Comparative Analysis of Single Phase and Multiphase Bi-Directional DC-DC Converter

Jil sutaria, Manisha shah and Chirag chauhan

***Abstract*--A dc-dc converter has its applications, such as in hybrid vehicles, solar inverters, in power supplies for microprocessors etc. A bidirectional dc-dc converter can be alternately operated as a step down converter in one direction of energy flow and as step up converter in reverse direction of energy flow, in places where both the sides have voltage sources. A high voltage supply using a single converter is not preferred as it leads to high ripple in output voltage and current, thus requiring large value of inductor and filter capacitor. To overcome these limitations multiphase interleaving technique is used in bidirectional dc-dc converters i.e. connecting the converters in parallel with the switching instants equally distributed among them. This paper presents a comparative study of the single phase and multiphase bi-directional dc-dc converter and the optimization of inductor and filter capacitor. The open loop simulation is done using simulink tool and conclusions are drawn.**

Keywords: Bi-directional, Interleaved, Multiphase, Ripple.

I. INTRODUCTION

The bidirectional DC-DC converters with energy storage device have become very useful these days in various applications where power flow is required to and from the energy storage devices. The various applications are listed below.

- Hybrid electric vehicles(HEV)
- Fuel cell energy systems
- Renewable energy storage systems
- Un-interruptible power supplies(UPS)
- Battery chargers
- Microprocessor applications

The DC-DC converters are designed in such a way that they regulate the output voltage against the changes in the input voltage and load current. It not only reduces the cost but improves the efficiency of the system.

The converters can be broadly classified into isolated and non-isolated converters depending on whether isolation is provided between source and load. Based on this the converters are reviewed in [1] and was concluded that the isolated converters mainly used in renewable energy applications , HEVs and more whereas the Non-isolated are used in supply to microprocessors, UPS etc.

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The isolated converters are commonly used for high voltage application such as battery charging, as they provide galvanic isolation between load and source [2]. The presence of transformer in them leads to increase in their size, cost and losses. The non-isolated bidirectional dc-dc converter (NBDC) is therefore preferred in those systems where high power density and high efficiency is required.

NBDC employing three inductors and four switches for reducing current stress on switch and to get zero voltage transition is used for HEV, but the control of the converter here becomes complex [3].

Two *n*-level diode-clamped converter legs connected back-to-back form an n-level converter. This topology is used where both the sides of converter need to have same grounding. The main feature of this topology is use of lower voltage rating devices due to requirement of lower blocking voltages. Two level and five level converters are proposed in [4] and [5]. The current unbalance in capacitors is the main limitation of the n-level topology.

The half bridge NBDC topology is used in [6], for energy storage during regenerative breaking of DC motor. The half bridge topology used here has less number of switches and is easy to control.

This paper explores the possibility of using half bridge NBDC connected in parallel for high voltage application, thereby eliminating the use of transformer, making it compact and achieving high power density and high efficiency.

Two bidirectional converters connected in parallel, with same input and output are used. The study of single phase and two phase bi-directional dc-dc converter is made and the values of inductor and filter capacitor are optimised.

II. DIFFERENT TOPOLOGIES USED IN NON-ISOLATED CONVERTERS

The NBDC topologies have been proposed in many ways some with two switches and diodes for implementing ZVS and ZCS, some having four switches .The four-switch NBDC is shown in fig. 1. The left to right power transfer mode, Q1 and Q4 act as active switches, while in the right to left power transfer the opposite switches (Q2 and Q3) are controlled [7].

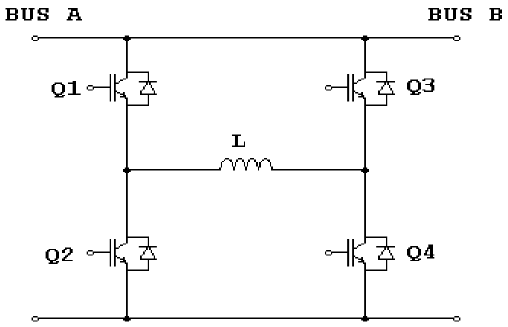

Fig. 1. Four switch NBDC.

