

Study of Interleaved Double Dual Boost Converter for Renewable Energy Source System

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Abstract. This paper presents an interleaved double dual boost converter used in renewable energy application, for example, photovoltaic cell. The converter is interesting because its high voltage gain property. Its operating functions in the possible cases are detailed. Moreover, the presence of negative current in a certain operating point is investigated. The validation of the proposed system is done through experimental results.

Introduction

The decreasing of fossil energy resources results in the increasing of their prices. Using fossil fuel leads to pollution and global warming problems. To handle with these problems, researchers have been working on renewable energy like solar energy, hydrogen, etc., which are clean and are friendly with the environment. However, most of them usually produce low level voltage of electricity as output [1]. To increase this voltage, a DC-DC converter like boost converter [2,3] or isolated converter [4] is usually integrated to the system.

The input ripple current of the conventional boost converter relates to their switching frequency, input voltage, duty cycle and inductance. If the input voltage is constant, one can reduce the ripple current by increase inductance or switching frequency. But when switching frequency increases, switching losses increase as well. When inductance increases; the size of converter increases. To reduce the ripple current without affect the aforementioned phenomena, the interleaved technique is usually utilized. This technique uses two or more identical converters connected in parallel and the commands of these converters are interleaved by $360^\circ/(\text{number of converters})$. In [5-6], authors have studied a converter, called interleaved double dual boost converter (IDDB) operating in continuous conduction mode (CCM), using two conventional boost converters but connecting differently. This converter gives two advantages including a higher output voltage gain compared with that of the conventional one and a lower input current ripple due to using interleaving technique.

In this paper, a two-phase boost converter operating under continuous conduction mode (DCM) with interleaved technique is studied in depth. The input current of the converter is considered and it is shown that there is negative current in some operating point of the converter.

Interleaved Double Dual Boost Converter

The schematic diagram of an interleaved double dual boost converter is shown in Fig. 1. For the sake of simplicity, all losses are neglected except specified and the input voltage is constant. This

converter consists of two conventional boost converters called sub-converter. The first one is connected to input voltage source as usual, but the second one is slightly different. Nonetheless, both converters are identical. Moreover, their operations are the same as the conventional boost converter e.g. continuous conduction mode (CCM) or discontinuous conduction mode (DCM). The output voltage V_2 of this converter is the difference of the sum of the capacitor voltages $V_{2,1}$ and $V_{2,2}$ and V_1 :

$$V_2 = V_{2,1} + V_{2,2} - V_1 \quad (1)$$

The input current i_1 is the difference between the sum of the current of each sub-converter and load current:

$$i_1 = i_{11} + i_{12} - i_2 \quad (2)$$

Per unit system. The voltage and current will be divided by based unit [7]:

$$X = \frac{L f_s}{V_1} \cdot I, Y = \frac{1}{V_1} \cdot V \quad (3)$$

Then, one can write:

$$Y_2 = \frac{V_2}{V_1}, Y_{2,1} = Y_{2,2} = \frac{Y_2 + 1}{2}, X_1 + X_2 = \frac{X_{1,1} + X_{1,2}}{2} \quad (4)$$

Continuous conduction mode. In this mode, the output voltage of each sub-converter and the voltage gain can be found as:

$$Y_{2,1} = Y_{2,2} = \frac{1}{1-\alpha}, Y_2 = \frac{1+\alpha}{1-\alpha} \quad (5)$$

where α represents the duty cycle.

Like boost converter, the switches of the two sub-converter can operate in the same time or can operate in interleaving manner. In the interleaving scheme, all the switches conduct at the same switching frequency f_s with the phase shifting from one to another by $T/2$ as shown in Fig. 1. With interleaving technique, the input current ripple is reduced. The phase of each converter can be paralleled N -phase like conventional interleaved boost converter to decrease ripple current and increase the input current capability. If converter operates in CCM, there are only 2 cases possible: 1) duty cycle $\alpha > 0.5$ and 2) $\alpha < 0.5$. The input current ripples Δx_1 and the currents of each sub-converter for CCM are shown in Fig. 1 (right). The per-unit ripple current detailed in Table 1.

