Optimal Design and Comparative Analysis of Different Bi-Directional DC-DC Converters for Energy Storage Applications

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Abstract

Bi-Directional DC-DC converters are widely used in many applications where two way power flow is required that is in forward and reverse direction. In this paper design and comprehensive analysis is carried out for Non-Isolated Bi-Directional Buck-Boost Converter and Isolated Dual Active Bridge DC-DC Converter, for same power rating and operating frequency. Detailed qualitative and quantitative comparison is carried out in terms of efficiency, number of components used and size. This comparison analysis helps to choose an appropriate topology for the specific application. The paper also discusses the novel method to switch the MOSFETs in Bi-Directional Buck-Boost converter and Dual Active Bridge converter. Furthermore, as an application of these converters, the concept of Bi- directionality charge and discharge of battery in one cycle is shown using MATLAB/SIMULINK software.

Keywords. Batteries, Bi-Directional, DC-DC Converters, Efficiency, SoC (State of Charge)

1. INTRODUCTION

One of the solution for the ongoing environmental problems such as depletion of non-renewable energy resources is to use electric vehicle (EV) for transportation [1]. Hence, Energy Storage Systems (ESSs) are gaining importance in real world applications [2]. Energy storage systems such as batteries and super capacitors are used in many emerging technologies.

Many emerging applications require energy to be transferred in both the directions. In the recent past, one of the important research area in the Power Electronics field is the design and implementation of Bi-Directional DC-DC converters. It is known that in Bi-Directional converters, power flows in both direction whereas in unidirectional power flows in one direction. Hence Bi-Directional DC-DC converters are used in many applications such as electric vehicles (EVs), Hybrid Electric Vehicle (HEVs), Uninterruptable power supplies (UPS), and renewable energy sources [3]. By integrating Bi-Directional DC-DC Converter in between the DC bus and Energy storage system the power wastage can be significantly reduced and also efficiency and reliability of overall system can be improved. One of the applications of Bi-Directional DC-DC converter in Electric Vehicle power train is shown in Fig 1.

DC-DC Converters are classified into two categories: Non-Isolated and Isolated Topologies. The Non – Isolated Bi-Directional converter has advantages like less complex circuit and design, less component count and simple control [3]. However isolation is not present between input and output. Isolated Bi-Directional DC-DC converter have high voltage gain ratio conversion factors and therefore used in high power applications. Isolated topologies provide good stability and reliability. However the circuit is more complex with high frequency transformer. The components counts is more that increases the overall size and weight of the converter.

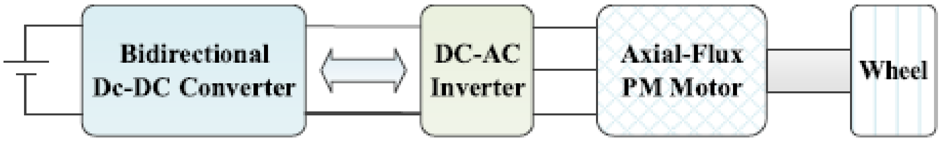

Fig.1 Use of Bi-Directional DC-DC Converter in EVs [3]

2. OPERATION AND DESIGN PROCEDURE

2.1. *Bi-Directional Buck-Boost Converter*

The Bi-Directional Buck-Boost topology which is Non – Isolated DC-DC converter is shown in Fig.2. Q1 and Q2 are two power stage MOSFETs and both will operate in complimentary fashion. In buck mode Q1 will be on and Q2 will be off and will operate as per duty cycle and in boost mode Q2 will be on and Q1 will be off. To avoid short circuit across the DC bus a small dead time will be provided between two MOSFETs [4]. This topology does not has transformer and hence used for low power application and also it has high efficiency.

