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A Single-Phase Grid-Connected PV Cell System Based on a Boost-Inverter

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ABSTRACT: In this project, the boost-inverter topology is used as a building block for a single-phase grid-connected photo voltaic cell (PV) system offering low cost and compactness. In addition, the proposed system incorporates battery-based energy storage and a dc–dc bidirectional converter to support the slow dynamics of the PV. The single-phase boost inverter is voltage-mode controlled and the dc–dc bidirectional converter is current-mode controlled. The low-frequency current ripple is supplied by the battery which minimizes the effects of such ripple being drawn directly from the PV itself. Moreover, this system can operate either in a grid-connected or stand-alone mode. In the grid-connected mode, the boost inverter is able to control the active (*P*) and reactive (*Q*) powers using an algorithm based on a second-order generalized integrator which provides a fast signal conditioning for single-phase systems. Design guidelines, simulation are presented to confirm the performance of the proposed system.

KEYWORDS: Boost inverter, PV cell, Grid-connected inverter, Power conditioning system (PCS), PQ control.

I. INTRODUCTION

Alternative energy generation systems based on solar photovoltaic's cells (PV) need to be conditioned for both dc and ac loads. The overall system includes power electronics energy conversion technologies and may include energy storage based on the target application. However, the PV systems must be supported through additional energy storage unit to achieve high-quality supply of power. When such systems are used to power ac loads or to be connected with the electricity grid, an inversion stage is also required. The typical output voltage of low-power PV is low and variable with respect to the load current. For instance, based on the current–voltage characteristics of a PV power module, the voltage varies between 26V to 43 V depending upon the level of the output current

The PV power conditioning system encounters drawbacks such as being bulky, costly, and relatively inefficient due to its cascaded power conversion stages. To overcome from these drawbacks, a topology that is suitable for ac loads and is powered from dc sources able to boost and invert the voltage. The double loop control scheme of this topology has also been proposed for better performance even during transient conditions. The single energy conversion stage includes both boosting and inversion functions and provides high power conversion efficiency, reduced converter size, and low cost.

The proposed single-phase grid-connected PV system can operate either in grid-connected or stand-alone mode. In the grid-connected mode, the boost-inverter is able to control the active (*P*) and reactive (*Q*) powers through the grid by the proposed *PQ* control algorithm using fast signal conditioning for single-phase systems .The simulation results are presented to document the performance of the proposed system

II. PROPOSED PV ENERGY SYSTEM

The proposed system is a high performance, single-stage boost inverter topology for grid connected PV systems. The proposed configuration can not only boost the usually low photovoltaic (PV) array voltage, but can also convert the solar dc power into high quality ac power for feeding into the grid, while tracking the maximum power from the PV array. Total harmonic distortion of the current, fed into the grid, is restricted.

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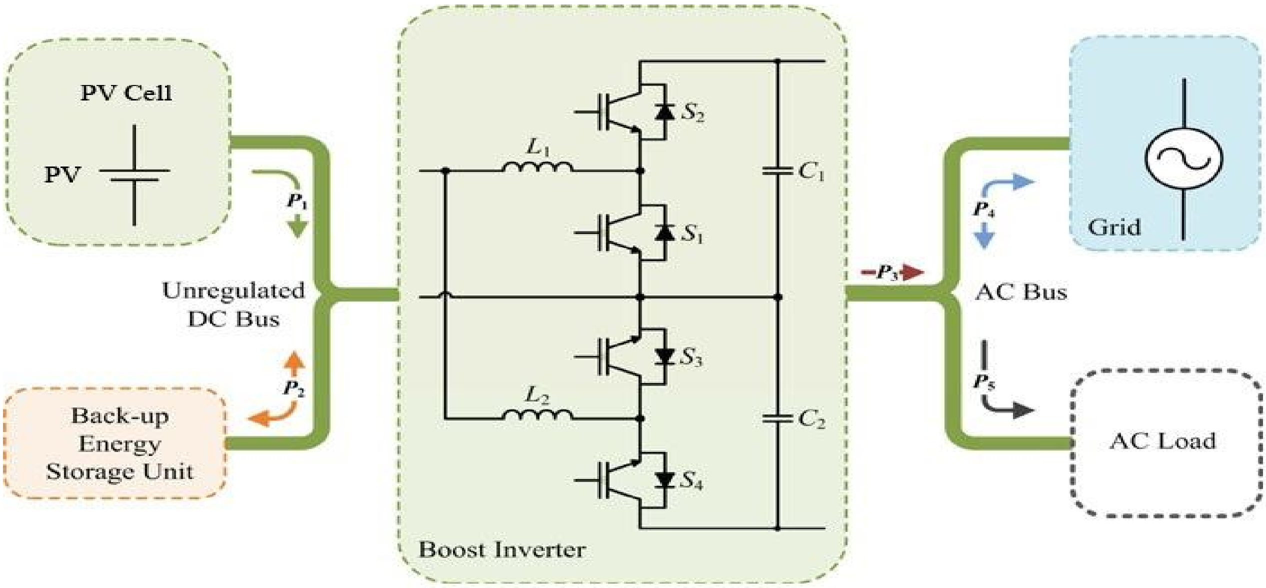