The limitation here is that four switches are used, so switching losses increases. For reducing the size of the inductor and filter capacitor multiphase interleaving is used. The fig. 2 shows multi device interleaved Boost converter with two phase [13]. The switch S1 and S3 are connected to inductor L1 are operated at 0 degree and 180 degree respectively. The switch S2 and S4 are connected to L2 are operated at 90 degree and 270 degree respectively.

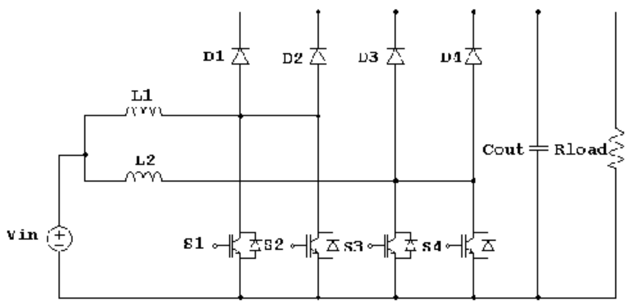

Fig. 2. Multidevice Boost converter.

The main drawback here is that the number of switches used per phase increases, thus increasing the switching losses, and also the duty cycle of the switches should be maintained equal, as any changes in it will lead to unequal current sharing per phase, leading to high output current ripple.

III. CIRCUIT DESCRIPTION AND OPERATION

A. Chosen topology

The Non-isolated half bridge converter topology consisting of two switches with anti-parallel diode connected across them is shown in Fig. 3. The switch and anti-parallel diode gives it the bidirectional nature. It is essentially a two quadrant chopper, where the output voltage always remains positive but the current becomes positive or negative depending on the direction of power flow [8].

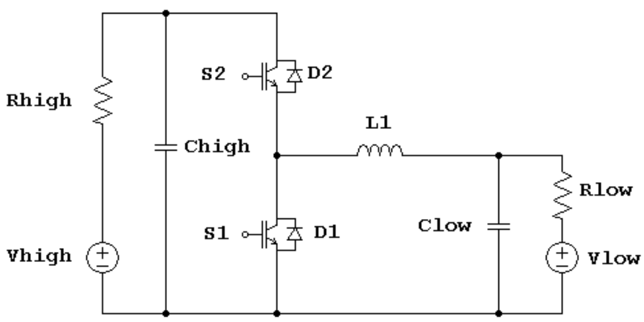

Fig. 3. Single phase half bridge bi-directional dc-dc converter.

The two phase topology shown in Fig. 4 along with interleaving switching scheme forms two phase interleaving converter. In the interleaving scheme [9] the PWM signals are separated in phase over a switching period in 2∏/N radians, being N the number of cells in parallel. The gating signals are generated by comparing ramp signal with constant, which is the duty cycle. As the individual input current of each converter is displaced from the others, the net effect is that the input and output current exhibits a switching frequency equal to N∗ fs with reduced current ripple. Thus the size of input and output capacitor reduces.

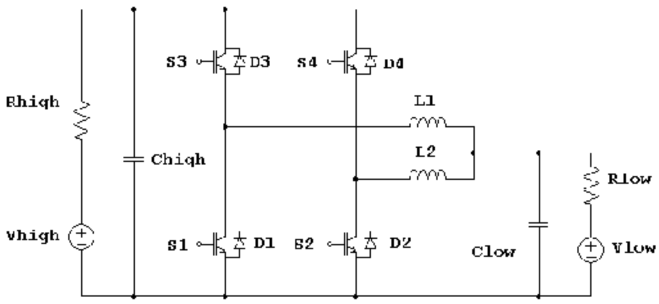

Fig. 4. Two phase half bridge topology.

B. Circuit description

The multiphase converter is represented by a general purpose model shown in fig. 2 [5]. There are two dc sources including high side bus voltage source V_{high} and low side battery source V_{low} representing both voltage sources of the bidirectional dc-dc converter. With two voltage sources, the averaged inductor current I_L or averaged output current Io can flow in both directions.