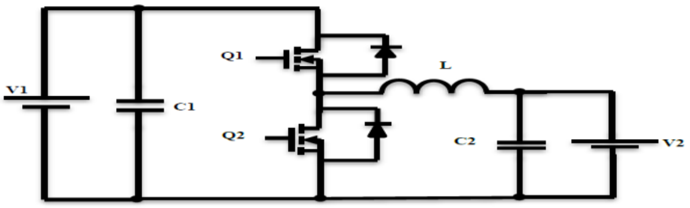

Fig.2 Bi-Directional Buck-Boost Converter [4]

2.2. *Specifications and Design*

Table 1: Specifications of Bi-Directional Buck-Boost converter

Parameter	Symbol	Value	Unit
Input Voltage	Vin	300	V
Output Current	Io	10	A
Switching Frequency	f	50 k	Hz
Output Voltage	Vo	24	V
Duty Cycle	D	50 %	-
Inductor	L	240 µ	H
Capacitor	C	416.67 µ	F

$$L = \frac{Vo*(1-D)}{\Delta I_l * f_s} = 240\ \mu\text{H};\ \Delta I_l = 10\ \%\ of\ total\ output\ current \qquad (1)$$

$$C = \frac{Io*D}{\Delta V_o * f_s} = 416.67\ \mu\text{F};\ \Delta V_o = 1\ \%\ of\ total\ output\ voltage \qquad (2)$$

2.3. *Dual-Active Bridge DC-DC Converter*

Fig.3 shows Dual Active Bridge converter which is an isolated Bi-Directional DC-DC converter. It consists of H–bridge inverter on the primary side. The DC input is fed to the inverter which gives the AC output of high frequency square pulses at the primary side of the transformer. The AC signal is then converted into DC using secondary side rectifier. The Secondary side MOSFETs are operated in Phase shift manner, since transformer provides a phase shift of 180 degrees [5], [6] and [7].

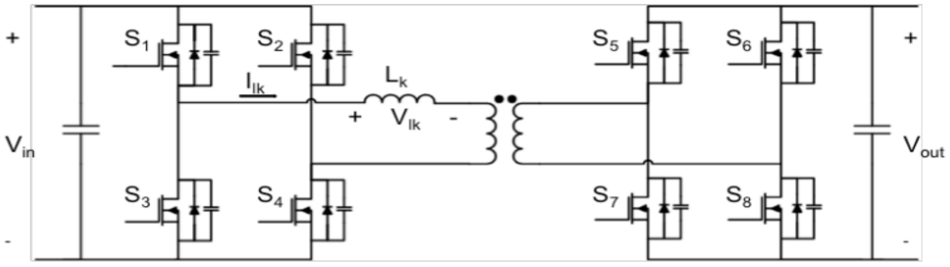

Fig.3 Isolated Dual Active Bridge DC-DC Converter [8]

2.4. *Specifications and Design*

Table 2: Specifications of Dual Active Bridge converter

Parameter	Symbol	Value	Unit
Input Voltage	Vin	300	V
Output Current	Io	10	A
Switching Frequency	f	50 k	Hz
Output Voltage	Vo	24	V
Duty Cycle	D	40 %	-
Inductor	L	24 µ	H
Capacitor	C	66.67 µ	F

$$L = \frac{Vl*D}{\Delta I_l * f_s} = 24\ \mu\text{H};\ \Delta I_l = 20\ \%\ of\ total\ output\ current \tag{3}$$

$$C = \frac{Il*D}{\Delta V_o * f_s} = 66.67\ \mu\text{F};\ \Delta V_o = 1\ \%\ of\ total\ output\ voltage \tag{4}$$

In this paper the simulation is carried out for both topologies of Bi-Directional DC-DC converter and the efficiency analysis is also carried out for same specifications.

3. SIMULATION RESULTS AND COMPARISON

3.1. Bi-Directional Buck-Boost Converter

To compare both non-isolated and isolated topologies, same specifications are considered and the simulation model is built in MATLAB/ Simulink. Li- Ion battery of 24V is used as storage device. The Initial SoC of the battery is considered to be 70% and the rated capacity of 10 Ah. The switching technique is described in the following sections

The Simulink model of non-isolated bi-directional buck-boost converter is shown in Fig.4