Fig. 1. Block diagram for the proposed grid-connected PV system. The backup unit and the PV power module are connected in the unregulated dc bus and the boost-inverter output is connected to the local load and the grid. (P1: PV output power, P2: backup unit input/output power, P3: inverter output power, P4: power between the inverter and the grid, and P5: power to the ac loads).

III.OPERATION PRINCIPLE

A. Description of the PV System

The block diagram of the proposed grid-connected PV system is shown in Fig. 1. Fig. 1 also shows the power flows between each part. This system consists of two power converters. The boost inverter is supplied by the PV and the backup unit, which are both connected to the same unregulated dc bus, while the output side is connected to the load and grid through an inductor. The system incorporates a current-mode controlled bidirectional converter with battery energy storage to support the PV power generation and a voltage-controlled boost inverter.

The PV system should dynamically adjust to varying input voltage while maintaining constant power operation. Moreover, the power has to be ramped up and down so that the PV can react appropriately, avoiding transients and extending its lifetime. The converter also has to meet the maximum ripple current requirements of the PV.

In the grid-connected mode, the system is also providing active (*P*) and reactive (*Q*) power control. A key concept of the *PQ* control in the inductive coupled voltage sources is the use of a grid compatible frequency and voltage droops . Therefore, the active and reactive powers are controlled by the small variations of the voltage phase and magnitude. The control of the inverter requires a fast signal conditioning for single-phase systems.

B. Boost Inverter

The boost inverter consists of two bidirectional boost converters and their outputs are connected in series. Each boost converter generates a dc bias with deliberate ac output voltage (a dc-biased sinusoidal waveform as an output), so that each converter generates a unipolar voltage greater than the PV voltage with a variable duty cycle. Each converter output and the combined outputs are described by

$V_1 = V_{dc} + ½ . A_1 . Sin\theta$ (1)

$V_2 = V_{dc} + ½ . A_2 . Sin(\theta-\pi)$ (2)

$V_0 = V_1 – V_2 = A_0. Sin\theta$, when $A_0 = A_1 = A_2$ (3)

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$V_{dc} > V_{in} + A0/2$ (4)

where V_{dc} is the dc offset voltage of each boost converter and have to be greater than $0.5\,A_O + V_{in}$.

From (3), it can be observed that the output voltage V_O contains only the ac component. This concept has been discussed in numerous papers. The boost inverter employs voltage-mode control. The double-loop control scheme is chosen for the boost-inverter control being the most appropriate method to control the individual boost converters covering the wide range of operating points. This control method is based on the averaged continuous-time model of the boost topology and has several advantages with special conditions that may not be provided by the sliding mode control, such as nonlinear loads, abrupt load variations, and transient short-circuit situations. Using this control method, the inverter maintains a stable operating condition by means of limiting the inductor current. Because of this ability to keep the system under control even in these situations, the inverter achieves a very reliable operation. The reference voltage of the boost inverter is provided from the *PQ* control algorithm being able to control the active and reactive power. The voltages across *C*1 and *C*2 are controlled to track the voltage references using proportional-resonant (PR) controllers. Compared with the conventional proportional integral (PI) controller, the PR controller has the ability to minimize the drawbacks of the PI one such as lack of tracking a sinusoidal reference with zero steady-state error and poor disturbance rejection capability.

