REVIEW OF UNCOUPLED, COUPLED INDUCTOR AND RCN BASED TWO-PHASE INTERLEAVED BOOST CONVERTER FOR PHOTO-VOLTAIC APPLICATIONS

Nithya Subramanian*, Pridhivi Prasanth*, R Srinivasan*, Dr. R. S. Seyezhai**, & R R Subesh*
*t* UG Student, Department of EEE, SSN College of Engineering, Chennai
**Associate Professor, Department of EEE, SSN College of Engineering, Chennai

Abstract

Photo-Voltaic application basically converts direct sunlight into electricity without causing any harmful environmental pollution and any moving parts. These are superior in comparison to the conventional sources like fossil fuels to satisfy world’s energy demands and so has a wide variety of applications. Different DC-DC converter topologies have been proposed in the literature but Interleaved Boost Converter (IBC) is widely used for photovoltaic generation due to its high power density and fast dynamic response. This paper presents a comparative study of uncoupled, coupled inductor and Ripple Cancellation Network (RCN) based IBC for photo-voltaic applications. IBC is more efficient than a conventional boost converter as it reduces the input current ripple, output voltage ripple and the component size and improves the transient response. Adding the Ripple Cancellation Network to the conventional IBC converter, minimizes the input current and output voltage ripple. The parameters that will help us decide the performance of the proposed converters are input current ripple and output voltage ripple. Simulation studies are carried out in MATLAB to verify the theoretical results.

Keywords: Coupled inductor, interleaved boost converter, photovoltaic, ripple cancellation network.

1 Introduction

Photo-voltaic is an efficient method that captures energy from direct sunlight and transforms it into electricity. Photo-voltaic applications can be grouped into utility interactive applications and stand-alone applications. Utility interactive applications provide a backup system to make sure that the electricity is available all throughout the year irrespective of the weather conditions. Another important application of PV is in stand-alone systems. They do not have the utility connection. Direct system which uses electricity where it is produced is a good example of stand-alone systems. However, to cater to the energy demands during the non-sunny period PV-charged battery storage system is used. PV serves as an ideal source for meeting mobile and remote lighting requirements using the availability of low power DC lighting, such as low pressure sodium and fluorescent lights [1].

This paper basically presents the three converter topologies - Uncoupled Interleaved boost converter, Coupled inductor Interleaved boost converter and Inter-leaved boost converter with ripple cancellation network. It compares the performances by reducing the input current ripple, output voltage ripple and the passive component size. In conventional IBC, to make the input current ripple minimum, the inductor size increases adding to the converter weight. These shortcomings can be overcome by using the second and third converter topologies. Interleaved parallel structure has been applied in many power density applications so as to reduce the input current ripple because of its frequency doubling characteristic, output voltage ripple, passive
component size and improve transient response. Coupled inductor IBC achieves ripple cancellation higher than the conventional IBC due to coupling of the inductor. It also reduces the component size of the coupled inductor IBC. However, the leakage inductance of the coupled inductor increases in the diode current stress causing extra EMI (Electromagnetic interference) problems [2]. Interleaved boost converter with ripple cancellation network (RCN) overcomes the above shortcomings. The RCN comprises of two capacitors, two inductors and two coupled inductors. The coupled inductors of the network share the same core as that of the main inductors. This topology achieves maximum ripple cancellation at the input current and output voltage without introducing any extra EMI problems.

The paper (in 4 sections) initially presents the topologies of the converters (Conventional, Coupled inductor IBC and IBC with RCN) with a brief explanation on how each works. In Section-1, the converter topologies are detailed along with their operations and workings. Section-2 starts with the design considerations for the different topologies chosen. Section-3 demonstrates the simulation outputs comprising of input current ripple, output voltage ripple, inductor current ripple and diode current ripple for the three different topologies. Section-4 finally draws a comparison in performances between the conventional IBC, coupled inductor IBC and IBC with RCN. The parameters compared are input current ripple, output voltage ripple, diode current stress and the input/inductor current ripple ratio. As a trade-off between the converter size and ripple, the chosen number of phases is two. The converter circuit diagrams, expected waveforms, design specifications, and design parameters are discussed. The simulations for demonstrating the different topologies are done using the MATLAB/SIMULINK.