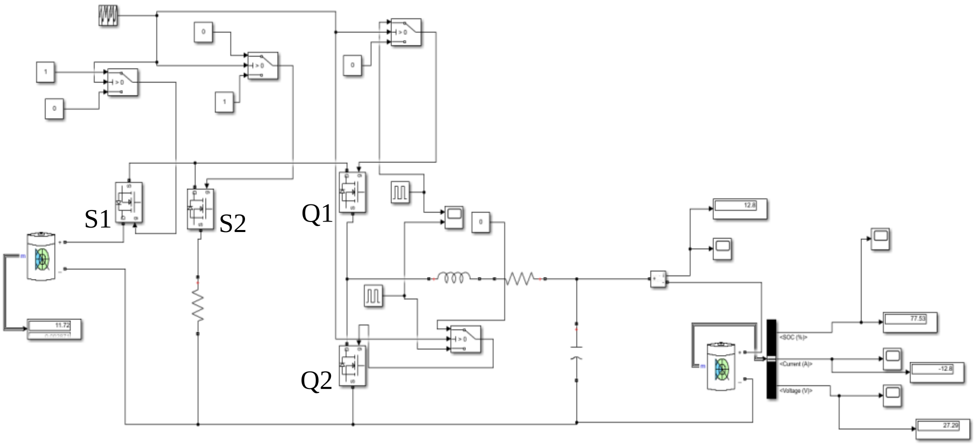

Fig.4 Bi-Directional Buck-Boost converter

By using two control stage MOSFETs S1 and S2 as shown in Fig.4. Both S1 and S2 switches are operated in such a manner that S1 will be enabled only during charging of the battery and S2 will be disabled, S2 will be enabled during discharging of the battery, and S1 will disabled. These S1 and S2 switches are enabled and disabled with high (1) and low (0) signal using two switches. In repeating sequence block corresponding output values are set, for respective time values. Discharging of the battery happens through the resistor which is connected across the input DC bus. Two power stage MOSFETs Q1 and Q2 are operated in complimentary manner. Initial SoC of the battery is set at 70%, and duty cycle set for the two power stage MOSFETs Q1 and Q2, the SoC of battery is increased from 70% to 75%. From Fig. 5 it can be seen that the battery is in charging mode up to 60 seconds and after that battery is in discharging mode up to 115 seconds. This is achieved by using the two control switches in the input section. During charging mode battery voltage was increased from 24 V to around 27 V and while battery is in discharge mode battery voltage is around 25 V. The transition can be seen in Fig. 6 at the point of discharging the battery. Similarly battery current during charging and discharging is shown in Fig.7

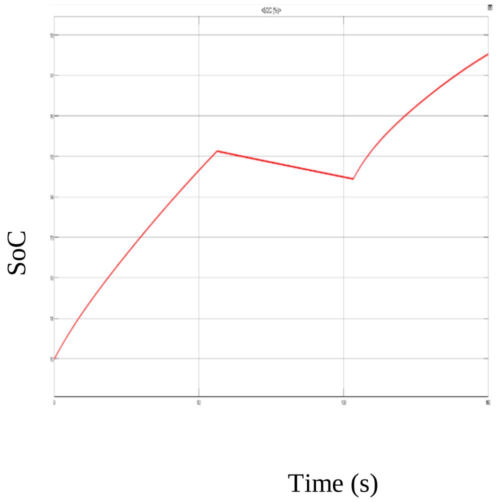

Fig.5 SoC of battery (charge-discharge-charge pattern)

