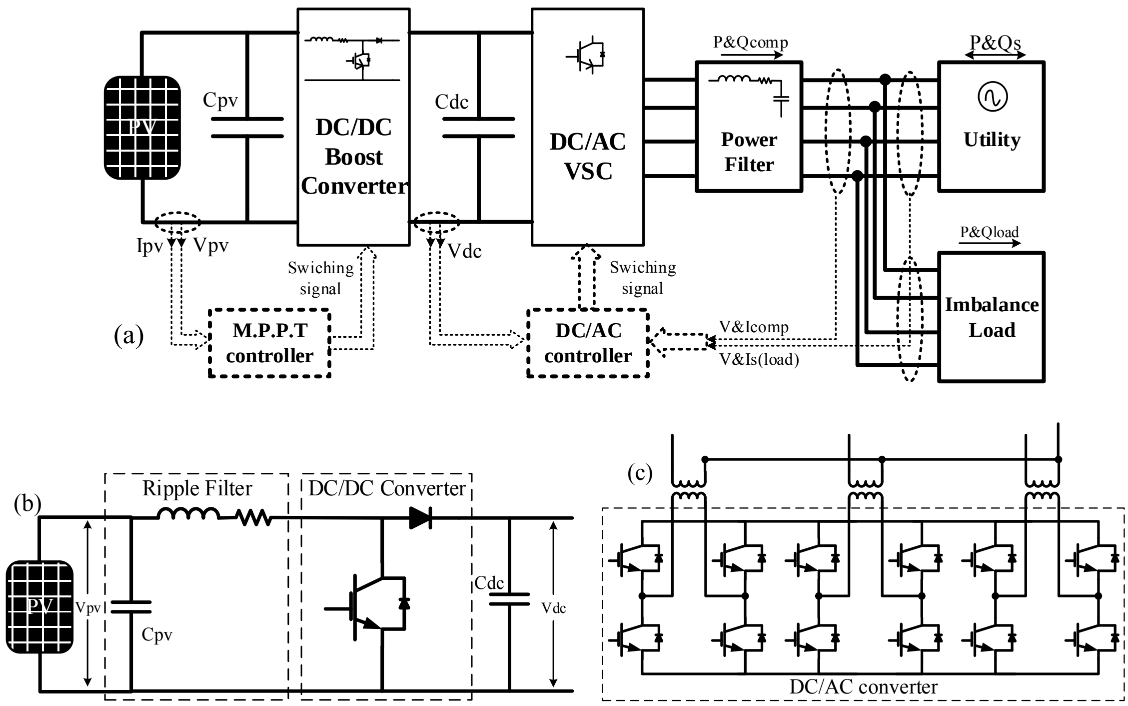

Fig. 1 Structure of the proposed system, (a) System Overview, (b) PV and DC/DC converter, (c) DC/AC inverter.

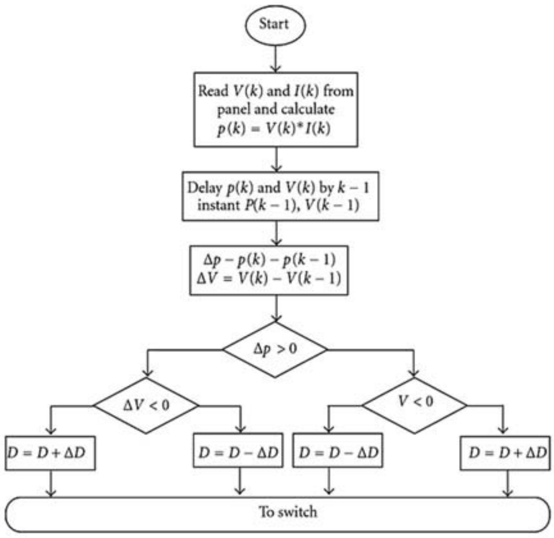

Fig. 2 Flowchart of P&O MPPT algorithm [15].

the operating point in the opposite direction [15]. Fig. 2 shows the flowchart of P&O MPPT algorithm. Duty cycle obtained through algorithm is applied to the switches via PWM.