## 2 Topologies of IBC for Photovoltaic Applications

Three different topologies of boost converter, conventional IBC, coupled IBC and IBC with RCN have been presented and the results are compared.

### 2.1 Uncoupled IBC

The two phase interleaved boost converter consists of two identical boost converters connected in parallel and controlled by the interleaved method which has the same switching frequency and phase shift. It is used to eliminate reverse-recovery losses of the boost rectifier by operating the two boost converters at the boundary of continuous conduction mode (CCM) and discontinuous conduction mode (DCM). In addition interleaving is used to reduce the input current ripple, and thereby minimize the size of the input filter that would have otherwise been large if a single boost converter was used. Further the output voltage and current ripples are also reduced. The circuit of two-phase IBC is shown in Figure1.

![Figure 1: Schematic of two-phase IBC (uncoupled)](image)

The steady waveforms of IBC are shown in Figure 2.
The main disadvantage of conventional IBC is that the size of the converter is big. In order to overcome this and also for further reduction in ripple we go for coupled inductor IBC.

2.2 Coupled Inductor IBC

This topology uses a coupled inductor in the place of the main inductors of the conventional IBC. By coupling the main inductors, we can further reduce the input current ripple. Moreover high power density can be easily achieved because there is only one core adopted. The coupled inductor IBC has the same switching sequence as the conventional IBC [3]. The circuit of coupled inductor IBC is shown in Figure 3.

The steady waveforms for coupled inductor IBC are shown in Figure 4.

Leakage inductance of coupled inductor increases the diodecurrent stress causing extra EMI (Electromagnetic Interference) problem[4].

2.3 IBC with Ripple Cancellation Network

This topology includes two capacitors, two coupled inductors and two inductors. The coupled inductors share the same core as the main inductors. The IBC with RCN minimizes the input current ripple to a greater extent without introducing an extra EMI problem. The circuit of IBC with ripple cancellation network is shown in Figure 5.
The key steady waveforms for IBC with RCN are shown in Figure 6.

![Steady waveforms for IBC with RCN](image)

Figure 6: Steady waveforms for IBC with RCN

The decision of the duty cycle is based on the number of phases. Depending on the number of phases, the ripple is the least at a certain duty ratio. For two phase interleaved boost converter, the ripple is the least at a duty ratio of 0.45 to 0.5. Hence, the design value of the duty ratio is chosen as 0.5. The duty cycle $D$ can be calculated by the following formula:

$$ D = \frac{V_o - V_{in}}{V_o} \quad (1) $$

where $V_o$ is the output voltage and $V_{in}$ is the input voltage.

### 3.3 Selection of Power Devices

The semiconductor devices chosen for constructing the two phase interleaved boost converter is MOSFET (IRFP90N20D) and a fast recovery diode (MUR 3020WT). The power MOSFET has lower switching losses and also higher switching frequency. The fast recovery diode has an advantage of ultra-fast recovery time[5].

The parameters chosen are $V_{in}=36V$, $V_o=50V$, $D=0.5$, $F=100$ kHz and $P_{out}=1000W$.

### 4 Design of Inductance and Capacitance

#### 4.1 Conventional IBC

The inductor value is calculated using the expression of input current ripple which is given by

$$ \Delta I_{in} = \frac{V_{in} DT (1 - 3D)}{L (1 - D)} \quad (2) $$

where $\Delta I_{in}$ represents the input current ripple, $D$ represents the duty cycle, $T$ represents the switching period and $L$ represents the inductance.