Resistor R_{high} represents either high side source internal resistance in buck mode or load in boost resistive load application. Resistor R_{low} represents either low-side source internal resistance in Boost mode or load in buck resistive load application. Capacitor C_{high} and C_{low} indicate the bus capacitor bank and the output capacitor at battery side respectively.

C. Circuit operation

The working of the circuit is in two modes:

- Boost mode
- Buck mode

To make the converter work in continuous conduction mode the duty cycle for Boost and Buck mode should be maintained such that D1 + D2 = 1, where D1 is duty cycle in boost mode and D2 is the duty cycle for Buck mode. The two phases work 180 degree phase shifted in one switching cycle, thus the charging and discharging time of each inductor is reduced to half .During Boost mode, V_{low} acts as a source with switching period T. The lower switch S1 gets the gating signal and the switch turns on, current flows through inductor L1, charging it for a period of D1*(T/2). The charged inductor and the Source get connected to the load R_{high} through the upper diode D3 for a period of (1-D1)*(T/2), giving high output. The other switch S2 turns on after 180 degree from the switch S1, charging the inductor L2 for D1*(T/2). The inductor and the source get connected to the load for a period of (1-D1)*(T/2). Both the inductors share equal amount of current.

During the Buck mode V_{high} acts as source, and the switches S3 and S4 conduct for a period D2*(T/2), and freewheeling is done through diodes D1 and D2 for a period (1-D2)*(T/2).

IV. DESIGN CALCULATION

The DC-DC converters can be classified as Buck bi-directional and Boost bi-directional depending on where the energy storing element is placed. The design equation of both Buck and Boost converter are valid in designing this converter. In this paper the converter is designed as Boost converter.
The specifications of the converter are given below:

TABLE I SPECIFICATIONS OF DC-DC CONVERTER

Parameters	Ratings
Power	1kW
Output voltage Vout	450 V
Input voltage Vin	120 V
Ripple voltage ΔV	1%
Ripple current ΔI	5%
Switching frequency fs	20kHz
Number of phases N	2

The maximum battery voltage can is 120 V. Therefore V_{inmax}= 120 V
As the battery can be allowed to discharge till 60 % the minimum input voltage comes out to be:

$$V_{inmin} = \frac{120 \times 60}{100} = 72 \text{ V} \qquad (1)$$

The Value the input current and the output current calculated are 8.33 A and 2.22 A respectively.

A. Inductor calculation

The calculation of inductor depends on the minimum input voltage, inductor charging time and allowed ripple current.
Now for single phase, the value of the inductor can be calculated as given below:

$$L = \frac{\Delta T_{on} \times V_{inmin}}{\Delta I_{in}} = 7.2\text{mH} \qquad (2)$$

Where, the time taken to charge the inductor ΔT_{on} ,

$$\Delta T_{on} = \frac{1}{f_s} \times D_{max} = 42 \times 10^{-6} \text{ s} \qquad (3)$$

The allowed input ripple current ΔI_{in}

ΔI_{in} = 8.33 × 0.05 = 0.4166 A
D_{max} depends on the maximum output voltage and minimum input voltage.

When 7.2 mH is used the input ripple current exceeds the allowed value of ripple current in single phase, so a larger inductor could be used to limit it or higher ripple can be allowed.
For two phase the same equation is valid but the value of ΔT_{on} is reduced by N as two inductors charge in the same switching cycle.
The current is divided among each phase so the overall ripple current allowed from each inductor can be increased.
The value of inductor is thus halved i.e. 3.6 mH, but doing so Input ripple current exceeds the ΔI_{in}.
The effect of reduced ripple is seen only at the input and output, the ripple through individual inductor comes to be higher. Therefore the same value of inductor i.e. 7.2 mH is used in single phase and two phase converter.

