Analysis and Experimentation of Soft Switched Interleaved Boost Converter for Photovoltaic Applications

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Paper history:
Received 17 June 2015
Received in revised form 01 July 2015
Accepted 03 September 2015

Keywords:
Soft Switching
Auxiliary Tank
Power Loss Reduction
Photovoltaic

ABSTRACT

Conventional energy sources are fast depleting due to poor conservation practises and excessive usage while the world’s energy demands are growing by minute. Additionally, the cost of producing conventional energy is rising also leading to an increase in harmful environmental pollution. Hence, there is a need to look at alternative energy sources such as sun, water and wind. Photovoltaic (PV) is a very promising option as it uses energy from naturally available sunlight distributed throughout the Earth which is not only pollution free but also abundant and recyclable in nature. Among the different DC-DC converters proposed in literature, interleaved boost converter is best suited for PV and other high power density applications. Conventional interleaved boost converters experience switching losses and switching stresses during turn-on and turn-off periods due to hard switching. In order to eliminate the power loss in the converter devices, soft switched interleaved boost converter (IBC) is proposed in this paper. Soft switching is achieved with the use of an LC resonant tank circuit. The tank circuit is responsible for zero voltage switching (ZVS) and zero current switching (ZCS), eliminating the power loss in the switches appreciably. Since photovoltaic source is used as the input to the converter, a maximum power point tracking (MPPT) algorithm is implemented to extract maximum available power from the PV panel. Furthermore, the device losses, ripple and current sharing based on input and output characteristics are recorded and examined. Simulation study of the design is carried out using MATLAB/SIMULINK software. A hardware prototype with PV module is developed to validate the simulation results.

1. INTRODUCTION

Interleaving in the boost converter effectively reduces the ripple as a function of duty cycle. Interleaving of boost converters is done to minimize the input current ripple, output voltage ripple, reduce the passive component size, improve the transient response and increase the power level making them ideal for high power density applications. In boost converters, due to fast turn-on and turn-off of the switches, there is considerable power loss in the devices. This method of switching the devices is called hard switching. These losses are highly responsible for lowering the converter performance. Hence, soft switching technique is used where the voltage and current through the switches are forced to zero before turning on and turning off the devices respectively. It is known as zero voltage switching (ZVS) and zero current switching (ZCS). The ZVS and ZCS are achieved using an LC resonant tank in the interleaved boost converter. The soft switching technique [1-4] helps in eliminating the switching losses and stresses to a large extent and is found to be more efficient when compared to the hard switching technique in conventional boost converters.

Photovoltaic system design has two parameters for consideration: solar irradiation and temperature. It is required to supply a constant output voltage to the load irrespective of the variation in the temperature and solar irradiation levels. Since the relationship between voltage and current in a PV array is non-linear, it is difficult to extract maximum power from the solar panel. As a result, it is necessary to employ a maximum
power point tracking algorithm to extract maximum power at any given point from a low voltage PV source which can then be used in supplying power. The low voltage PV source is coupled with the soft switched interleaved boost converter that encounters low levels of switching losses and switching stresses in the converter circuit. As a result of coupling, the ripple contents at the input current and output voltage are reduced maximising the system efficiency. This is accomplished by adopting a soft switched interleaved boost converter topology. The input current is shared equally between the switches. The circuit can drive heavy loads with high levels of efficiency due to impedance matching achieved by energy storing elements (resonant tank and variable output capacitor). Better switch timing for ZVS and ZCS is also obtained using bypass networks [5]. The clamped diode acts as a bypass path reducing the conduction losses. Coupling capacity between auxiliary unit and main switches reduces the voltage stress of the switches during switching operations.

The paper in sections begins with outlining the phases of operation of soft switched IBC circuit with explaining how each phase works [6]. The next section highlights the design considerations of IBC. The subsequent section covers interfacing of IBC with PV module, whose validation is done through the simulation results of soft switched IBC with PV module and MPPT and PV panel characteristics.

The section that follows, details the simulation waveforms of soft switched IBC highlighting the advantages of soft switching over conventional hard switching techniques. The ripple values, switching device losses and IBC efficiency are calculated to amply prove that the soft switched IBC using an auxiliary resonant tank circuit is indeed an ideal fit for PV applications. Finally, to validate the simulation results a hardware prototype is implemented.