3.2 Control of DC/AC Converter

The objectives of the controller are reducing load imbalance along with injection of solar cell power into the grid.

DC/AC converter while injecting solar cell power to the load and grid, compensates the load imbalance. To achieve the purposes of control, theory of single-phase instantaneous power is used to develop reference currents. According to this theory, any single-phase system can be defined similar to a two-phase system, with 90° lead or lag and current of a three-phase system can be considered with three separate two-phase systems. The two-phase systems can be presented in α-β frame. In this theory, real load voltages and currents are considered as quantities of α axis, whereas voltage or current with 90° lead or lag is considered as quantity of β axis [16]. In this paper, the desired objectives in the controller are followed based on this theory, and a strategy is recommended to be used for control of solar cells in grid-connected mode.

Based on the single-phase p-q theory, in this paper, real voltages and currents are considered as quantity of α axis and voltages and currents with 90° lead are considered as quantity of β axis. Thus, for phases a, b and c, assuming balanced voltages for each phase, we will have:

Voltages and currents of α-β frame for phase a:

$$\begin{bmatrix} V_{La\_\alpha} \\ V_{La\_\beta} \end{bmatrix} = \begin{bmatrix} V_{La}(\omega t) \\ V_{La}\left(\omega t + \frac{\pi}{2}\right) \end{bmatrix} = \begin{bmatrix} V_{lm}\sin(\omega t) \\ V_{lm}\cos(\omega t) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_{La\_\alpha} \\ i_{La\_\beta} \end{bmatrix} = \begin{bmatrix} i_{La}(\omega t + \varphi_l) \\ i_{La}\left(\omega t + \varphi_l + \frac{\pi}{2}\right) \end{bmatrix} \tag{2}$$

Voltages and currents of α-β frame for phase b and c:

$$\begin{bmatrix} V_{Lb,c\_\alpha} \\ V_{Lb,c\_\beta} \end{bmatrix} = \begin{bmatrix} V_{Lb,c}(\omega t) \\ V_{Lb,c}\left(\omega t + \frac{\pi}{2}\right) \end{bmatrix} = \begin{bmatrix} V_{lm}\sin(\omega t \mp 120) \\ V_{lm}\cos(\omega t \mp 120) \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_{Lb,c\_\alpha} \\ i_{Lb,c\_\beta} \end{bmatrix} = \begin{bmatrix} i_{Lb,c}(\omega t + \varphi_l) \\ i_{Lb,c}\left(\omega t + \varphi_l + \frac{\pi}{2}\right) \end{bmatrix} \tag{4}$$

Based on the p-q theory for three-phase balanced systems, instantaneous active and reactive powers are defined as follows [17]:

$$P_{L,abc} = V_{L,abc_\alpha}.i_{L,abc_\alpha} + V_{L,abc_\beta}.i_{L,abc_\beta} \tag{5}$$

$$q_{L,abc} = V_{L,abc_\alpha}.i_{L,abc_\beta} - V_{L,abc_\beta}.i_{L,abc_\alpha} \tag{6}$$

Thus, on the basis of definition of power of three-phase systems, active and reactive powers for each phase are obtained according to the single-phase p-q theory.

$$\begin{bmatrix} P_{La,b,c} \\ q_{La,b,c} \end{bmatrix} = \begin{bmatrix} V_{La,b,c\_\alpha} & V_{La,b,c\_\beta} \\ -V_{La,b,c\_\beta} & V_{La,b,c\_\alpha} \end{bmatrix} . \begin{bmatrix} i_{La,b,c\_\alpha} \\ i_{La,b,c\_\beta} \end{bmatrix} \tag{7}$$

To balance unbalanced load power, unbalanced load power must be properly distributed between the grid and the inverter, so that the whole load being seen from the grid is balanced.