B. Capacitor calculation

The value of allowed output voltage ripple is 1 %.Thus the voltage ripple is equal to,

$$\Delta V = \frac{1 \times V_{out}}{100} = 4.5 \text{ V} \qquad (4)$$

In a multiphase converter the frequency as seen by the input and output capacitor is N *fs, since the two converters are connected in parallel and are operated 180 degree out of phase. The ripple frequency thus increases leading to reduction in size of capacitor. The value of capacitor can be calculated as follows:

$$C = \frac{D \times I_{out}}{N \times f_s \times \Delta V} = 8.88 \text{ µf} \qquad (5)$$

The used value capacitor used in two phase converter is 9 µf, whereas in single phase converter it is 18 µf.

V. SIMULATION RESULTS

loop simulation is done for both Buck and Boost mode of operation in continuous conduction mode of the converter. The specifications considered for simulation are given in Table I and the value of passive components used are as calculated in design parameters. Fig. 4 shows the generalized model used for simulation.
The results for single phase and two phase are shown and compared. Resistive load of 202.5 Ω is used when operated in Boost mode and 14.4 Ω is used in Buck mode.

A. Boost mode

The resulting Output voltage, Input current for single phase and two phase are shown below.

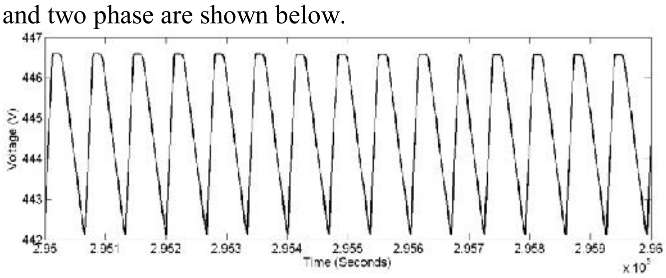

Fig. 5(a). Output voltage: single phase converter.

[X-axis: 1 div = 0.001 Sec Y-axis: 1 div =1 V]

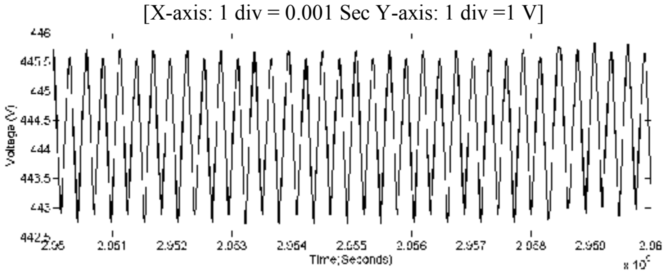

Fig. 5(b). Output voltage: Two phase converter.
[X-axis: 1 div = 0.001 Sec Y-axis: 1 unit =1 V]

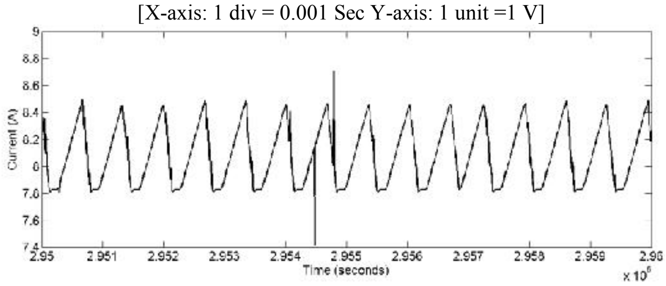

Fig. 6(a). Input current: single phase.
[X-axis: 1 div = 0.001 Sec Y-axis: 1 div = 0.2 A]

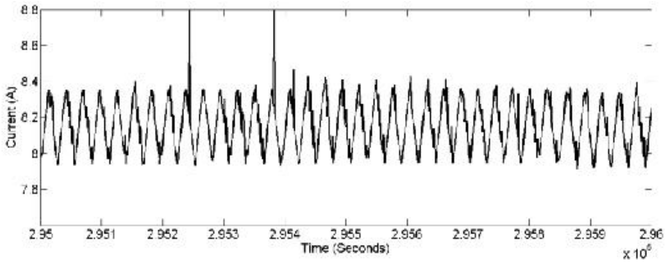

Fig. 6(b). Input current: two phase.
[X-axis: 1 div = 0.001 Sec Y-axis: 1 div = 0.2 A]

It can be observed from Fig. 5(b), Fig. 6(b) that the ripple frequency at the output and input is twice then that in single phase. The peak to peak (pk-pk) ripple in output voltage and input current is lower in two phase. The ripple in output voltage is 33.3% less in two phase as compared to single phase. The input current ripple in single phase is 75% higher than that in two phase.

