Multi Device Interleaved DC/DC Converter for Fuel Cell Applications

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***Abstract*—Among all types of green energy, fuel cells are widely known for its applications in standalone or grid connected systems because of its efficiency and reliability. Unfortunately, the fuel cell has some weak points, which are low output voltage and high input current ripple. This paper presents the multi device interleaved boost converter (MDIBC) to overcome the weakness that mention above. MDIBC produced high efficiency compared to other DC-DC converter which have reduced the input ripple current and size of passive component. The MDIBC is compared with an interleaved boost converter (IBC) to analyse its efficiency. The MDIBC and IBC converters structures are simulated using MATLAB/Simulink. The simulations have shown that MDIBC is more efficient and less input current ripple produced compared to the IBC.**

***Index Terms*—DC/DC Converter; Fuel Cell.**

I. Introduction

Problems with energy supplies and use become the trending because of environmental concerns such as air pollution, acid precipitation and radioactive substance submissions. To avoid these issues from getting bigger, some potential solutions have been developed, including the energy conservation through improved energy efficiency, a reduction in fossil fuel use and increase in environmentally friendly energy supplies. Among the renewable energy development nowadays, fuel cell (FC) is considered as one of the reliable alternative energy sources for the future. The fuel cell is chosen because of their cleanliness, high efficiency and high reliability [1]. There are various types of fuel cells available for many applications such as alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten-carbonate fuel cell (MCFC), proton exchange membrane Melaka fuel cell (PEMFC), and solid oxide fuel cell (SOFC). PEMFC has been chosen to be the most suitable since it has high power density with lower operating temperature [2, 3].

Unfortunately, this type of fuel cell has several limitations. It has a wide range of low DC output voltage, slow dynamic performances during load variations and low efficiency [4]. In order to deal with the variant low voltage fuel cell, a stable DC-DC boost converter is needed. It generated the desired level of voltage without increasing the fuel cell stack, thus maintain the cost of constructions [5]. Abutbul et al integrated a switched-capacitor circuit inside boost converter to achieve a desired voltage ratio [6]. The slow response in fuel cell system leads to the additional secondary energy storage to support the system during transient power or overload condition [7]. A discussion on high power interleaved boost converter for fuel cell were presented in [8], which can reduce the high frequency switching ripple. Ripple and harmonic content are those phenomena that could affect the lifespan of fuel cell. Thus, to ensure energy efficient operation of the fuel cell stack, the output current ripple should be reduced [9]. This research will cover the low voltage and ripple current in fuel cell system. A DC-DC converter that interfaced between fuel cell system and load had been chosen to solve this problem.

Figure 1 shows the interleaved boost converter (IBC), while Figure 2 shows the multi device interleaved boost converter (MDIBC). Even though MDIBC has more IGBTs compared to the IBC, the value of passive component is reduced and cause the reduction in converter weight as the high power passive component is weighted more than the IGBTs. Due to more advantages of MDIBC compare to IBC, the detail analysis of MDIBC is investigated in this paper. Table I shows the comparison between the two converter's advantages.

Table 1
Converters comparisons [10]

Converter	Advantages
IBC	• Simple configurations • Reduce ripple in current/voltage signal
MDIBC	• Higher conversion efficiency • Reduced the total converter size/weight • Reduced more ripple to provide more efficient power conversion

In this paper, a MDIBC has been studied and analysed to reduce the size and weight of the passive components. Meanwhile, the input current ripple and output voltage can be minimized efficiently. This converter will be compared with an IBC to study the efficiency and dynamic performances. Simulation results are provided.

II. Operating of MDIBC

MDIBC converter was chosen because of its power conversion efficiency is higher compared to the other interleaved converter. In this paper, the structure of MDIBC is shown in Figure 2 [10]. This converter consists of a two-phase interleaved boost converter with two switches and two diodes connected in parallel. To reduce the size of the inductor, capacitor and input/output EMI filter, the frequency of the inductor, capacitor in parallel. To reduce the size of the inductor, capacitor and input/output EMI filter, the frequency of the inductor current ripple and the output voltage ripple should be increased. To achieve the control strategy, the phase-shift interleaved will be applied. This control strategy provides the doubled ripple frequency in inductor current at a same switching frequency. This could contribute to higher system bandwidth. The bandwidth helps in fast dynamic response in the converter and passive component size reduction. Figure 1 shows the conventional interleaved boost converter (IBC) that will be compared to the MDIBC for performance analysis.