Active and reactive powers of the whole unbalanced load is calculated according to the following equation:

$$P_L = P_{La} + P_{Lb} + P_{Lc} \tag{8}$$

$$q_L = q_{La} + q_{Lb} + q_{Lc} \tag{9}$$

Thus, for the balanced load, the power consumption of each phase is:

$$P_{L_{ph}} = \frac{P_L}{3} \;\&\; q_{L_{ph}} = \frac{q_L}{3} \tag{10}$$

This concept is used to determine reference signals in order to load balancing. In addition to deliver the power generated by solar cells, the converter must divide the power between the phases so that the grid load be balance. Thus, injected currents into the grid in α-β frame are:

$$\begin{bmatrix} i_{Ca,b,c\_\alpha} \\ i_{Ca,b,c\_\beta} \end{bmatrix} = \begin{bmatrix} V_{La,b,c\_\alpha} & V_{La,b,c\_\beta} \\ -V_{La,b,c\_\beta} & V_{La,b,c\_\alpha} \end{bmatrix}^{-1} . \begin{bmatrix} P_{La,b,c} - \left(P_{L_{ph}} + P_{dc}\right) + P_{pv\_mppt} \\ q_{La,b,c} - q_{L_{ph}} \end{bmatrix} \tag{11}$$

where $P_{La,b,c}, q_{La,b,c}$ are load powers per phase, $P_{L_{ph}}, q_{L_{ph}}$ are the reference powers obtained by Eq. (10), P_{pv_mppt} is maximum solar power cells obtained from the MPPT algorithm, and P_{dc} is the active power in order to maintain the DC-link voltage at a constant level.

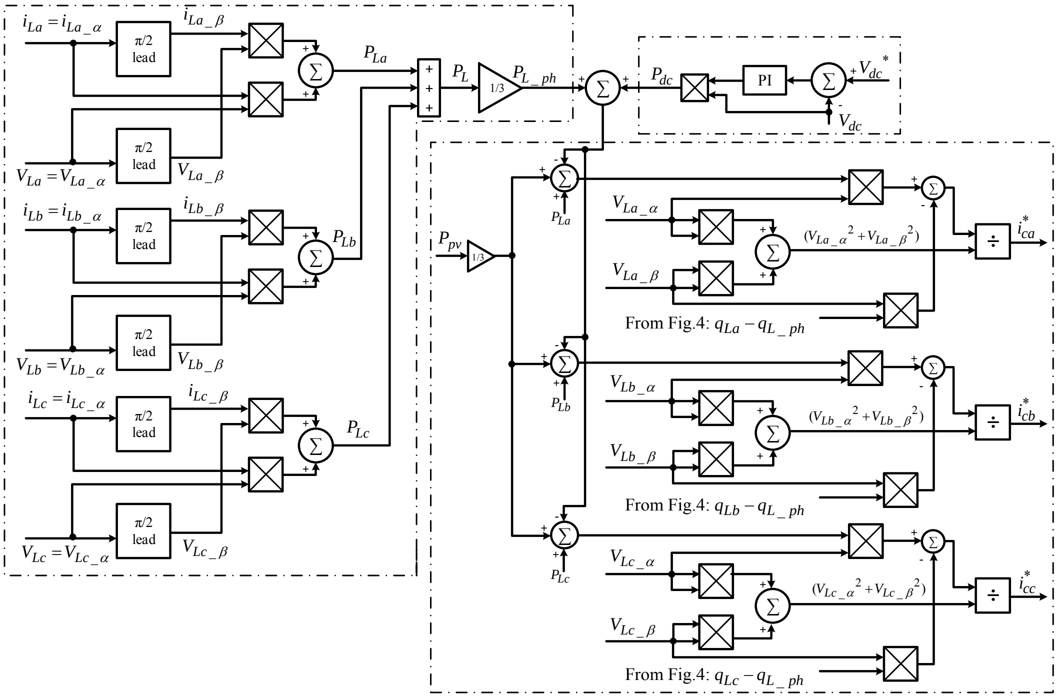

Fig. 3 DC/AC converter control block diagram (balanced per-phase active power estimation, DC link voltage control loop, and reference current generation).