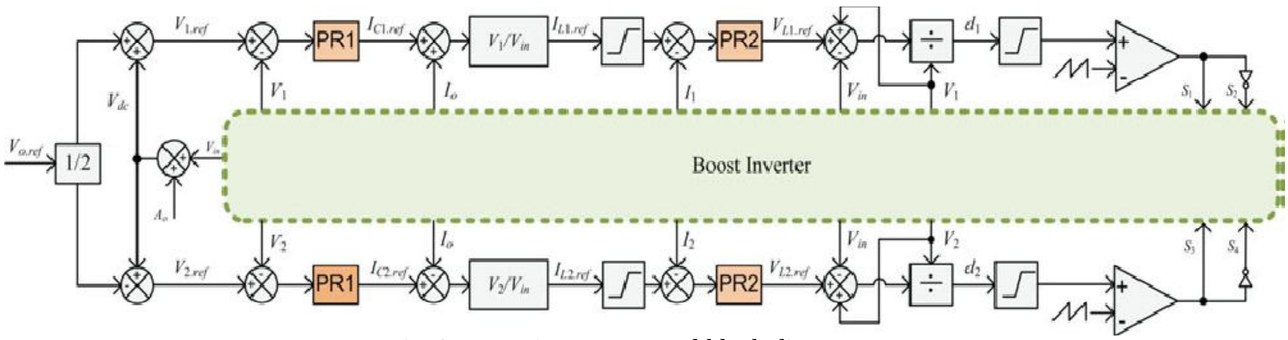

Fig. 2. Boost-inverter control block diagram.

The currents through L1 and L2 are controlled by PR controllers to achieve a stable operation under special conditions such as nonlinear loads and transients. The control block diagram for the boost inverter is shown in Fig. 2. The output voltage reference is divided to generate the two individual output voltage references of the two boost converters with the dc bias, Vdc. The dc bias can be obtained by adding the input voltage Vin to the half of the peak output amplitude. Vdc is also used to minimize the output voltages of the converters and the switching losses in the variable input Voltage condition.
The output voltage reference is determined by

$V_{o.ref} = (V_{pp} + dV_{pp}) \cdot \sin(\omega_o t + \delta)$, when
$A_o = V_{pp} + dV_{pp}$ and $\theta = \omega_o t + \delta$ (5)

Where Vpp is the peak value of the typical grid voltage, dVpp is a small variation of the output voltage reference affecting to the reactive power, ωo is the grid fundamental angular frequency, and δ is the phase difference between Vo and Vg relating with the active power. Then, V1.ref and V2.ref are calculated by (1) and (2).

C. Backup Energy Storage Unit

The functions of the backup energy storage unit are divided into two parts. First, the backup unit is designed to support the slow dynamics of the PV. Second, in order to protect the PV system, the backup unit provides low-frequency ac current that is required from the boost inverter operation. The low-frequency current ripple supplied by the batteries has an impact on their lifetime, but between the most expensive PV components and the relatively inexpensive battery components, the latter is preferable to be stressed by such low-frequency current ripple.
The backup unit comprises of a current-mode controlled bidirectional converter and a battery as the energy storage unit. For instance, when a 1-kW load is connected from a no-load condition, the backup unit immediately provides the 1-kW power from the battery to the load, as shown in Table I.

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P_3 Increases ($P_1 + P_2 \rightarrow P_3$)	P_3 Decreases ($P_1 \rightarrow P_2 + P_3$)	Normal ($P_1 = P_3$)
Discharge ↓ Charge ↓ Normal	Charge ↓ Normal	Normal

Table. 1. Backup unit sequence of modes of operation under load change

On the other hand, when the load is disconnected suddenly, the surplus power from the PV could be recovered and stored into the battery to increase the overall efficiency of the energy system. The backup unit controller is designed to control the output current of the backup unit in Fig. 3. The reference of I_{Lb1} is determined by I_{dc} through a high-pass filter and the demanded current I_{demand} that is related to the load change. The ac component of the current reference deals with eliminating the ac ripple current into the PV power module while the dc component deals with the slow dynamics of the PV.

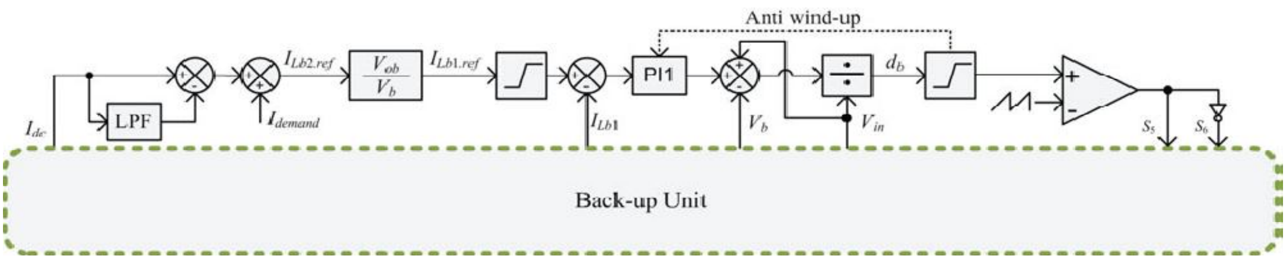

Fig. 3. Backup unit control block diagram.