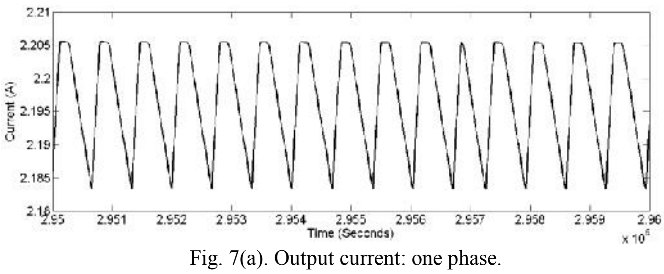

Fig. 7(a). Output current: one phase.
[X-axis: 1 div = 0.001 Sec Y-axis: 1 div = 0.005 A]

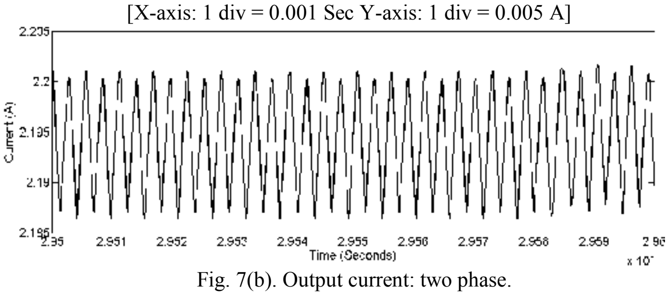

Fig. 7(b). Output current: two phase.
[X-axis: 1 div = 0.001 Sec Y-axis: 1 div = 0.005 A]

The value of output current remains same in both single phase and two phase but the ripple in output current is much less in case of two phase than in single phase. The value of ripple content is tabulated in table 2.

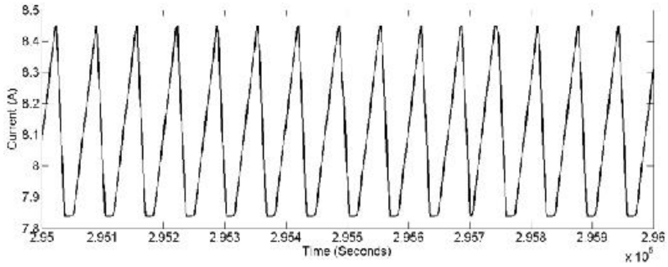

Fig. 8(a). Inductor current: one phase.
[X-axis: 1 div = 0.001 Sec Y-axis: 1 div = 0.1 A]

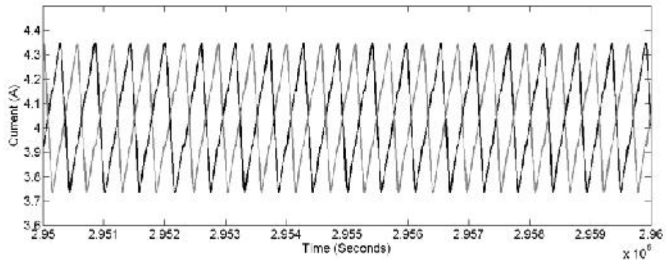

Fig. 8(b). Inductor current: two phase.
[X-axis: 1 div = 0.001 Sec Y-axis: 1 div = 0.1 A]

As observed from Fig. 8(b), the inductor current in two phase is shared equally among the two inductors, thus the ripple current allowed in both the inductors can be increased. Also it is noticeable that current through one inductor rises while the other falls, thus cancelling out the ripple, resulting in ripple reduction in output current.

