Loss Analysis of Interleaved Buck Converters

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ABSTRACT: Generally interleaved buck converters are hard switched and hence the switching losses are high. Here an interleaved zero-current transition (ZCT) buck converter where two sets of switches are operating out-of-phase and share the load power equally is introduced. Turn-on transitions at zero current helps to reduce switching losses and a significant reduction of the losses associated with diode reverse recovery are accomplished through addition of two small inductors. The simulation of different interleaved buck converters is completed with MATLAB. This paper also presents a comparison of switching loss and conduction loss of interleaved hard switched buck converter, interleaved zero current transition buck converter, and interleaved zero current transition three level buck converter. The loss analysis of different interleaved buck converters is completed with the help of thermal modules in Powersim.

KEYWORDS: buck converter, zero current transition (ZCT), interleaving technique, Switching loss, Conduction loss

1. INTRODUCTION

Power conversion is in and of itself a general topic, one that is addressed within the field of Power Electronics. There are four general forms of power converting circuits ac-to ac, ac-to dc, dc-to ac, and dc to dc. Power conversion in general is used to provide the correct form of energy needed by the load. Buck converters are step-down DC-DC converters that are widely being used in different electronic devices like laptops, cell phones and also electric vehicles to obtain different level of voltages. These converters are nothing but high frequency switching devices operating on PWM principle.

Even though buck converter is commonly used for step down conversion, it has many disadvantages such that low efficiency, high output voltage ripple, unable to operate at high switching frequencies etc. So we are using interleaving technique in buck converters. Interleaving technique can be thought of as a method of paralleling converters. However, it has additional benefits to offer in addition to those obtained from conventional approaches of paralleling converters. Interleaving technique is widely used in personal computer industry to power central processing units [1], [4].

The switching technique used in buck converters for IGBT switching are hard switching and soft switching. Hard Switching occurs when there is an overlap between voltage and current when switching the IGBT on and off. This overlap causes energy loss which can be minimized by increasing the di/dt and dv/dt. However, fast changing di/dt or dv/dt causes EMI to be generated. Therefore the di/dt and dv/dt should be optimized to avoid EMI issues. There are a few additional problems in hard switching. The device stress increases because the switching locus moves through the active region of the safe operating area (SOA). The reliability of the device can be impaired due to prolonged hard switching operation. High dv/dt, di/dt and parasitic ringing effect at switching of a fast device can create severe electromagnetic interference (EMI) problems, which may affect the converter control circuit and nearby sensitive apparatus [3], [6].

The main idea of soft switching is to prevent or minimize the overlap between the voltage and current so that the switching loss is minimal. Zero current switching (ZCS) and zero voltage switching (ZVS) are two techniques used for soft switching. In the proposed interleaved zero current transition converter soft switching (ZCT) is used, which has some advantages over traditional hard switching. With substantially reduced switching loss, the switching frequency can be increased above the audio frequency range as desired [2].
Interleaved hard switched buck converter is the traditional interleaving technique used for buck converter. Fig. 1 shows the traditional interleaved hard switched buck converter. The disadvantage of this converter is that the switching losses are high since hard switching is employed in this configuration. The switching loss in IGBTs and the diode reverse recovery losses are high in this circuit.

**II. INTERLEAVED ZCT BUCK CONVERTER**

Interleaved zero current transition (ZCT) buck converter is derived from the standard buck converter. The key modifications include the addition of two small inductors $L_1$ and $L_2$ and the phase shifted operation of the two stages. The phase shifted interleaved operation is the same as the operation of switches in multiphase converters commonly applied in microprocessor power supplies and in the interleaved boost PFC rectifiers. Fig. 2 shows interleaved ZCT buck converter.

