Modeling of Single Stage Grid-Connected Buck-Boost Inverter for Domestic Applications

Maruthi Banakar 1  M.Tech Student (Power Electronics)  Mrs. Ramya N 2  Assistant Professor  1,2  Department of Electrical & Electronics Engineering  1,2  REVA Institute of Technology and Management Bengaluru-560064, Karnataka, India

Abstract—This paper introduces the implementation of conventional multistage inverter into single-stage grid-tie buck-boost photovoltaic inverter topology for domestic purposes where Buck-boost and inversions are takes place in single stage only. Instead of using transformer here we will use special energy conversion device called Coupled Inductor. And this topology has a low component count with only three power switches, while conventional PV inverters may require four to five switches in two-stage power conversions for the same functions. And also it has numerous desirable features such as low cost, smaller size, simple control scheme and good efficiency. Switching of inverter circuit will be done by combination of sinusoidal pulse width modulation (SPWM) and square wave signal under grid synchronization condition. To regulate the inverter’s instantaneous ac output voltage, a closed-loop SPWM control technique is used to stabilize the output and to regulate the inverter’s instantaneous ac output voltage.

The proposed model design is mathematically modeled in MATLAB or PSIM. Simulation results are presented to verify the viability of proposed inverter for grid connected photovoltaic application and shows the capability of the inverter to feed a sinusoidal current to the utility grid at wide range of input photovoltaic dc voltage.

Key words: MATLAB, PSIM, SPWM

I. INTRODUCTION

Distributed generation (DG) systems are small modular devices close to electricity users, such as wind turbines, solar energy systems, fuel cells, micro gas turbines, and small hydro systems, as well as relevant control and energy storage systems. Such systems normally need inverters as interfaces between their ac loads and sources as shown in Figure 1, which depicts a typical renewable DG system using photovoltaic (PV) as energy source. DG inverters often experience a wide range of input voltage variations due to the fluctuations of energy sources, which impose stringent requirements for inverter topologies and controls.

![Fig. 1: Typical PV System Configuration](image1)

Renewable energy such as solar energy play a vital role due to is pollution free nature. Solar energy is not directly interfaced with the utility grid because of its economic reasons. Hence power electronics interfaces such as an inverter offer the necessary means to convert the constant-voltage output of the photovoltaic panels into a useable sinusoidal ac power in grid-connected photovoltaic system. Traditional, the grid-connected inverters are classified as single-stage & two-stage configuration.

Now a days multiple stage or two-stage configuration of four-switch buck-boost GTI is usually used in photovoltaic application. Such inverter systems have dc-dc or dc-ac-dc converters added to achieve a higher dc voltage before inversion. Though a two-stage buck-boost inverter can reach a reasonably high power capacity, the extra power stage necessitates further power components, which condenses circuit complexity as well as shoots up the cost.

Normally a single-stage inverter is an inverter with only one stage of conversion for both stepping-up and stepping-down the dc voltage from PV sources and modulating the sinusoidal output voltage or current. The inverter involves three switching devices, diodes, coupled inductor for energy conversion and filter circuit. A transformer and an inductor that links to a utility grid line are not essential for the system. Compared to two-stage buck-boost inverters, single-stage buck-boost inverters present a compact design with a good performance-cost ratio.

The inverter switching control circuit and grid synchronization schemes are exemplified in detail in this paper. The inverter’s parameters are designed mathematically, and the designed inverter is simulated via MATLAB to verify the inverter’s output performances. Fig. 2 displays the block diagram of the proposed PV power system.

![Fig. 2: Block Diagram of Proposed Transformer-Less GTI](image2)

In this paper, first we show the buck-boost inverter power circuit, and mathematical design results. Next, from these results the basic characteristics such as output voltage and output power of the inverter are introduced. Finally, control methods and simulation results are discussed in following sections.