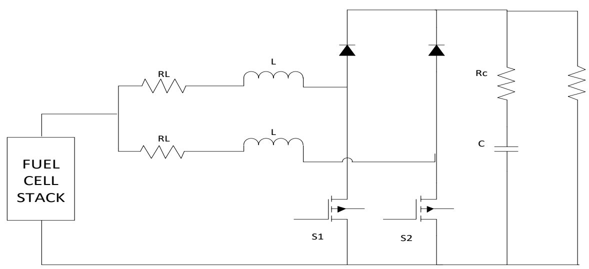

Figure 1: Interleaved boost converter, IBC

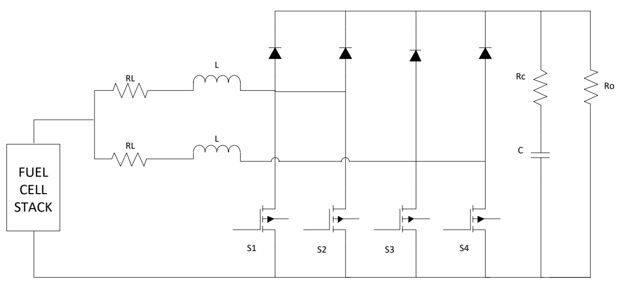

Figure 2: Multi device interleaved boost converter, MDIBC

The converter is simulated using MATLAB/Simulink in order to analyse the performances. These simulations are carried out with input voltage of 24V; 10 kHz switching frequency, Fs. The value *m* is the number of parallel switches per channel, and *n* is the number of channels or phases.

The design parameters are shown as below:

i. Boost ratio, the voltage gain of the converter is a function of the duty cycle and defined as:

$$V_o = \frac{V_{in}}{1-mD} \qquad (1)$$

ii. Input current can be calculated as below:

$$I_{in} = \frac{I_o}{1-mD} \qquad (2)$$

iii. Inductor current ripple peak-peak amplitude is given by:

$$\Delta I_{l1,l2} = \frac{V_{in}D}{F_S.\ L} \qquad (3)$$

iv. Selection of inductor and capacitor:

$$L = \frac{V_{in}D}{\Delta i_L Fs} \qquad (4)$$

$$C = \frac{V_o D Fs}{\Delta V_o R} \qquad (5)$$

v. Choosing the number of phases:
The ripple content reduce with the increasing number of phases. But, there is the limitation of the number of phase because it might increase the cost of components.

vi. Duty ratio:
The duty ratio selection is based on the number of phases. The ripple reduces at appropriate value of duty cycle. In this simulation, the duty cycle is in the range of 0.25.

vii. Selection the device:
The converter chosen is MDIBC and its use power MOSFET because of its high speed commutation and high efficiency at low voltage.

viii. Efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \qquad (6)$$

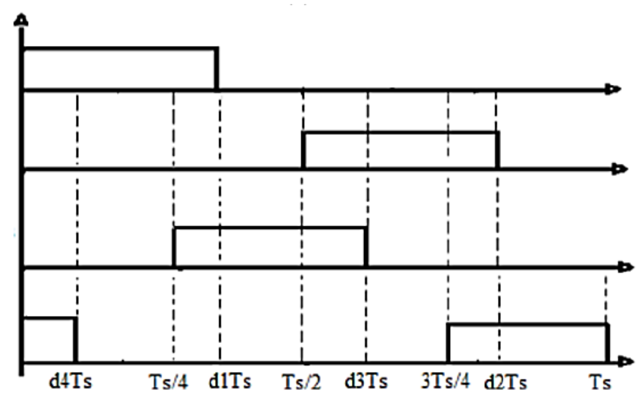

Figure 3: Sequence of gate signals for switches, D ≥0.25

Sequence for the switching status is shown in Figure 3. Figure 4 shows the operation of the converter based on the switching status for D=0.25.