**2. SOFT SWITCHED IBC CIRCUIT**

The circuit of soft switched IBC is shown in Figure 1. The circuit consists of two main switches (S1 and S2), an auxiliary switch Saux, three diode rectifiers (D3, D51, D52) and two clamped diodes (D1 and D2). The circuit has two boost inductors L1 and L2 as in the basic IBC topology and soft switching is achieved using a resonant tank comprised of a resonant capacitor Cr and resonant inductor Lr, which are responsible for ZVS and ZCS function [7, 8].

**2.1 Operation of Soft Switched IBC**

The IBC is operated with a duty cycle of 40%. There are eighteen operational phases in one complete cycle.

Out of the eighteen phases, nine are related to main switch S1 and the others to main switch S2. The output is equal for both switches due to the symmetrical nature of the interleaving circuit [2].

The driving signals for the main switches and the auxiliary switch are shown in Figure 2. The various current waveforms and voltage waveforms during the different phases are also shown in Figure 3.

The modes of operation are divided into nine modes and in mode-1, the control of switches is excited by pulse which is meant to turn off the switches S1 and S2. Hence, the parasitic capacitance of the two main switches C1 and C2 gets charged. The voltage across the parasitic capacitors C1 and C2 of the main switches and resonant capacitor Cr are all equal to the output voltage i.e., V1=V2=Vns in the previous phase. The resonant inductor current I1 ramps up linearly until it reaches I1n at t=t1. During t1-t2, the resonant inductor keeps on charging and continues to increase to the peak value during which the main switch voltages V1 and V2 decrease to zero, because of resonance among C1, C2, Cr, Lr. Then, the body diodes D1 and D2 of switches S1 and S2, respectively, can be turned ON. In the interval t2-t3, the main switch voltage V1 decreases to zero. As a result the body diode D1 of switch S1 is turned ON at t2. At this time, the main switch can achieve ZVS.

During t3-t4, the auxiliary switch Saux is turned OFF and the clamped diode D3 is turned ON. During this time interval, the energy stored in the resonant inductor Lr is transferred to the output load. The resonant inductor current I1 decreases to zero and the clamped diode D1 is turned OFF at t4. In the interval t5-t5, the clamped diode D1 is turned OFF. The energy of the boost inductor L2 is transferred to Cr and C2 and the energy stored in the parasitic capacitor Cr of the auxiliary switch is transferred to the resonant inductor Lr and the resonant capacitor Cr at this time.

During t5-t6, the clamped diode D2 is turned ON. The energy stored in the resonant inductor Lr is transferred to the output load by the clamped diode D2. At t6, the clamped diode D2 is turned OFF because the auxiliary switch S1 is turned ON.
During the time interval $t_7-t_8$, the resonant inductor current continues to increase to the peak value and the main switch voltage $V_{S2}$ decreases to zero because of resonance among $C_{S2}$, $C_{rc}$ and $L_{rc}$. At $t=t_8$, the body diode $D_{S2}$ of switch $S_{S2}$ is turned ON. In this phase, the resonant inductor current $I_{Lrc}$ equals the inductor current $I_{L2}$. This state is called critical state where the rectified input to the switches is zero. So, the switch $S_{S1}$ tends to achieve ZCS. As a result the switch $S_{S1}$ is turned OFF at the end of $t_9$. The energy stored in the resonant inductor $L_{rc}$ is transferred to the output load by the clamped diode $D_r$.

2. Design of IBC

The output voltage of IBC can be obtained from the following relation:

$$V_0 = \frac{V_m}{1-D}$$  \hspace{1cm} (1)

where $V_0$ is the output voltage, $V_m$ is the input voltage and $D$ is the duty cycle.

The boost inductors $L_1$ and $L_2$ are calculated based on parameters such as switching frequency $f_s$, input and output voltage, inductor current ripple $\Delta I_L$.

$$L_1 = L_2 = L = \frac{V_m(V_o - V_{in})}{f_s \cdot \Delta I_L}$$  \hspace{1cm} (2)

$\Delta L$ is calculated as:

$$\Delta L = 0.2 \cdot I_{out max} \cdot \frac{V_m}{V_i}$$  \hspace{1cm} (3)

The value $I_{out max}$ is calculated as:

$$I_{out max} = \frac{P_o}{V_o}$$  \hspace{1cm} (4)

where $P_o$ is the output power of IBC.