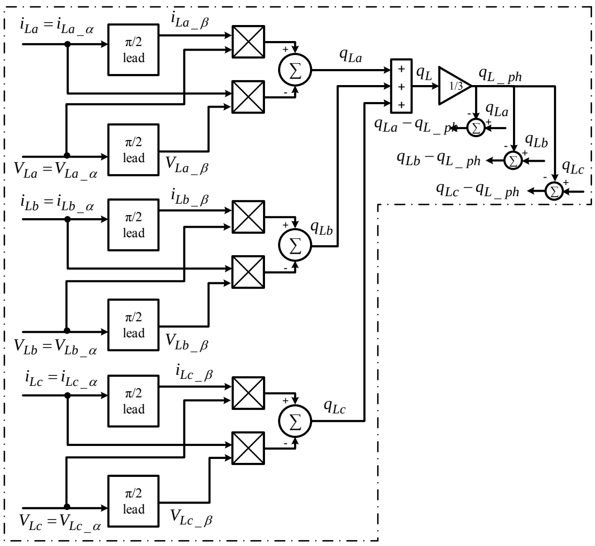

Fig. 4 DC/AC converter control block diagram (balanced per-phase reactive power estimation).

Table 1 Features and parameters of simulation.

Grid Parameters	$V_{rms\_phase} = 220V, f = 50Hz$
Load Characteristics	load 1: phase a: $P = 800W, Q_C = 800Var$ phase b: $P = 10W, Q_C = 10Var$ phase c: $P = 50W, Q_L = 150Var$
	load 2: phase a: $P = 3000W, Q_C = 1000\,var$ phase b: $P = 1000W, Q_C = 10\,var$ phase c: $P = 500W, Q_L = 150\,var$
DC/DC Converter	$C_{in} = 200\mu F, L = 0.5mH, R = 0.0005\Omega,$ $C_{dc} = 500\mu F, f_{sw} = 10kHz$
DC/AC Converter	Transformer Turn Ratio is 1. fsw=10kHz
LC filter	$V = 6.6\mu F, var, L = 5mH, R = 0.005\Omega$

Thus, three-phase reference currents of converter in grid-connected mode is:

$$i^*_{Ca,b,c} = i_{Ca,b,c\_\alpha} \tag{12}$$

The reference current generation block diagram is shown in Figs. 3 and 4.

4. Simulation Results

Parameters of simulation are shown in Table 1. Fig. 5 shows the dynamic model of solar cell. The series resistance RS represents the internal resistance to the current flow. The shunt resistance R_{Sh} is inversely related to leakage current to the ground. The PV array involves N strings of modules connected in parallel, and each string consists of M modules connected in series to obtain a suitable power rating [18].

Current-voltage and voltage-power Characteristic curves of the solar panel in various solar radiations is shown in Fig. 6.

Simulation for the proposed controlling method has been performed for two different load and variation in solar power.

In the first case, the power of load 1 is less than the power of solar cells. The power of solar cells is injected

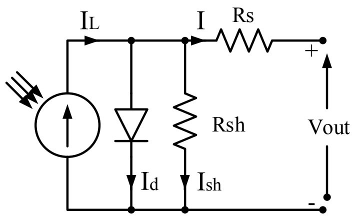

Fig. 5 Equivalent circuit of the solar cell.