D. Control of the Grid-Connected Boost Inverter

Fig. 4 illustrates the equivalent circuit of the grid-connected PV system consisting of two ac sources (*Vg* and *Vo*), an ac inductor *Lf* between the two ac sources, and the load. The boost inverter output voltage (including the PV and backup unit) is indicated as *Vo* and *Vg* is the grid voltage. The active and reactive powers at the point of common coupling (PCC) are expressed by

$$P = \frac{V_g \cdot V_o}{\omega_o \cdot L_f} \sin(\delta) \qquad (6)$$

$$Q = \frac{V_g^2}{\omega_o \cdot L_f} - \frac{V_g \cdot V_o}{\omega_o \cdot L_f} \cos(\delta) \qquad (7)$$

where *Lf* is the filter inductance between the grid and the boost inverter.From (6) and (7), the phase shift δ and voltage difference *Vg* – *Vo* between *Vo* and *Vg* affect the active and the reactive powers, respectively. Therefore, to control the power flows between the boost inverter and the grid, the PV system must be able to vary its output voltage *Vo* in amplitude and phase with respect to the grid voltage *Vg*.power is zero by the magnitude of *Vo* equals *Vg* .The droop control for the boost inverter requires the fast acquisition of *P* and *Q*.
The measurement of *P* and *Q* at the PCC is obtained based on the following expressions

$$P_{meas} = 1 \; (v_{g\alpha} \cdot i_{g\alpha} + v_{g\beta} \cdot i_{g\beta}) \qquad (8)$$

$$Q_{meas} = \frac{1}{2}\left(v_{g\beta} \cdot i_{g\alpha} - v_{g\alpha} \cdot i_{g\beta}\right) \qquad (9)$$

where $v_{g\alpha}$ and $v_{g\beta}$ are the instantaneous orthogonal voltages at PCC, and $i_{g\alpha}$ and $i_{g\beta}$ are the instantaneous orthogonal currents at PCC. The orthogonal voltage and current are obtained using a SOGI-based algorithm which provides a fast signal conditioning for single-phase systems.

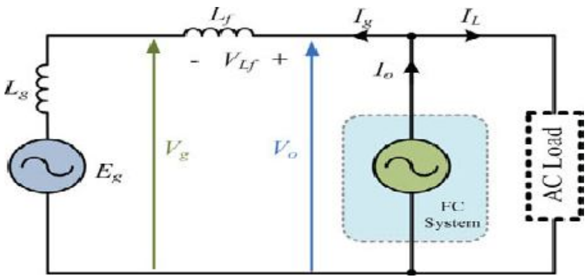

Fig. 4. Equivalent circuit of the grid-connected PV system

E. Design Guidelines

The power components of the proposed system were designed with the parameters given in Table II.

PV DC output voltage	26-43V
AC output voltage	100V RMS, Single phase, 50 Hz
AC grid Voltage	220V, 50HZ
Switching frequency	20kHz
Output power	1.2kW
V_{in}	26V (min)
Ra (resistance of L_1 and L_2)	$=10m\ \Omega$
V_1(t)	353V (max)
V_2(t)	42V (min)
Δt_1 (maximum on time)	42.5µs (max at 20kHz)
ΔiL_{max}	5% of $i_{L(max)}$
ΔV_c	5% of V_{1max}
R_1 (load)	48.4_ (1kW)
V_b (battery voltage)	22 V (min) – 27.3 V (max)
I_{lb1}	45.5 A (max)

Table. 2. The power components of the proposed system were designed with the parameters

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IV. MODELING AND SIMULATION USING MATLAB

The proposed PV system has been analyzed, designed, simulated to validate its overall performance. The simulations have been done using Simulink/MATLAB. The ac output voltage of the system was chosen to be equal to 220 V, while the dc input voltage varied between 43 and 69 V. The parameters of the proposed PV system for the simulation are summarized in Table 2.