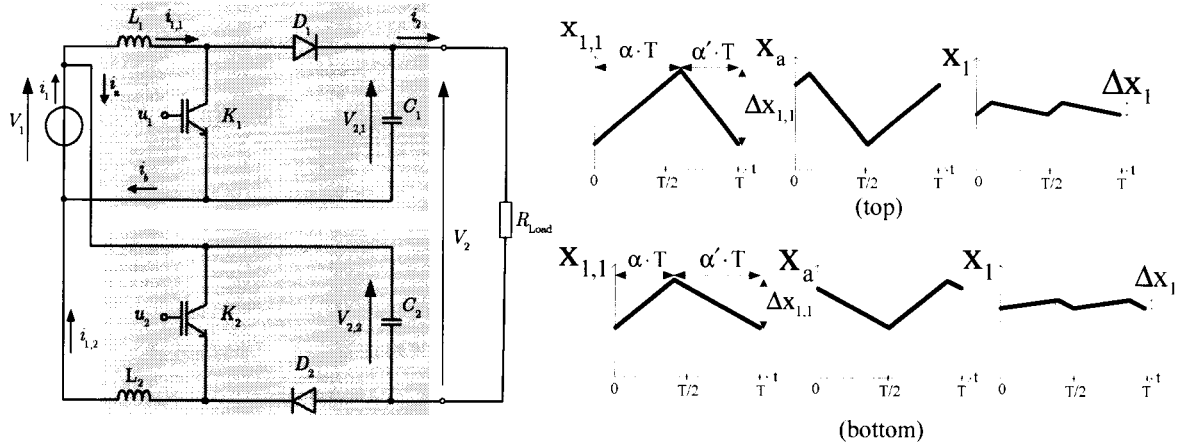


Fig 1. Interleaved double dual boost converter and its CCM waveforms, (top) duty cycle $\alpha > 0.5$, (bottom) $\alpha < 0.5$.

Discontinuous conduction mode. The output voltage of each sub-converter and of the converter are:

$$Y_{2,1} = Y_{2,2} = 1 + \frac{\alpha^2}{2 \cdot X_{2,1}}, Y_2 = 1 + \frac{\alpha^2}{2 \cdot X_2} \quad (6)$$

The current waveforms are given in Fig. 2 for different 5 possible cases. $\alpha' \cdot T$ is the duration, which diode conducts. According to (2), the current i_a will be negative for all cases. The sum of the i_a and $i_{1,1}$, which is the input current will be negative depending on load current. This current might cause problems to energy source which cannot tolerate negative current, for example, a PEM fuel cell (PEMFC). To avoid this phenomenon, a diode should be used by connecting in series with the energy source. However, in the commercial PEMFC generator, a series diode is usually used to

protect negative current inside the generator. That's why this converter can be used for the FC [2]. From the possible 5 cases, the ripple current for each are detailed in Table 2 including the conditions that make the presence of negative current. Moreover, the ripple current, when a series diode is used to protect the aforementioned negative current, is included. The negative current for the first case detailed in Fig.2 can be found in percent as $\frac{\Delta x_{1(-)}}{\Delta x_1} \times 100\% = \frac{\alpha'}{2} \times 100\%$.