A capacitor filter is needed at the output to limit the peak to peak ripple of the output voltage. The value of capacitance is given by the formula:
Using the above mentioned parameters and the design equations, the value of L is calculated as 15.625µH and \(C_o\) is 0.1mF.

### 4.2 Coupled Inductor IBC

Each leg of the converter is switched at a frequency of 10kHz with a phase shift of 180°. The inductor value is calculated from the phase current ripple as follows:

The expression for equivalent inductance \(L_{eq}\) for coupled-inductor IBC is

\[
L_{eq} = \frac{V_{in}DT}{\Delta I_{\text{phase}}} \tag{4}
\]

where \(\Delta I_{\text{phase}}\) is the phase current ripple.

The expression for phase current ripple is given by

\[
\Delta I_{\text{phase}} = \frac{V_{in}DT}{L} \left[1 + \alpha + 2\alpha \frac{V}{1 - b}\right] \tag{5}
\]

where \(\alpha\) is the coupling coefficient.

The values of \(L_m\) and \(L_k\) are calculated by:

\[
L_m = \alpha L \tag{7}
\]

\[
L_k = (1 - \alpha) L \tag{8}
\]

The overall input current ripple is as follows:

\[
\Delta I_{in} = \frac{V_{in}DT}{L} \left[1 + \alpha - 2\alpha^2\right] \tag{9}
\]

From the above equation it can be found that increasing the value of coupling coefficient reduced the input current ripple but the phase current ripple is increased. So, the selection of coupling coefficient is very important so that both the input and phase current ripple is effectively reduced[7-8].

The coupling coefficient \((\alpha)\) was chosen as 0.61 and the value of \(L\) was found as 15.625µH and the value of \(L_m\) was found as 9.53µH. The output capacitor is similar to the conventional IBC.

### 4.3 IBC with RCN

When the switch \(S_1\) is ON, the other switch \(S_2\) remains OFF. During this time, the main inductor \(L_1\) is charged linearly. In the meantime, the main inductor \(L_2\) starts to transfer its energy to the load \(R_o\). Similarly during the next cycle, the switch \(S_2\) is ON and the switch \(S_1\) remains OFF. The main inductor \(L_2\) is charged linearly and at the same time the inductor \(L_1\) starts transferring its energy to the load \(R_o\). In the proposed converter, \(L_1=L_2=L, L_{1A}=L_{2A}=L_A, L_{1B}=L_{2B}=L_B\) and \(M_1=M_2=M\). So, the input current ripple is be expressed as

\[
\Delta I_{in} = \frac{(M - L_A - L_B)(2V_{in} - V_{out})(V_{out} - V_{in})}{(M^2 - LL_A - LL_B)} \tag{10}
\]

The current stresses of the switches and diodes in the converter are equal to the maximum inductor current value as follows:

\[
I_{I\text{max}} = \frac{P}{V_{in}} + \frac{\Delta I_{in}}{2} \tag{11}
\]

The values of \(C_1\) and \(C_2\) in the RCN depends on the voltage ripple of the capacitor and current ripple of the conventional IBC[9-10]. With 5-10% voltage ripple of the voltage difference between input and output on the capacitor and current ripple of the conventional IBC, the value of \(C_1\) and \(C_2\) are calculated.
Table 1: Parameter for IBC with RCN

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage, $V_{in}$</td>
<td>36V</td>
</tr>
<tr>
<td>Output Voltage, $V_o$</td>
<td>50V</td>
</tr>
<tr>
<td>Output Power, $P_{out}$</td>
<td>1000W</td>
</tr>
<tr>
<td>Switching Frequency, $F$</td>
<td>100kHz</td>
</tr>
<tr>
<td>Coupling coefficient, $\alpha$</td>
<td>0.61</td>
</tr>
<tr>
<td>Main inductor, $L_1, L_2$</td>
<td>15µH</td>
</tr>
<tr>
<td>Coupled inductor, $L_{1A}, L_{2A}$</td>
<td>2 µH</td>
</tr>
<tr>
<td>Inductor, $L_{1B}, L_{2B}$</td>
<td>3.5 µH</td>
</tr>
<tr>
<td>Capacitor, $C_1, C_2$</td>
<td>10 µF</td>
</tr>
<tr>
<td>Output capacitor, $C_o$</td>
<td>470 µF</td>
</tr>
</tbody>
</table>