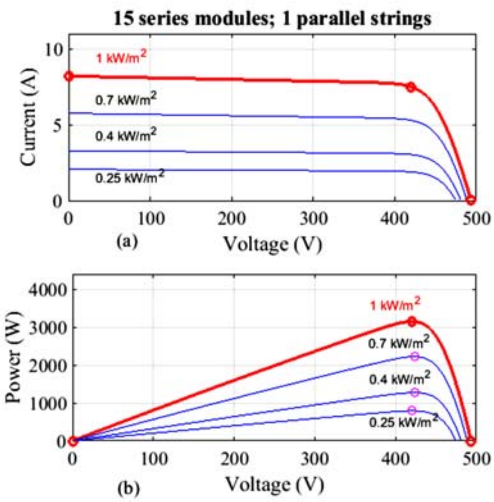

Fig. 6 Characteristic curves of solar panel (a) current-voltage (b) power–voltage.

to the load and network. The controller of DC/DC converter is responsible for maximum power point tracking and controller of DC/AC converter is responsible for injecting power of solar cells into the grid as well as load balancing. Figs. 7(a)-7(g) shows the results obtained from the simulations in this case. load voltage is equal to grid voltage which is shown in Fig. 7(a). Fig. 7(b) shows the load current that is unbalanced due to load imbalance. Fig. 7(c) also shows the grid balanced current. In Fig. 7(d) the load neutral and grid neutral currents can be seen. As it can be seen, load imbalance has been significantly reduced and DC/AC converter control functions properly.

Converter injecting power should be in such a way that in addition to injection of power of solar cells into the grid and load, compensate for load imbalance.

Figs. 7(e) and 7(f) shows active and reactive power of converter, grid and load. As can be seen in the figure, the active power of grid is negative and the active and reactive power of grid are equal in every phase. This means that active Power is injected into the grid and grid is balanced. Regarding the shape and features of solar cells, proper MPPT function can be seen. DC voltage converter and PV is shown in Fig. 7(g) which has been regulated in the average value of 500 volts for DC/AC converter and 430 V for PV that is MPPT point.

In the second case, Load 2 power is more than the power of solar cells. In this case, the power of solar cells and grid is injected to load. The controller of DC/DC converter is responsible for maximum power point tracking and controller of DC/AC converter is responsible for injecting power of solar cells into the load as well as load balancing. Figs. 8(a)-8(g) shows the results obtained from the simulations in this case. Fig. 8(a) shows the load voltage. Figs. 8(b) and 8(c) show the load current and the grid balanced current respectively. The load neutral and grid neutral currents are shown in Fig. 8(d). As it can be seen, DC/AC converter control functions properly. Fig. 8(e) and Fig. 8(f) show active and reactive power of converter, grid and load. As can be seen in the figures, the active power of grid is positive and the active and reactive power of grid are equal in every phase. This means that both of the PV and grid supply the load and grid is balanced.

DC voltage converter and PV is shown in Fig. 8(g) which has been regulated in the average value of 500 V for DC/AC converter and 430 V for PV that is MPPT point.

Figs. 9 and 10 show the results of the simulation for load 1 and load 2 in the conditions of variable radiation. In this case the solar radiation is variable between 0.4 to 1.4 seconds as shown in Figs. 9(a) and 10(a). The variation radiation causes changes in production capacity of solar cells, which in Figs. 9(b) and 10(b) can be seen. Figs. 9(c) and Fig. 10(c) show that by reducing the production capacity of solar cells, power injected into the network and load is reduced. However, the power drawn from the grid are balanced that shows the control system works properly. Figs. 9(d) and 10(d) shows reactive power of network load and converter. The role of converter is only balancing the reactive power. In Figs. 9(e) and 10(e) neutral currents of grid and load are shown. As can be seen neutral current of grid is dropped to zero, which indicates a good performance.

5 Conclusion

In this paper, a method for balancing of load active and reactive power in distribution networks, using PV grid interface converters, based on the single phase p-q theory, has been proposed. The introduced structure is consisted of two DC/DC and DC/AC converters. The presented structure is capable of reducing load imbalance. Moreover, a proposed control strategy is presented in this paper. The proposed strategy, control the converter and two case study are simulated. The simulation results by MATLAB/Simulink shows that the converter can control the following objectives:

(1) Transmission of maximum power of solar cells into the grid and the load,

(2) Compensation for of load active and reactive power imbalance,

The advantage of the proposed method is having simple control without using energy storage devices.