II. REQUIREMENTS OF GRID-SYNCHRONIZATION

The GTI design varies a bit from conventional stand-alone inverter. The output voltage from GTI is necessary to meet
certain conditions for the inverter to be connected to the grid. They are,

1) Voltage magnitude and phase of inverter must be same as grid.
2) The GTI output frequency must match with the grid frequency (In india 50 Hz).

To meet the above conditions, the grid voltage is sampled and then kept as a reference for the design of switching signal. This require for the GTI has to force power produced from the PV panels into the grid. The real and reactive power flow of the GTI into grid are given by,

\[
P = \frac{V_{inv} V_{grid}}{z_t} \sin \phi \quad (1)
\]

\[
Q = \frac{V_{inv}^2 V_{grid}}{z_t} \cos \phi \quad (2)
\]

Where, \( z_t = \) Linking line impedance
\( V_{inv} = \) Output voltage of inverter
\( V_{grid} = \) grid power voltage
\( \phi = \) angle different between \( V_{inv} \) and \( V_{grid} \)

From equation (1), it is apparent that to send back maximum real power to the grid, the phase angle \( \phi \) must be 90°. Practically for stability reasons, the phase angle should be kept less than 90°. From equation (1), the value of sine both have negative and positive value. In positive value, inverter output voltage leading the grid voltage. Then real power will flow from GTI into the grid line. However, the real power will flow from opposite direction if the value is negative.

III. DESIGN OF PROPOSED BUCK-BOOST GTI

A. Power Circuit Design and Operation of GTI:

Fig. 3 shows the power circuit of a single stage grid-tie buck-boost photovoltaic inverter. Due to the nature of this inverter circuitry, power components need to be rearranged to simplify the control circuit. Switch \( S_2 \) is repositioned such that \( S_2 \) and \( S_3 \) share a common ground. As a result, \( S_2 \) and \( S_3 \) can use non-isolated drive circuits and one isolated. The proposed circuit configuration consists of three MOSFET switches \( S_1, S_2, \) and \( S_3 \), three diodes \( D_1, D_2, \) and \( D_3 \), two coupled inductors \( L_1 \) and \( L_2 \) of having same inductances and same turns, and capacitor \( C \). The main use of using coupled inductor is to transfer energy from input PV array to utility grid. The inverter operation can be divided into two cycles i.e (1) Positive half cycle (2) Negative half cycle.

1) Positive Half Cycle:

In this cycle switch \( S_3 \) is always turned off. The equivalent circuit of the inverter on positive half cycle is shown in figure 4. During charging state in positive half cycle, switches \( S_2 \) and \( S_3 \) are turned off, and the switch \( S_1 \) is turned on to charge inductor \( L_1 \) through diode \( D_1 \). At this time the capacitor provides continuous current to the load. During discharging state, the switches \( S_1 \) and \( S_3 \) are turned off, and energy stored in inductor \( L_1 \) is released through the switch \( S_3 \) to grid.

2) Negative Half Cycle:

Switch \( S_2 \) is always turned off in this cycle. The equivalent circuit of inverter in this cycle is shown in figure 5. During charging state of negative half cycle, the switches \( S_2 \) and \( S_3 \) are turned off, and \( Q_1 \) is turned on to charge the inductor \( L_1 \) through diode \( D_1 \), during this capacitor supplies continuous current to load. During discharging state, the switches \( S_2 \) and \( S_3 \) turned off, and switch \( S_3 \) turned on. The stored energy in \( L_1 \) is transferred to the inductor \( L_2 \) which discharge to the load through switch \( S_3 \) and load.