5 Simulation results

5.1 Gating Pattern

The gating pulses of the Mosfet switches of the two phases are shifted by $360/n$, i.e., $360/2$ because $n=2$ for two phases and so the gating pulses are 180 degrees apart. The gating pattern is similar for all the topologies.

![Figure 7: Gating pattern](image)

5.2 Conventional IBC

The output waveform for uncoupled IBC was observed as shown in Figure 8.

![Figure 8: Input / Output voltage comparison of Uncoupled IBC](image)

The ripple waveforms were observed as shown in Figure 9.

![Figure 9: Ripple waveforms for uncoupled IBC](image)

From Figure 9, the output voltage ripple was found as 0.0566% and the input current ripple was found as 0.15567%. The diode current stress was calculated as 28.17A.

5.3 Coupled Inductor IBC

The output waveform for coupled IBC was observed as shown in Figure 10.

![Figure 10: Input / Output voltage comparison of Coupled inductor IBC](image)

The ripple waveforms were observed as shown in Figure 11.

![Figure 11: Ripple waveforms for coupled IBC](image)

From Figure 11, the output voltage ripple was found as 0.0325% and the input current ripple was 0.0325%.
was found as 0.19179%. The diode current stress was calculated as 28.379A.

5.4 IBC with RCN

The output waveform for IBC with RCN was observed as shown in Figure 12.

![Figure 12: Input /Output voltage comparison of IBC-RCN](image)

The ripple waveforms were observed as shown in Figure 13.

![Figure 13: Ripple waveforms for IBC with RCN](image)

From figure 13, the output voltage ripple was found as 0.0315% and the input current ripple was found as 0.1743%. The diode current stress was calculated as 28.367A [9-10].

Table 2: Comparison of performances of all three Converter topologies

<table>
<thead>
<tr>
<th>Parameters</th>
<th>IBC</th>
<th>Coupled IBC</th>
<th>IBC-RCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Current Ripple (%)</td>
<td>0.15</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>Output Voltage Ripple (%)</td>
<td>0.056</td>
<td>0.032</td>
<td>0.034</td>
</tr>
<tr>
<td>Diode Current Stress (A)</td>
<td>28.2</td>
<td>28.37</td>
<td>28.41</td>
</tr>
<tr>
<td>Ratio (Input Current Ripple/Inductor Current Ripple)</td>
<td>0.001976</td>
<td>0.001549</td>
<td>0.001413</td>
</tr>
</tbody>
</table>

6 Inference

Interleaved boost converter with Ripple Cancellation Network has the least ripple in output voltage and input current in comparison to the other two topologies. Also, the diode current stress remains constant for all three topologies. The ratio of input ripple current to the inductor ripple current is found for all three cases. It is found that the ratio is the least for IBC with RCN when compared to coupled inductor IBC and conventional IBC. On increasing the duty cycle, the ripple content reduces. The chosen value of duty cycle is 0.5 for the proposed converters as the ripple is least at 0.5 duty cycle.

Graphs showing the relation between input current ripple and coupling coefficient are as follows:
7 Conclusion

This paper has discussed the different topologies of IBC for photovoltaic applications. From the results, it is observed that IBC with RCN gives the least input current ripple and output voltage ripple for a duty cycle of 0.5 (two-phase). Moreover, it has been recorded that the input current ripple is minimum for a high coupling coefficient and the diode stress is reduced. Therefore, the proposed IBC with RCN achieves the maximum ripple cancellation compared to the other two topologies. Hence, IBC with RCN proves to be a suitable topology for photovoltaic applications.

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References