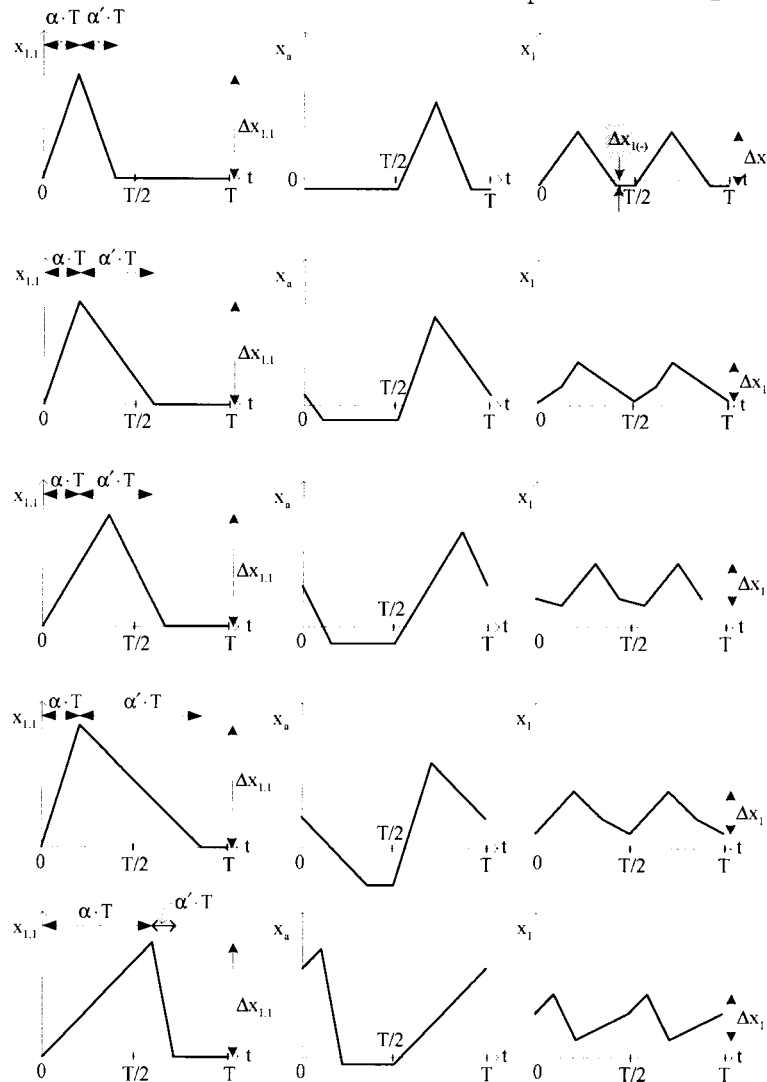


Fig 2. Waveforms of DCM IDDB, from top to bottom: 1. $\alpha + \alpha' < 0.5$; 2. $\alpha' < 0.5$, $0.5 < \alpha + \alpha'$ and $Y_2 < 3$;

3. $\alpha' < 0.5$, $0.5 < \alpha + \alpha'$ and $3 < Y_2$; 4. $0.5 < \alpha'$; 5. $0.5 < \alpha$.

Table 1. Input Ripple current when each sub-converter operating in CCM

Case	Input Ripple Current
$\alpha < 0.5$	$\Delta x_1 = \frac{\alpha \cdot (1 - 2 \cdot \alpha)}{2 \cdot (1 - \alpha)}$
$\alpha > 0.5$	$\Delta x_1 = \alpha - \frac{1}{2}$

EXPERIMENTAL RESULTS

To validate the theoretical part, a prototype of the proposed converter is realized using SEMISTACK module using IGBTs (SKM50GB123D) manufactured by SEMICRON. The parameter of the converter are following: inductors L_1 and $L_2 = 0.3$ mH, output capacitors $C_1 = C_2$

$=1,100 \mu\text{F}$, switching frequency $f_s = 5 \text{ kHz}$. The input energy source is a lead-acid battery $V_1 \cong 12 \text{ V}$ 120 Ahr. The PWM is realized under Matlab/Simulink with dSPACE 1104 interfacing card. The test bench is depicted in Fig. 3.

Table 2. Input ripple current when each sub-converter operating in DCM and the cases that the input current become negative.

Case	Input Ripple Current	$x_1 < 0$ (negative current)
$\alpha < 0.5 < \alpha'$	$\Delta x_1 = \frac{\alpha}{2} \cdot \left(1 - \frac{\alpha}{\alpha'}\right) = \frac{\alpha}{4} \cdot (3 - Y_2)$	if $2 \cdot \alpha < (1 - \alpha')^2$
$\alpha < \alpha' < 0.5$ $0.5 < \alpha + \alpha' < 1$	$\Delta x_1 = \frac{\alpha}{2 \cdot \alpha'} \cdot \left(\frac{1}{2} - \alpha\right) = \frac{Y_2 - 1}{4} \cdot \left(\frac{1}{2} - \alpha\right)$	if $2 \cdot \alpha < (1 - \alpha')^2$
$\alpha' < \alpha < 0.5$ $0.5 < \alpha + \alpha'$	$\Delta x_1 = \frac{1}{2} \cdot \left(\frac{1}{2} - \alpha'\right) = \frac{1}{4} - \frac{\alpha}{Y_2 - 1}$	Never
$0 < \alpha + \alpha' \leq 0.5$	$\Delta x_1 = \frac{1}{2} \cdot \alpha$	Always
$0 < \alpha + \alpha' \leq 0.5$ with a series diode	$\Delta x_1 = \frac{1}{2} \cdot \alpha \cdot \left(1 - \frac{1}{2} \cdot \alpha'\right) = \frac{1}{2} \cdot \alpha \cdot \left(1 - \frac{\alpha}{Y_2 - 1}\right)$	Never
$\alpha < 0.5$	$\Delta x_1 = \frac{\alpha - \alpha'}{2} = \frac{\alpha}{2} \cdot \frac{Y_2 - 3}{Y_2 - 1}$	Never

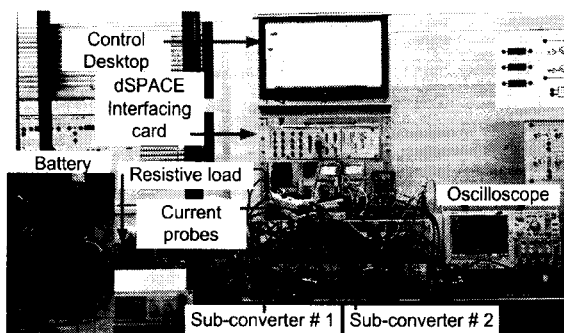


Fig. 3. Experimental setup.