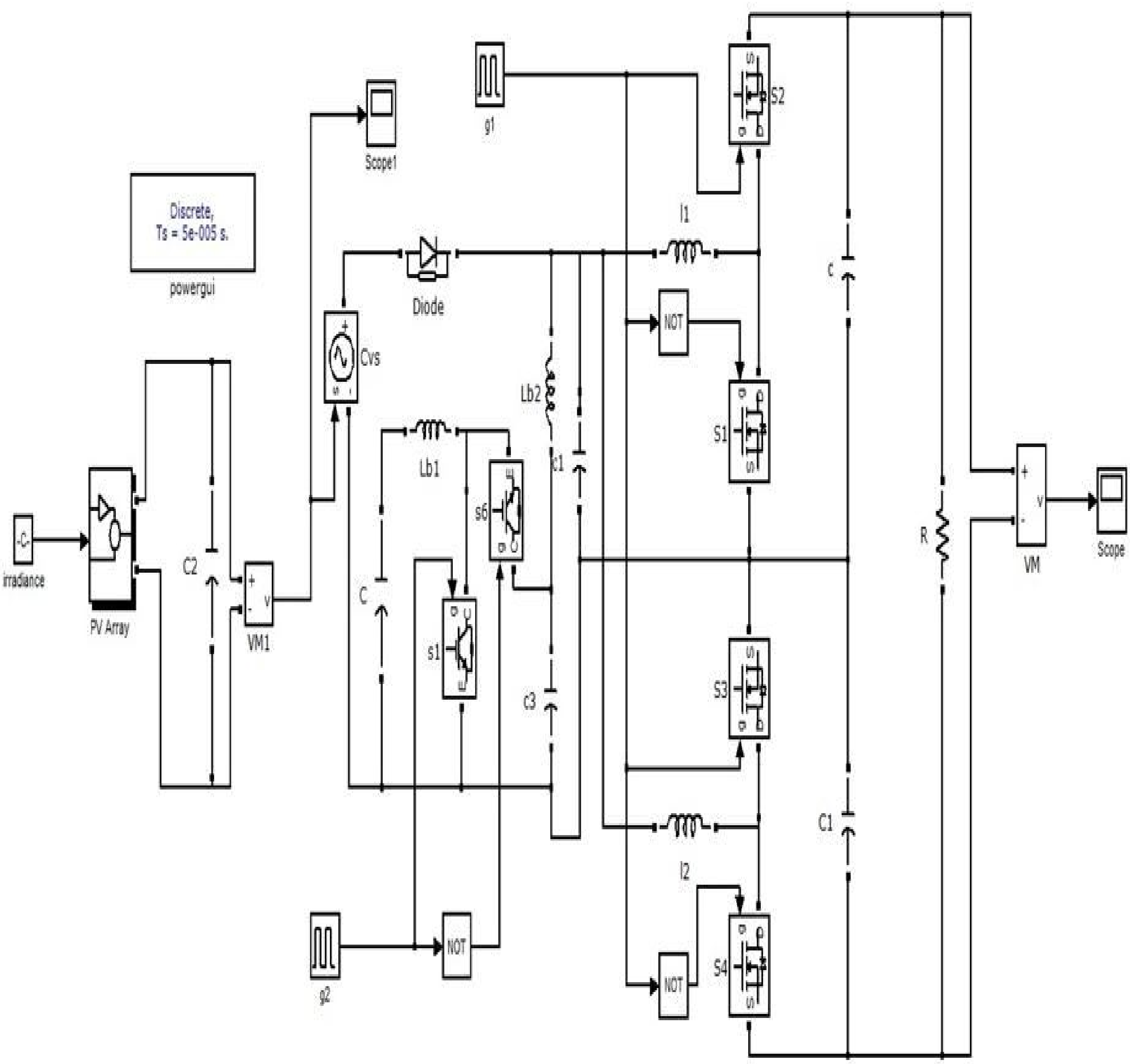

Fig. 5. Simulation of PV energy system

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V. RESULT AND DISCUSSION

The simulation results show the operations of the boost inverter and the backup unit. In particular, Fig. 6(a) illustrates the output voltages of the boost inverter (*V*1 , *V*2 , and *Vo*) and Fig. 6(b) shows the input currents of each boost converter flowing through the inductors *L*1 and *L*2. Fig. 6(c).shows , the PV output current *I*pv , Fig. 6(d) shows the grid voltage and grid current at the PCC. Fig. 6(e) illustrates the waveforms of the inverter input current *I*dc, and Fig. 6 (f) also illustrates how the backup unit supports the PV power in transients when the load is increased at 0.15 s. When full-load is required from the no-load operating point, the entire power is provided by the backup unit to the load, as shown in Fig. 6(f).