B. Buck mode

Similar results were observed in Buck mode.

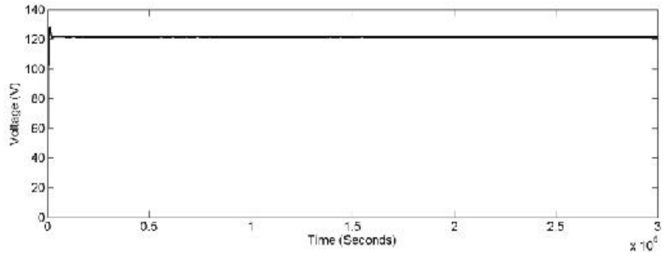

Fig. 9. Output voltage: two phase converter.
[X-axis: 1 div = 0.5 Sec Y-axis: 1 div =20 V]

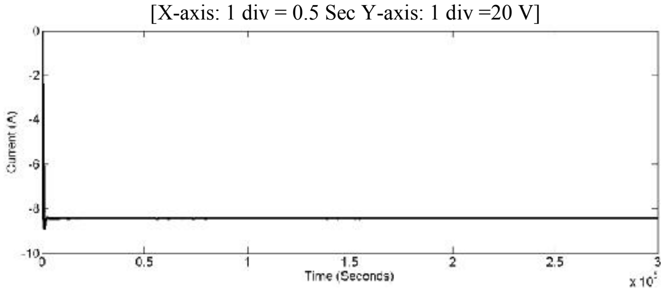

Fig. 10. Output current: two phase converter.
[X-axis: 1 div = 0.5 Sec Y-axis: 1 div =2 A]

Fig. 9 and Fig. 10 show the output voltage and output current in Buck mode for two phase. The value of output voltage is positive 120 V, whereas the value of current is negative 8.33 A proving bi-directional power flow. Also the value of ripple in output current is 0.3 % of the allowed ripple.

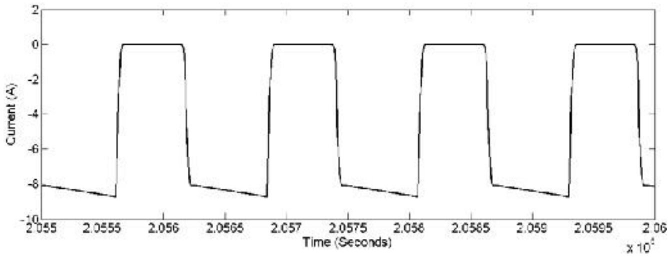

Fig. 11(a). Input current: single phase.
[X-axis: 1 div = 0.0005 Sec Y-axis: 1 div =2 A]

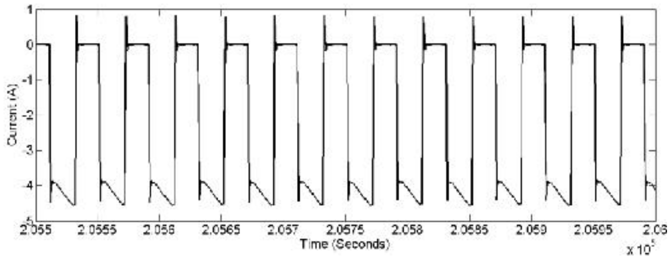

Fig. 11(b). Input current: two phase.
[X-axis: 1 div = 0.0005 Sec Y-axis: 1 div =2 A]

It can be observed from Fig. 11(a) that the input current shows the rising slope for a time when inductor charges and becomes zero during freewheeling time. The value of input current is double in single phase than that in two phase as shown in Fig. 11(b).