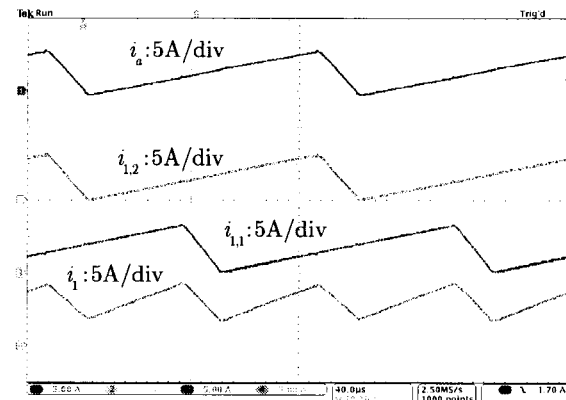


Fig. 4. Inductor current $i_{1,1}$, $i_{1,2}$, i_a , and input current i_1 for BCM and duty cycle $\alpha > 0.5$ and $f_s = 10 \text{ kHz}$.

The current waveforms when the converter functions under CCM are not given in this paper. They can be found in literature [2]. Fig. 4 shows current of the converter in steady-state where the converter is working under boundary conduction mode (BCM). All currents are positive, except i_a . The ripple of the total current is not much reduced compared to the current of each phase. This is due to the selected operating point. In Fig. 5, the currents of the converter when it is in between mode 1 ($\alpha + \alpha' < 0.5$) and 2 ($\alpha' < 0.5$, $0.5 < \alpha + \alpha'$ and $Y_2 < 3$), which are detailed in Fig. 2., are depicted. It should be noted that even the current of each phase is discontinuous, the input current is quasi-continuous. Fig. 6 shows the current when each sub-converter working under DCM and $\alpha + \alpha' < 0.5$. This can cause the negative input current. The input current depicted in Fig. 5 and 6 has shown that if each sub-converter operating under these modes; the input current ripple is the same level as of each sub-converter.

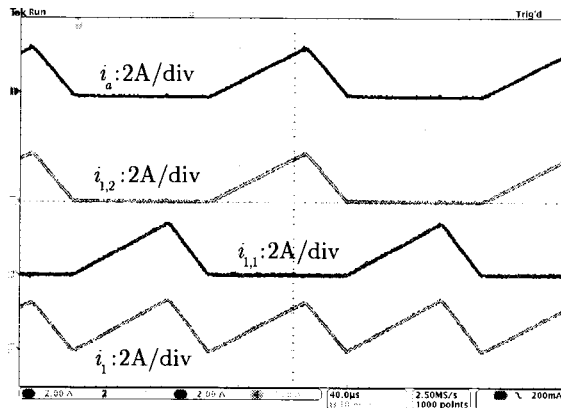


Fig. 5. Inductor current $i_{l,1}$, $i_{l,2}$, i_a , and input current i_1 for DCM and duty cycle, $f_s = 5$ kHz. This converter is working between mode 1 and 2 detailed in Fig. 2.

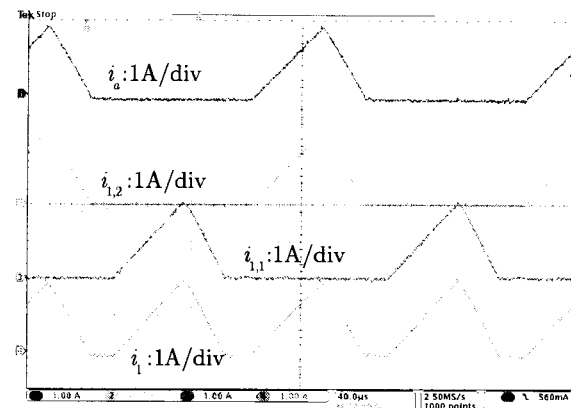


Fig. 6. Inductor current $i_{l,1}$, $i_{l,2}$, i_a , and input current i_1 for DCM, $f_s = 5$ kHz and duty cycle $\alpha + \alpha' < 0.5$.

Summary

The paper has presented an interleaved double dual boost converter. With interleaving technique, the input ripple current is reduced like the conventional interleaved boost converter. The possible cases operations of the converter were detailed. The conditions that the negative current will be presented at the input are discussed. To avoid the negative input current, a series diode connected between the energy source and the converter can be used. The experimental results have shown in some cases to validate of the theoretical analysis.

Acknowledgements

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