B. Mathematical Design of Circuit Parameters:

In this section, mathematical calculations involved in the three switch grid-tie buck-boost photovoltaic inverter is presented. Table 1, illustrates the design specifications of proposed 600W grid-tie buck-boost photovoltaic inverter

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{dc} )</td>
<td>Desire RMS Output Voltage</td>
<td>220V</td>
</tr>
<tr>
<td>( f_s )</td>
<td>Switching frequency</td>
<td>10KHz</td>
</tr>
<tr>
<td>( f_o )</td>
<td>Output frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>( M_o )</td>
<td>Modulation index</td>
<td>93%</td>
</tr>
<tr>
<td>( I_{pk} )</td>
<td>Inductor current in simulation</td>
<td>10.5A</td>
</tr>
<tr>
<td>( P_{out} )</td>
<td>Maximum power output</td>
<td>600W</td>
</tr>
</tbody>
</table>

1) Modulation Index:

For the discontinuous current mode operation(DCM), the modulation index \( M_o \) can be calculated by
Coupled Inductor selection:

For a grid-tie inverter a simple critical method, based on input-output power balance is applied to unearth the mathematical control-output solution and to determine inductor value. The value of coupled inductance $L$ for DCM operation is calculated by following equation.

$$L = \frac{M_a^2 V_{\text{dc}}^2}{4 P \nu_{\text{sw}}} = \frac{0.93^2 \times 24^2}{4 \times 600 \times 10,000} \approx 20 \mu H$$ (4)

2) Duty Cycle:
The duty cycle is determined by following equation.

$$D = \frac{V_{\text{out}}}{V_{\text{out}} + V_{\text{dc}}} = \frac{220 \times \sqrt{2}}{2 \times 220 \times \sqrt{2} + 24} = 93\%$$ (5)

Where, $V_{\text{dc}}$ is PV array voltage. $V_{\text{out}}$ is maximum output voltage.

3) Filter Inductor Selection:
In order to limit the current ripple a filter inductor is being used in the inverter circuit. The value of inductor $L_{\text{filter}}$ can be expressed as.

$$L_{\text{filter}} = \frac{1}{\Delta f \times f_{\text{g}}} \times \frac{1}{V_{\text{dc}} V_{\text{out}}}$$ (6)

4) Output Capacitor Selection:
The average differential equation for output filter capacitor is given by:

$$C \frac{dV_c}{dt} = (1-D) i_L - \frac{V_{\text{out}}}{R}$$ (7)

C. Control Circuit Design:

In conventional inverter design, only one type switching method is used. But, in this proposed design instate of using one type of switching signal to switch the inverter, a combination of square wave and SPWM is employed. With this kind of combination switching, the switching loss across the switches of the inverter will be significantly reduced due to minimize the switching frequency. Block diagram of the proposed switching control circuit is shown in Fig. 6. In order to simplify the synchronizing process, the sine wave of proposed design will be sampled from power grid by using the voltage transformer to step down peak 312 V (RMS 220 V) grid voltage into peak 7.07 V (RMS 5 V).

With the sampled sine wave from the grid and used to generate SPWM signal. Thus the frequency of the output from the GTI will be having the same frequency as the grid voltage and current where this is one of the most significant requirement for the GTI.

After sampling, the sine wave is rectified with a precision rectifier. In addition, a high frequency triangle wave of 10 kHz frequency is used. Then the two signals are passed through a comparator to generate the uni-polar SPWM signal. This unipolar signal only has positive values, which changes from +5V to 0V and again back to +5V. A square wave signal is used as the line frequency (50 Hz in India) and is in phase with the SPWM signal. Then the square wave signals is transmitted through a NOT gate to produce a signal that is 180° out of phase of the original signal. The inverter requires three switching signals since it has used three MOSFET switches. In order to generate three switching signals, an AND operation is performed between square wave and the SPWM signals. The switching signals can be categorized in three groups. The first group contains MOSFETs $S_1$, the second group contains MOSFETs $S_2$, and third group contains MOSFET $S_3$. The resulting switching gate pulse of the inverter circuits are shown in Fig. 7.

D. Closed-loop Control:

In this proposed GTI design, we used a closed-loop controller scheme where the output current is measured and compared with an ac reference current signal. Fig. 8 shows the block diagram of real-time waveform feedback closed-loop SPWM control method.