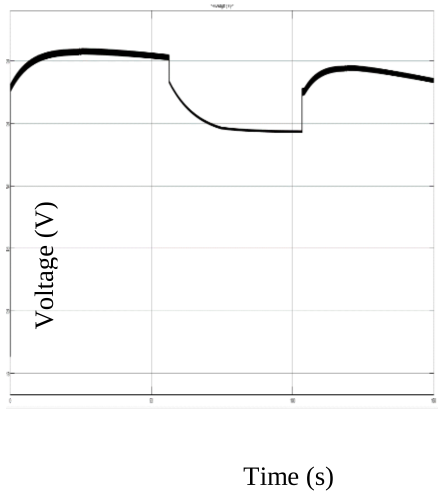

Fig. 6 Output Voltage

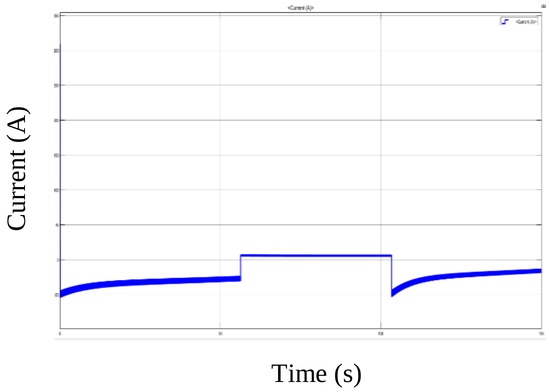

Fig.7 Output Current

3.2. *Dual- Active Bridge Converter*

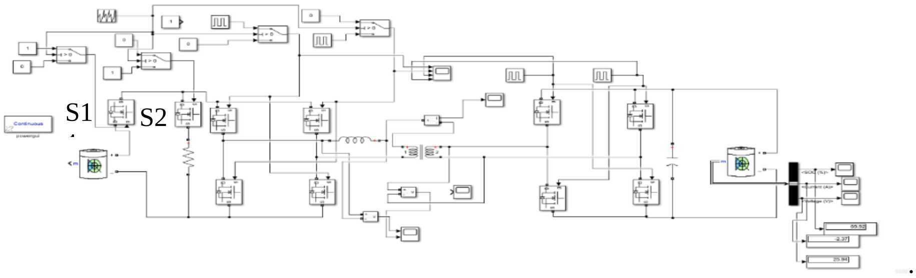

Fig.8 Dual Active Bridge

By using two control switches S1 and S2 as shown in Fig.8 in the input section. These two switches are controlled in such a way that when S1 is enabled battery starts charging and S2 is disabled, by providing the high (1) and low (0) signal to the two MOSFETs. Similarly when S2 is enabled battery discharges through the resistor and S1 is disabled. In this topology also initial SoC of the battery was set at 70 and by using two control switches S1 and S2, the charge-discharge-charge pattern is achieved, since current through the battery is positive as well as negative. We can say that power is flowing in both direction that is from source to load and vice versa. Respective SoC, Voltage and Current waveforms as shown in Fig 9, 10 and 11.