The output capacitance is calculated as:

$$C_o = \frac{I_{out max} \cdot D}{f_s \cdot \Delta V_o}$$  \hspace{1cm} (5)

where $\Delta V_o$ is the output voltage ripple and it is taken as 5% of the output voltage $V_o$. The resonant frequency $f_r$ is:

$$f_r = \frac{1}{2\pi \sqrt{L_{rc} C_{rc}}}$$  \hspace{1cm} (6)

By fixing the value of $f_r$ and $C_{rc}$, the value of $L_{rc}$ is calculated as:

$$L_{rc} = \frac{1}{f_r^2 \cdot 4\pi^2 \cdot C_{rc}}$$  \hspace{1cm} (7)

Using the above design equations [9], the simulation parameters for IBC is calculated as shown in Table 1.

3. INTERFACE OF IBC WITH PV MODULE

In order to use the IBC for photovoltaic applications, a PV module is used to supply power to the IBC [10]. The relationship between current and voltage in a PV panel is shown in Figure 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage ($V_i$)</td>
<td>21.16V</td>
</tr>
<tr>
<td>Duty cycle(D)</td>
<td>40%</td>
</tr>
<tr>
<td>Switching frequency($f_s$)</td>
<td>25kHz</td>
</tr>
<tr>
<td>Inductors ($L_1$ and $L_2$)</td>
<td>376.18µH</td>
</tr>
<tr>
<td>Resonant frequency ($f_r$)</td>
<td>50kHz</td>
</tr>
<tr>
<td>Resonant inductor ($L_{rc}$)</td>
<td>6.67µH</td>
</tr>
<tr>
<td>Resonant capacitor ($C_{rc}$)</td>
<td>1.5µF</td>
</tr>
<tr>
<td>Output capacitor ($C_0$)</td>
<td>25µF</td>
</tr>
<tr>
<td>Output resistor ($R_0$)</td>
<td>13.05Ω</td>
</tr>
</tbody>
</table>

![Figure 4. I-V and P-V curve characteristics for a sample panel](image_url)
From the figure, it can be found that the relationship between current and voltage is non-linear and it is difficult to draw the maximum power from the panel. Hence, a maximum power point tracking (MPPT) algorithm is used to draw maximum power from the panel [11]. According to maximum power transfer theorem, when the load impedance matches with the source impedance, maximum power can be transferred from the source to the load. Hence the problem of tracking the maximum power point reduces to an impedance matching problem. There are many types of algorithm to track the maximum power. The algorithm used here is the Perturb and Observe algorithm [2]. It is the simplest algorithm of all. The algorithm is shown in Figure 5. The complete block diagram is shown in Figure 6. The specification of the PV panel is shown in Table 2.

### 4 SIMULATION OF SOFT SWITCHED IBC WITH PV MODULE AND MPPT

#### 4.1 Simulation Results of PV Panel Characteristics

Using the simulation parameters as in Table 2, the simulation results of the PV panel characteristics is shown in Figures 7 and 8 [1]. From the above curves, it can be seen that the maximum attained power is 95W at a voltage of 21V.

#### 4.2 Simulation Waveforms of Soft Switched IBC

Various waveforms obtained as a result of simulation of the soft switched IBC are shown in Figures 9-16.

### Table 2. Simulation parameters for PV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage (V&lt;sub&gt;OC&lt;/sub&gt;)</td>
<td>21.16V</td>
</tr>
<tr>
<td>Short circuit current (I&lt;sub&gt;SC&lt;/sub&gt;)</td>
<td>5.87A</td>
</tr>
<tr>
<td>Voltage at maximum power point (V&lt;sub&gt;MPP&lt;/sub&gt;)</td>
<td>17.53V</td>
</tr>
<tr>
<td>Current at maximum power point (I&lt;sub&gt;MPP&lt;/sub&gt;)</td>
<td>5.43A</td>
</tr>
<tr>
<td>Maximum power</td>
<td>95.187W</td>
</tr>
</tbody>
</table>
4.3. Steady State Ripple Waveforms of IBC

4.4. Calculation of Ripple Value

The ripple values are calculated from the simulation. Waveforms and its comparsion with conventional IBC are shown in Table 3. From Table 3, it is found that, the proposed soft-switched IBC gives a reduced output voltage and input current ripple compared to the conventional one.