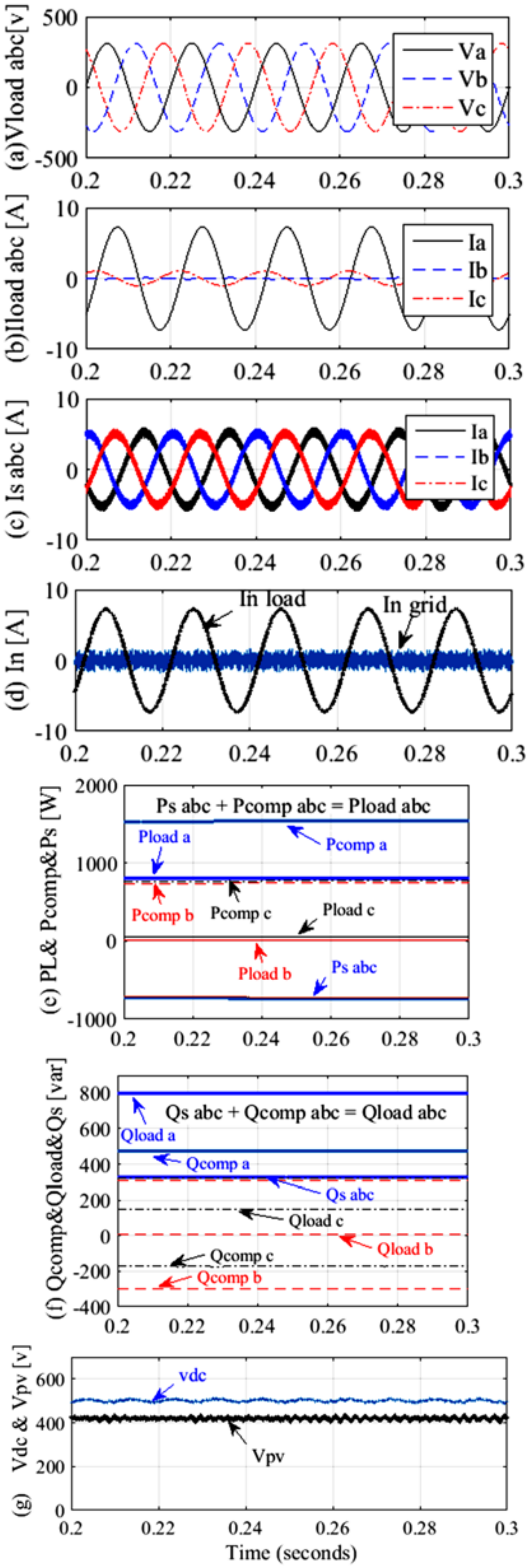

Fig. 7 The results of the simulation for load 1. (a) Load voltage, (b) load current, (c) grid current, (d) load and grid neutral current, (e) three phase active power (load, compensator, grid), (f) three phase reactive power (load, compensator, grid), (g) DC link and PV voltage.