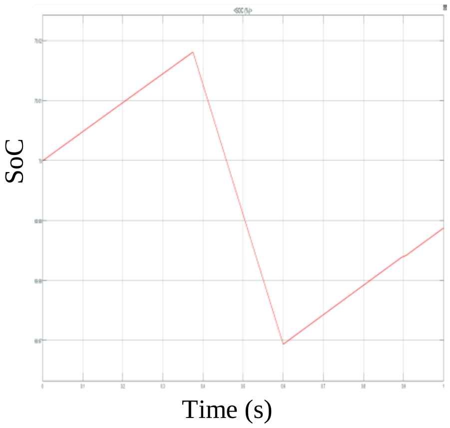

Fig.9 SoC of battery (charge-discharge-charge pattern

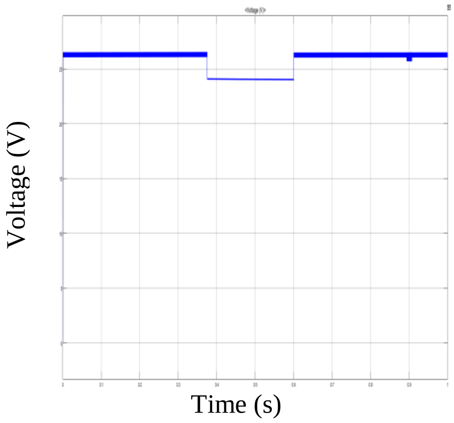

Fig.10 Output Voltage

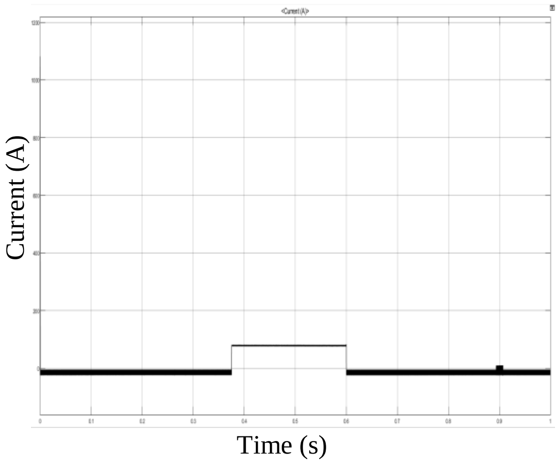

Fig.11 Output Current

4. EFFICIENCY CALCULATION COMPARISONS

Losses occurring in the converter are represented, from equation 3 to 10 [9].

4.1. Bi-Directional Buck - Boost Converter

1. $The\ inductor\ power\ loss\ P_L = \frac{rIo^2}{(1-D)^2}$ = 0.178 W (5)

r = equivalent series resistance of inductor; D= Duty Cycle; Io = Output Current

2. $Power\ Loss\ in\ MOSFETs\ during\ charging\ and\ discahrging\ mode$

$$P_{MOS} = \frac{D.r_{DS.}Io^2}{(1-D)^2} \tag{6}$$

$r_{DS.}$= Drain to source resistance of MOSFET, 45 mOhm [10]

$P_{charging} =$ 8.89 W

$P_{discharging}$ = 0.72 W

3. $The\ Capacitor\ Power\ loss\ P_{Cap} = \frac{D*r_C*Io^2}{1-D}$ = 0.033 W (7)

$P_{Total} = P_L + P_{MOS} + P_{Cap} + P_{Other\ losses}$

= 0.178+8.89+0.72+0.033+1

= 10.821 W

Other losses implies MOSFET switching losses, quiescent current losses etc.

Efficiency = $\frac{Po}{Po+P_{Total}} = \frac{24*10}{24*10+10.821} = 95.6$ % (8)

4.2. Dual-Active Bridge Converter

1. $The\ inductor\ power\ loss\ P_L = \frac{rIo^2}{(1-D)^2}$ = 0.4 W (9)

   r = equivalent series resistance value of inductor

2. $Power\ Loss\ in\ MOSFETs\ during\ charging\ and\ discahrging\ mode$

$$P_{MOS} = \frac{D.r_{DS.}Io^2}{(1-D)^2} \tag{10}$$

$P_{charging}$ = 5.76 W
$P_{discharging}$ = 16.64 W

3. $The\ Capacitor\ Power\ loss\ P_{Cap} = \frac{D*r_C*Io^2}{1-D}$ = 0.1 W (11)

$$P_{Total} = P_L + P_{MOS} + P_{Cap} + P_{Other\ losses}$$

= 0.4+5.76+16.64+0.1+4

= 26.9 W

Other losses implies MOSFET switching losses, quiescent current losses and Transformer magnetic losses etc.

$$\text{Efficiency} = \frac{Po}{Po+P_{Total}} = \frac{24*10}{24*10+26.9} = 89.9\ \% \qquad (12)$$

Table 3: Qualitative and Quantitative Comparison table

Parameters	Bi-Directional Buck-Boost	Dual-Active Bridge
Input Voltage (V)	300	300
Output Voltage (V)	24	24
Inductor Value (µH)	240	24
Output Current (A)	10	10
Output Power (W)	240	240
Efficiency (η)	95.6	89.9
Components count	Less	More
High Gain Voltage Ratio Application	Not Recommended	Recommended
Size of overall converter	Less	More

5. CONCLUSION

This paper mainly focuses on the comparison of Isolated and Non – Isolated DC-DC converters with same specifications in terms of efficiency, components counts and size of the converter and charge-discharge of battery in one time period. From simulations it is found that bi-directional buck-boost converter has an efficiency of 95.6 % whereas dual active bridge dc-dc converter has an efficiency of 89.9 %, which is slightly less due to losses in the transformer and more components count. However, Dual-Active Bridge DC-DC converters can be used in applications with high voltage gain ratio.

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