Compared with the standard hard-switched PWM converter, each switch in interleaved ZCT buck converter operates at two times lower switching frequency and conducts half of the time. Furthermore, both switches in the interleaved ZCT configuration participate in the power processing function of the converter and share the power equally. The small auxiliary inductors $L_1$ and $L_2$ enable the ZCT turn-on and reduced switching losses, whereas the larger inductor $L_0$ results in a continuous conduction mode (CCM) of operation with good average current sharing and low current ripple, which is well suited for plasma power supplies.
The circuit operations in one switching cycle can be divided into six stages. The key waveforms of these stages are given in Fig. 3.

Figure 3: Waveforms of interleaved ZCT Buck converter

Interleaved zero current transition buck converters can be modified to an Interleaved zero current transition three level buck converter. Fig. 3.2 shows an Interleaved zero current transition three level buck converter.

Figure 4: Interleaved ZCT three level Buck converter
III. SIMULATION RESULTS

The simulations of different circuits are done with the help of MATLAB. The circuit used for simulation of interleaved hard switched buck converter is shown in fig. 5. There are two IGBTs used in the circuit. The two IGBTs are switched at 16 kHz frequency and thus the effective switching frequency is 32 kHz. Fig. 6 gives the current and voltage waveforms across the IGBT. An overlapping between current and voltage waveforms occurs because of the switching losses.

![Simulation circuit for interleaved hard switched buck converter](image1)

![Voltage and current waveforms across IGBT](image2)
The circuit used for simulation of interleaved ZCT buck converter is shown in fig. 7. There are two IGBTs used in the circuit. The two IGBTs are switched at 16 kHz frequency and thus the effective switching frequency is 32 kHz. Fig. 8 gives the current and voltage waveforms across the IGBT. Current increases just after the voltage becomes zero. Thus a zero current turn on is obtained. This helps in reducing switching losses.

![Simulation circuit for interleaved ZCT buck converter](image1)

![Voltage and current waveforms across IGBT](image2)
IV. LOSS CALCULATION USING PSIM

The IGBT switching losses and conduction loss are calculated using Powersim (PSIM). PSIM is the leading simulation and design software for power electronics, motor drives, and dynamic system simulation. With fast simulation and easy-to-use interface, PSIM provides a powerful and efficient environment to meet our simulation needs. In order to calculate the loss we need Thermal module. Thermal Module is an add on option to the PSIM software. It allows users to add semiconductor device data sheet information into a database, and use these devices in the simulation for the loss calculation. Thermal Module provides a quick way of estimating device conduction losses and switching losses [7].

In this example an IGBT Powerex CM150du-24nfh is added to the database. So we will create a new device file called Powerex.dev, and we will place it in the 'device' sub-folder in PSIM. Go to File > New Device File, and under the PSIM device sub-folder, create the file Powerex.dev. This file will appear in the File Name list box at the upper left corner of the Device Database Editor to create the thermal module. Device database editor is shown in fig. 9. We have to add different electrical characteristics of IGBT to device data editor. Once the thermal module is created it can be used for loss calculation.

![Device database editor](image)

Fig.9. Device database editor

![Thermal module](image)

Fig.10. Thermal module

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Fig. 11, Fig. 12 and Fig. 13 shows the loss calculation circuit of standard buck converter and the switching loss and conduction loss of transistor and switching loss and conduction loss of diode in IGBTs of the buck converter. The switching frequency used is 32 kHz. The input voltage is 300v.

![Loss analysis circuit of buck converter](image)

![Switching and conduction loss of transistor in IGBT](image)

![Switching and conduction loss of diode in IGBT](image)
Fig. 14, Fig. 15 and Fig. 16 shows the loss calculation circuit of interleaved hard switched buck converter and the switching loss and conduction loss of transistor and switching loss and conduction loss of diode in IGBTs of the converter. The switching frequency used is 16 kHz for each IGBT. Thus the effective switching frequency is 32 kHz. The input voltage is 300v.