4.5. Calculation of Losses in Switching Devices

The losses for the proposed IBC [3, 4] is calculated by finding the conduction and switching losses of the switches as discussed below:

- **Switching loss**

  \[ P_{sw} = 0.5 \times V_{DS} \times I_D \times f_s \times t_{on} \]

  where \( V_{DS} \) is the drain to source voltage \( I_D \) is the drain current \( f_s \) is the switching frequency \( t_{on} \) is the sum of the rise time and fall time

- **Conduction loss**

  \[ P_c = I^2 \times R_{d(on)} \times D \]

  where \( I \) is the current through the device, \( R_{d(on)} \) is the on state resistance.

The switching and conduction losses for both the switches \( S_1 \) and \( S_2 \) are as follows:

Switching loss for \( S_1 \) and \( S_2 \): 0.157092W
Conduction loss for \( S_1 \) and \( S_2 \): 1.1859W

### Table 3. Ripple calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Soft switched IBC</th>
<th>Conventional IBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage ripple</td>
<td>0.144V</td>
<td>2.33V</td>
</tr>
<tr>
<td>Input current ripple</td>
<td>0.0779A</td>
<td>1.234A</td>
</tr>
<tr>
<td>Inductor current ripple</td>
<td>0.4416A</td>
<td>0.845 A</td>
</tr>
</tbody>
</table>
Total device losses=Switching losses+Conduction Losses. Total losses for individual switches are as follows:

Switch S\textsubscript{1}=0.157092W+1.1859W=1.342992W
Switch S\textsubscript{2}=0.157092W+1.1859W=1.342992W
Total losses=2.685984W

4. 6. Calculation of Efficiency of IBC

From Figures 12 and 13, the input power and output power of the IBC are input power, \(P_{\text{in}}=95.09\text{ W}\) and output power, \(P_{\text{out}}=89.5\text{ W}\)

\[
\text{Efficiency}=\frac{P_{\text{out}}}{P_{\text{in}}}=(\frac{89.5}{95.09})\times100=94.11\%.
\]

5. HARDWARE IMPLEMENTATION

The entire hardware consists of the gate drive, the converter circuit and a PV panel to provide input voltage to the converter. Here the implementation is done without the use of an MPPT algorithm. For the switches, MOSFETs are used and to provide isolation between the drive circuit and the switches, optocouplers are used. The output pulse from the optocoupler is used to trigger the switches.

The output voltage from the PV panel is not a constant one. It keeps varying with temperature and irradiance. So, the converter is not directly fed from the PV panel. Instead, it is used to charge a battery using a charge controller. The converter maintains proper charging voltage on the batteries. It also blocks reverse current and also prevents battery overcharge.

Here, a 12V battery is charged from the PV panel using a charge controller. This 12V is fed as input to the IBC circuit. The input voltage fed to the IBC is 11.5V. The duty cycle of operation is 40%. Thus, using the relation \(V_{\text{out}}=V_{\text{i}}/(1-D)\), we can find that, \(V_{\text{out}}=11.5/(1-0.4)=19.3\text{ V}\) which is shown in Figure 19. From the hardware, the losses of the device was found to be 2.978W and the output voltage ripple was 0.144V. Therefore, the proposed IBC is a better topology for PV applications.

6. CONCLUSION

This paper provides an insight to the use of soft switching technique for an interleaved boost converter (IBC) for photovoltaic (PV) applications. The primary objective is to reduce switching losses and switching stress on the main switches. This is achieved using ZVS (zero voltage switching) and ZCS (zero current switching) methods operating in lower and higher duty cycles. By using the concept of impedance matching between the resonant tank circuit and output capacitor, the circuit can drive heavy loads with high efficiency. In order to use the converter for photovoltaic applications, it is coupled with a PV panel since solar energy is freely available. Thus by implementing soft switching, the voltage stress on the main switches is reduced, the losses are reduced and also the ripples in the voltage and current waveforms are less. Additionally, the efficiency of the converter is also increased. Hence, the proposed soft switched IBC is an ideal choice for PV applications.

7. ACKNOWLEDGEMENT

The authors wish to thank the Management of SSNCE for funding this research work.

8. REFERENCES

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