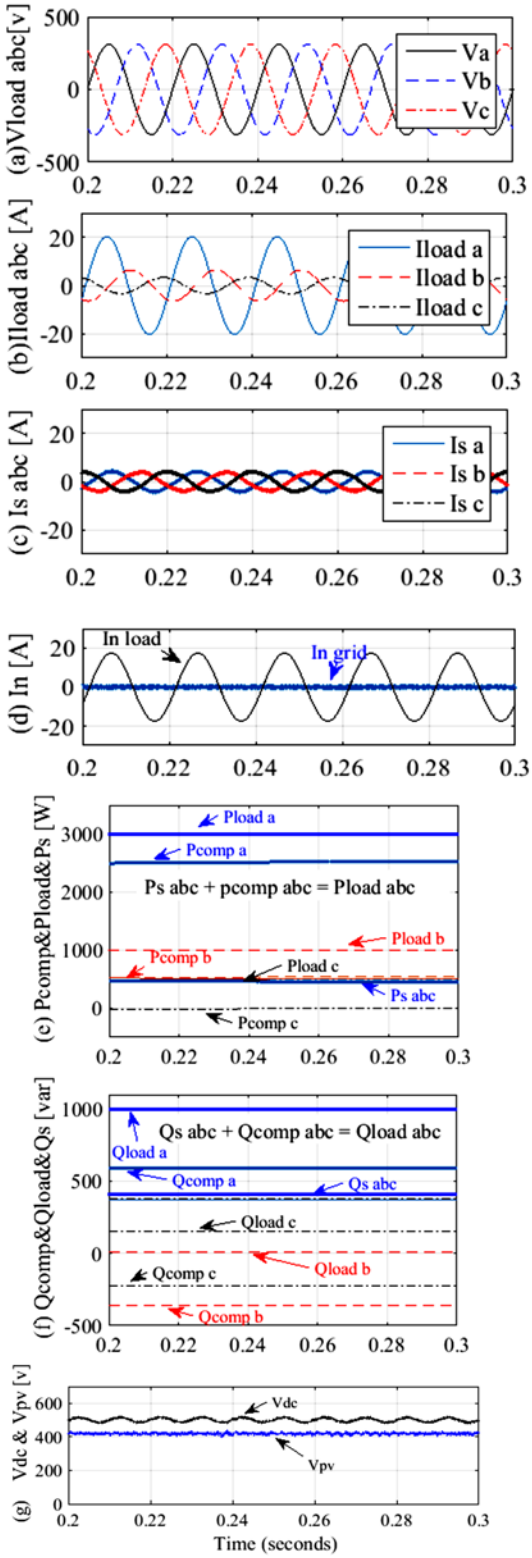

Fig. 8 The results of the simulation for load 2. (a) Load voltage, (b) load current, (c) grid current, (d) load and grid neutral current, (e) three phase active power (load, compensator, grid), (f) three phase reactive power (load, compensator, grid), (g) DC link and PV voltage.