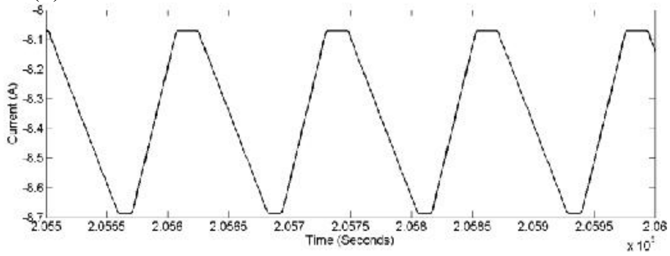

Fig. 12(a). Inductor current: single phase.
[X-axis: 1 div = 0.0005 Sec Y-axis: 1 div = 0.1 A]

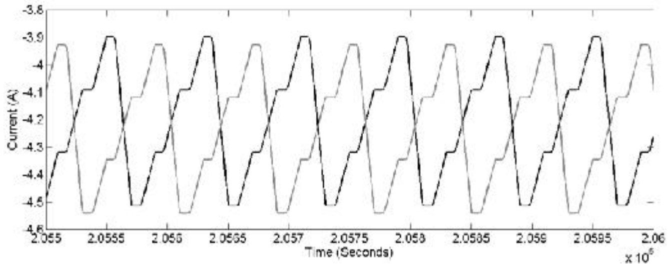

Fig. 12(b). Inductor currents: two phase.
[X-axis: 1 div = 0.0005 Sec Y axis: 1 div = 0.1 A]

Fig. 12(a) and Fig. 12(b) show the single phase and two phase inductor currents.
It is observed from Fig. 12(a) that as only one inductor charges and discharges in a cycle, so the charging time taken by it is more, so its value is higher. As seen in Fig. 12(b) two inductors are used, so the current as well as time of operation is shared among them, thereby reducing the values.

VI. COMPRISION OF SINGLE AND TWO PHASE BI-DIRECTIONAL CONVERTER

The comparison of peak to peak ripple in single phase and two phase output voltage, input and output current ripple is tabulated below.

TABLE II COMPARISION OF RIPPLE CONTENT IN SINGLE PHASE AND TWO PHASE CONVERTER

Parameters	mode	Allowed ripple	Single phase	Two phase
Inductor			7.2 mH	7.2mH
Capacitor			18 µf	9 µf
Output voltage ripple	Boost	4.5 V pk-pk	4.5 V pk-pk	3 V pk-pk
Output current ripple	Boost	0.11 A pk-pk	0.022 A pk-pk	0.014 A pk-pk
Input current ripple	Boost	0.41 A pk-pk	0.6 A pk-pk	0.4 A pk-pk
Inductor current ripple	Boost	0.8 A pk-pk	0.6 A pk-pk	0.6 A pk-pk
Output voltage ripple	Buck	1.2 V pk-pk	0.24 V pk-pk	0.14 V pk-pk
Output current ripple	Buck	0.41 A pk-pk	0.016 A pk-pk	0.005 A pk-pk
Inductor current ripple	Buck	0.8 A pk-pk	0.6 A pk-pk	0.6 A pk-pk

From Table II it can be concluded that the ripple content obtained in two phase converter is well within the range of allowed ripple content. The value of input current ripple in single phase Boost mode is 0.6Apk-pk whereas in two phase it is 0.4Apk-pk, which is allowed. Thus in single phase the value of inductor is to be increased to almost double of the value used in two phase to bring back the ripple in allowable range. The value capacitor decreases to half the value in single phase, due to the use of multiphase interleaving. Thus the value of passive components is optimized, making the converter compact.

VII. CONCLUSION

In this paper the open loop simulation of single phase and two phase half bridge bidirectional DC-DC converter is done using Simulink tool on resistive load. The converter can be used in applications where one side source is battery and other side source is constant DC link voltage like in UPS or HEV. The converter acts in buck mode while charging the battery and acts in Boost mode while discharging the battery. It was observed that by using the two phase topology with interleaving switching technique the ripple frequency seen at the input and output is twice as compared to single phase thus leading to reduced ripple in both the working modes. As the switching frequency seen is twice the actual switching frequency, the value of capacitor reduces to half along with reduction in switching losses. This increases the efficiency and power density of the two phase converter. The overall thermal losses of the two phase converter are limited due to division of the power between the two phases.

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