Fig. 14. Loss analysis circuit of interleaved hard switched buck converter

Fig. 15. Switching and conduction loss of transistor in IGBT

Fig. 16. Switching and conduction loss of diode in IGBT
Fig.17, Fig.18 and Fig.19 shows the loss calculation circuit of interleaved ZCT buck converter and the switching loss and conduction loss of transistor and switching loss and conduction loss of diode in IGBTs of the converter. The switching frequency used is 16 kHz for each IGBT. Thus the effective switching frequency is 32 kHz. The input voltage is 300V.

Fig. 17: Loss analysis circuit of interleaved ZCT buck converter

Fig. 18: Switching and conduction loss of transistor in IGBT

Fig. 19: Switching and conduction loss of diode in IGBT
Fig. 20, Fig. 21 and Fig. 22 show the loss calculation circuit of interleaved ZCT three level buck converter and the switching loss and conduction loss of transistor and switching loss and conduction loss of diode in IGBTs of the converter. The switching frequency used is 8 kHz for each IGBT. Thus the effective switching frequency is 32 kHz. The input voltage is 300v.

Fig. 20: Loss analysis circuit of interleaved ZCT three level buck converter

Fig. 21: Switching and conduction loss of transistor in IGBT

Fig. 22: Switching and conduction loss of diode in IGBT
From the graph of switching loss and conduction loss of hard switched interleaving buck converter and interleaved zero current transition buck converters it is clear that the switching loss and conduction loss of hard switched interleaving buck converter is higher than that of interleaved zero current transition buck converters. The switching losses of buck converter, interleaved hard switched buck converter, interleaved ZCT buck converter and interleaved ZCT three level buck converters are tabulated below.

**TABLE I**

**ESTIMATED LOSSES FOR DIFFERENT BUCK CONVERTERS**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Buck</th>
<th>Interleaved Buck</th>
<th>ZCT Buck</th>
<th>3-Level ZCT Buck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transistor Switching Loss (W)</td>
<td>140</td>
<td>65</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Transistor Conduction Loss (W)</td>
<td>60</td>
<td>22</td>
<td>62</td>
<td>22</td>
</tr>
<tr>
<td>Total Transistor Loss (32 KHz) (W)</td>
<td>200</td>
<td>87</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Diode Switching Loss (W)</td>
<td>150</td>
<td>65</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Diode Conduction Loss (W)</td>
<td>70</td>
<td>17</td>
<td>42</td>
<td>15</td>
</tr>
<tr>
<td>Total Diode Loss (32 KHz) (W)</td>
<td>220</td>
<td>82</td>
<td>60</td>
<td>31</td>
</tr>
<tr>
<td>Total Loss (32 KHz) (W)</td>
<td>420</td>
<td>338</td>
<td>280</td>
<td>284</td>
</tr>
</tbody>
</table>

V. EXPERIMENTAL RESULTS

The experimental setup of proposed interleaved ZCT buck converter is shown in figure 23. In experiment a 230/12V transformer with rectifier is used for DC input. In order to turn on the switch, switching pulses are required and it is developed using PIC 16F877A microcontroller. The pulses obtained from the microcontroller are around 5V, which is not enough to turn on the switch. Hence a driver circuit is used to boost the voltage triggering signal to 9V to 20V. The driver circuit forms the most important part of the hardware unit, because it gives the triggering pulse to the switches in the proper sequence.
For the proposed model, it is provided with a 16 V DC supply and obtained a 7.2 V output. The switching frequency is 16 kHz. The switching pulses are developed using PIC 16F877A micro controller. Figure 24 shows the input voltage waveform. Figure 25 shows output voltage waveform.

VI. CONCLUSION

The concept of zero current transition is introduced in interleaved buck converters. In the proposed interleaved ZCT converters the switches are operating out-of-phase. The turn-on transitions at zero current and a significant reduction of the losses associated with the diode reverse recovery are accomplished through the addition of two small inductors. The output voltage ripple is also minimized in the proposed interleaved ZCT buck converter. Also, the loss in IGBT is calculated using thermal modules in PSIM. From the thermal module calculation of switching losses, proposed interleaved zero current transition converter has minimum loss compared with the interleaved hard switched buck converter.
REFERENCES