Fig. 6: Control Circuit of Proposed Grid-Tie Inverter

Fig. 7: Switching Gate Pulses for MOSFET $S_1$, $S_2$ and $S_3$

Fig. 8: Closed-Loop Control Block Diagram

The error in between the measured output current and the reference current is compensated by a Proportional Integral (PI) controller and is used to generate the desired SPWM switching gate signals for MOSFET $S_1$, $S_2$ and $S_3$. In this closed-loop operation initially we calculate the peak modulation index $M_a$ for 50 Hz grid voltage cycle by using of equation (4) and then this peak value is used to produce sinusoidal modulation index. A normalized sine table is used to get the modulation index in each switching cycle, from the peak modulation index. However, this modulation index
is corrected via calculating new modulation index from the error between the measured ac current and reference current.

**E. Grid Synchronization:**

This proposed grid-connected inverter design operation involves a grid synchronization part. During synchronization, the inverter produces output in phase with grid. The sine wave from grid is sampled and phase shift is set to zero. The un-shifted sine wave is rectified and compared with high frequency triangular wave to generate SPWM signal. SPWM signal is then undergoes an AND operation with square wave and generates three sets of switching signals. With this kind of switching and zero phase shifts, the output voltage and current of GTI controlled with the same phase with the grid. Whenever, the inverter and grid in phase once zero crossing of both voltages are detected the contactor is activated and the inverter is fed into grid. Fig. 9 is showing zero crossing result of GTI.

**IV. RESULTS AND DISCUSSION**

The proposed GTI design will undergo a computer simulation using MATLAB simulink software. To confirm the mathematical modeling analysis in the previous section, 600W of the proposed buck boost GTI is simulated. The complete simulated schematic diagram of the proposed buck-boost GTI is shown in Fig. 10. The operation of the inverter is simulated for different values of input voltages from 12V dc to 100V dc. Fig. 11 shows the sinusoidal ac output voltage waveform i.e 312V(Maximum value) , 50Hz after tied the inverter to grid, and GTI output current at 600W when output voltage is 24V dc. Therefore this is affirmed that voltage, frequency and phase of the inverter output are exactly matched with the grid voltage, frequency and phase.
<table>
<thead>
<tr>
<th>$V_{dc}$ (V)</th>
<th>Coupled Inductor Value, L (µH)</th>
<th>Output Capacitor, $C_{out}$(mF)</th>
<th>$I_{out}$ (Max) (A)</th>
<th>$I_{out}$ (rms) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>5</td>
<td>15</td>
<td>14.31</td>
<td>10.12</td>
</tr>
<tr>
<td>24</td>
<td>20</td>
<td>10</td>
<td>14.85</td>
<td>10.50</td>
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<tr>
<td>48</td>
<td>80</td>
<td>8</td>
<td>20.18</td>
<td>14.27</td>
</tr>
<tr>
<td>60</td>
<td>130</td>
<td>5</td>
<td>21.92</td>
<td>15.50</td>
</tr>
<tr>
<td>100</td>
<td>360</td>
<td>3</td>
<td>26.52</td>
<td>18.75</td>
</tr>
</tbody>
</table>

Table 2: Summary of Buck-Boost Grid-Tie Inverter Simulation Result in PSIM.

V. CONCLUSION

This paper has presented the analysis, mathematical modeling and MATLAB simulation of proposed 600W single-phase single stage buck-boost GTI. Next adoption of a simple control scheme and grid synchronization strategy is also presented. The proposed buck-boost inverter has many advantages as compared to conventional two-stage buck-boost inverters. Its low component count and compact design will help to reduce the size and cost of the inverter. The ability to convert wide range of input dc voltage is very important in small PV applications. The simulated results show the feasibility of proposed single stage buck-boost inverter for grid connected PV application and confirmed the capability of inverter to feed sinusoidal current to the grid at wide range of input PV dc voltage.

REFERENCES