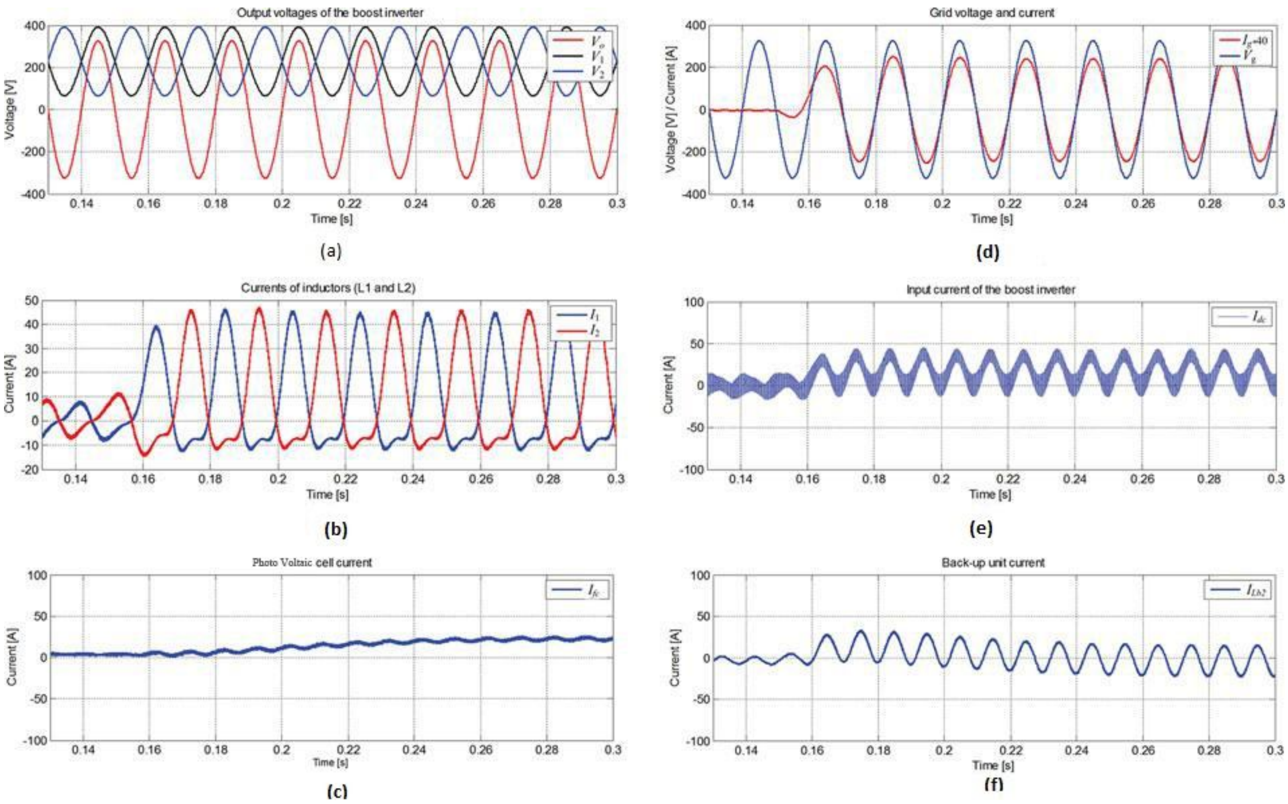

Fig. 6. Simulation results of the proposed PV system. (a) Output voltages of the boost inverter. (b) Current waveforms of *L*1 and *L*2 . (c) PV output current during transient, *I*pv . (d) Grid voltage *Vg* and current *Ig* with full power feeding to the grid. (e) Input current of the boost inverter, *I*dc . (f) Output current of the backup unit, *I*Lb 2 .

VI. CONCLUSION

A single power stage PV system based on the buck-boost inverter topology with a back-up battery-based energy storage unit has been reported in this chapter. The simulated results have verified the operation characteristics of the proposed PV system. The results of the proposed PV system taken from a simulated result have confirmed its satisfactory performance for delivering boosting and inversion functions within the single-stage to generate 220V AC from 43V DC at rated power. The back-up energy storage unit has also provided the ramping operation to deal with the slow dynamics of the PV and eliminate the ripple current to increase the efficiency and life time of the PV. In summary, the proposed PV system provides a number of benefits, such as single main power stage with high efficiency, simplified topology, low cost, compactness and stand-alone operation.

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BIOGRAPHY

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