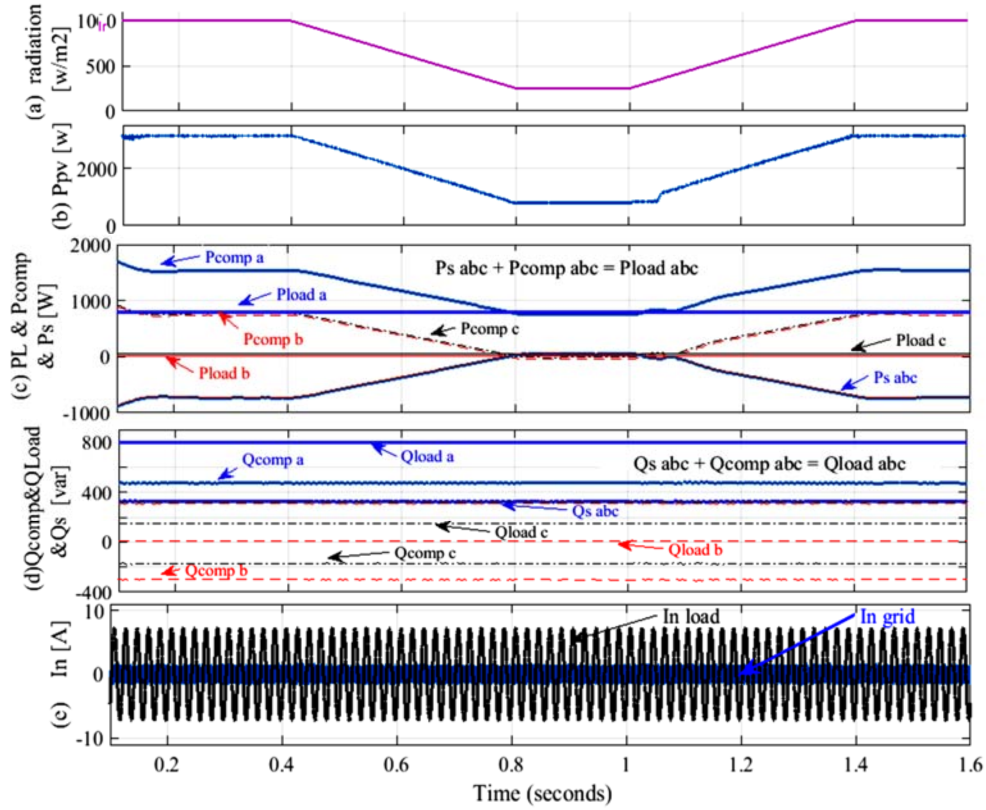

Fig. 9 The results of the simulation for load 1 and variable radiation between 0.4-1.4 seconds. (a) Variable radiation, (b) power of solar cells, (c) three phase active power (load, compensator, grid), (d) three phase reactive power (load, compensator, grid), (e) load and grid neutral current.

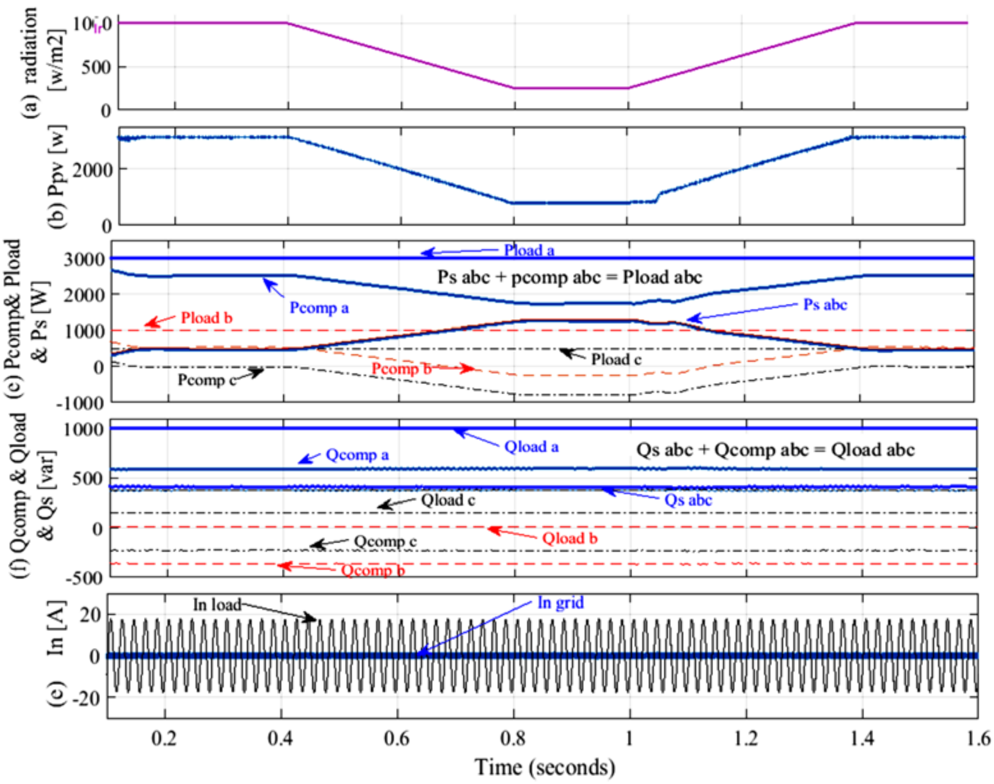

Fig. 10 The results of the simulation for load 2 and variable radiation between 0.4-1.4 seconds. (a) Variable radiation, (b) power of solar cells, (c) three phase active power (load, compensator, grid), (d) three phase reactive power (load, compensator, grid), (e) load and grid neutral current.

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