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

G.R.Rajeshkanna¹, S.Thiagarajan²

PG Student [PED], Dept. of EEE, Raja College of Engineering & Technology, Madurai, Tamilnadu, India¹
Assistant Professor, Dept. of EEE, Raja College of Engineering & Technology, Madurai, Tamilnadu, India²

ABSTRACT: In this project, the boost-inverter topology is used as a building block for a single-phase grid-connected photovoltaic 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.

DOI: 10.15662/IJAREEIE.2015.0410053

ISSN (Online): 2278 – 8875
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

\[ V_1 = V_{dc} + \frac{1}{2} \cdot A_1 \cdot \sin \theta \]  
\[ V_2 = V_{dc} + \frac{1}{2} \cdot A_2 \cdot \sin (\theta - \pi) \]  
\[ V_0 = V_1 - V_2 = A_0 \cdot \sin \theta, \text{ when } A_0 = A_1 = A_2 \]
\[ V_{dc} > V_{in} + A0/2 \]  

(4)

where \( V_{dc} \) is the dc offset voltage of each boost converter and have to be greater than .

From (3), it can be observed that the output voltage \( V_G \) 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.

The currents through \( L_1 \) and \( L_2 \) 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, \( V_{dc} \). The dc bias can be obtained by adding the input voltage \( V_{in} \) to the half of the peak output amplitude. \( V_{dc} \) 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

\[
V_{\text{ref}} = (V_{pp} + dV_{pp}) \cdot \sin(\alpha, t + \delta), \text{ when } A_o = V_{pp} + dV_{pp} \text{ and } \theta = \alpha, t + \delta
\]

(5)

Where \( V_{pp} \) is the peak value of the typical grid voltage, \( dV_{pp} \) is a small variation of the output voltage reference affecting to the reactive power, \( \omega_0 \) is the grid fundamental angular frequency, and \( \delta \) is the phase difference between \( V_0 \) and \( V_g \) relating with the active power. Then, \( V1.\text{ref} \) and \( V2.\text{ref} \) 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.
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.

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

<table>
<thead>
<tr>
<th>Condition</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_3$ Increases</td>
<td>$P_3$ Decreases</td>
</tr>
<tr>
<td>$(P_1 + P_2 - P_3)$</td>
<td>$(P_1 - P_2 + P_3)$</td>
</tr>
<tr>
<td>Discharge</td>
<td>Charge</td>
</tr>
<tr>
<td>Charge</td>
<td>Normal</td>
</tr>
</tbody>
</table>

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 ($V_g$ and $V_o$), an ac inductor $L_f$ between the two ac sources, and the load. The boost inverter output voltage (including the PV and backup unit) is indicated as $V_o$ and $V_g$ is the grid voltage. The active and reactive powers at the point of common coupling (PCC) are expressed by

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

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

where $L_f$ is the filter inductance between the grid and the boost inverter. From (6) and (7), the phase shift $\delta$ and voltage difference $V_g - V_o$ between $V_o$ and $V_g$ 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 $V_o$ in amplitude and phase with respect to the grid voltage $V_g$ power is zero by the magnitude of $V_o$ equals $V_g$. 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:

$$P_{meas} = \frac{(v_g a - ig \alpha + v_g b - ig \beta)}{\omega_o}$$

Copyright to IJAREEIE

DOI: 10.15662/IJAREEIE.2015.0410053

8363
\[
Q_{\text{meas}} = \frac{1}{2} (v_{g\beta} \cdot i_{g\alpha} - v_{g\alpha} \cdot i_{g\beta})
\]  \hspace{1cm} (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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV DC output voltage</td>
<td>26-43V</td>
</tr>
<tr>
<td>AC output voltage</td>
<td>100V RMS, Single phase, 50 Hz</td>
</tr>
<tr>
<td>AC grid Voltage</td>
<td>220V, 50HZ</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>20kHz</td>
</tr>
<tr>
<td>Output power</td>
<td>1.2kW</td>
</tr>
<tr>
<td>(V_{in})</td>
<td>26V (min)</td>
</tr>
<tr>
<td>(R_a) (resistance of (L_1) and (L_2))</td>
<td>= 10\Omega</td>
</tr>
<tr>
<td>(V_1(t))</td>
<td>353V (max)</td>
</tr>
<tr>
<td>(V_2(t))</td>
<td>42V (min)</td>
</tr>
<tr>
<td>(\Delta t_f) (maximum on time)</td>
<td>42.5\mu s (max at 20kHz)</td>
</tr>
<tr>
<td>(\Delta iL_{\text{max}})</td>
<td>5% of (i_{L(\text{max})})</td>
</tr>
<tr>
<td>(\Delta V_c)</td>
<td>5% of (V_{1\text{max}})</td>
</tr>
<tr>
<td>(R_1) (load)</td>
<td>48.4% (1kW)</td>
</tr>
<tr>
<td>(V_b) (battery voltage)</td>
<td>22 V (min) – 27.3 V (max)</td>
</tr>
<tr>
<td>(I_{bl1})</td>
<td>45.5 A (max)</td>
</tr>
</tbody>
</table>

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

![Simulation of PV energy system](image-url)
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 (V1, V2, and Vo) and Fig. 6(b) shows the input currents of each boost converter flowing through the inductors L1 and L2. Fig. 6(c) shows the PV output current Ip, Fig. 6(d) shows the grid voltage and grid current at the PCC. Fig. 6(e) illustrates the waveforms of the inverter input current Idc, 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).

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.
REFERENCES


BIOGRAPHY

G.R.Rajeshkanna was born in Tamilnadu, India in 1989. He Received Diploma from the Electrical and Electronics Engineering from the K.L.Nagamasamy Polytechnic College in 2008. He received the B.E. degree from the Electrical and Electronics Engineering from the Raja College of Engineering and Technology in 2012. After his graduation he worked as a Sr.CAD Engineer at Practical Technologies, (ATC) Madurai for period of two years. He received the M.E. degree from the Power Electronics and Drives from the Raja College of Engineering and Technology in 2015. Currently he is working as a Centre Manager at Practical Technologies, (ATC) Madurai. He is a student member of Indian Society of Electrical and Electronics Engineers (ISEEE). His research interest includes Neural Network Control, Grid Connected System.

S.Thiagarajan was born in Tamilnadu, India in 1989. He received the B.E. degree from the Electrical and Electronics Engineering from the Raja College of Engineering and Technology in 2010. He received the M.E. degree from the Power Electronics and Drives from the Raja College of Engineering and Technology in 2014. Currently he was an Assistant Professor with the Department of Electrical and Electronics Engineering in Raja College of Engineering and Technologies. His research interest includes Instrumentation and Control, Grid Connected System, FACTS.