i. Mode 1: $0 \le t \le d4T\,s$ [Figure 4(a)]
In this mode, the switches S1 and S4 are on and all the diodes are off. The capacitor discharge and supply the load.

ii. Mode 2: $d4Ts \le t \le Ts/4$ [Figure 4(b)]
In this mode, S1 is on which is in reverse biased. D3 and D4 is in forward biased. This condition makes both inductor L1 and L2 de-energised through the output capacitor and resistor.

iii. Mode 3: $Ts/4 \le t \le d1Ts$ [Figure 4(c)]
In this mode, S1 and S3 are on. All diodes are in off states. The capacitor supply the energy to the load R. The voltage can be defined as,

$$V_L = V_{in} \qquad (7)$$

iv. Mode 4: $d1Ts \le t \le Ts/2$ [Figure 4(d)]
In this mode, D1 and D2 is in forward biased. Only S3 in on. The capacitor is again recharged. The loads takes supply from the V_{in}. The voltage can be defined as,

$$V_L = V_{in} - V_C \qquad (8)$$

v. Mode 5: : $Ts/2 \le t \le d3Ts$ [Figure 4(e)]
In this mode, S2 and S3 are on. The capacitor is supply the load with voltage.

vi. Mode 6: $d3Ts \le t \le 3Ts/4$ [Figure 4(f)]
In this mode, only S2 is on. D3 and D4 also in forward biased. During this mode, the capacitor is recharge and also supply the loads.

vii. Mode 7: $3Ts/4 \le t \le d2Ts$ [Figure 4(g)]

In this mode, S2 and S4 are on. No diodes are on. The charged capacitor supplies the load.

viii. Mode 8: d2$Ts \leq t \leq Ts$ [Figure 4(h)]

In this mode, only S4 is on. D1 and D2 are in forward biased. The source recharged back the capacitor and supply the load.

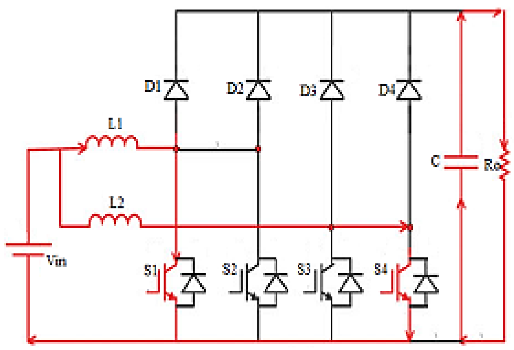

Figure 4(a): Mode 1

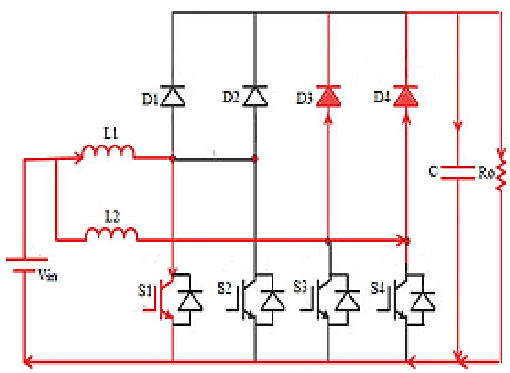

Figure 4(b): Mode 2

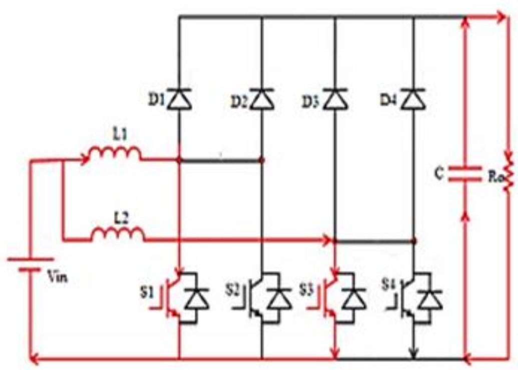

Figure 4(c): Mode 3

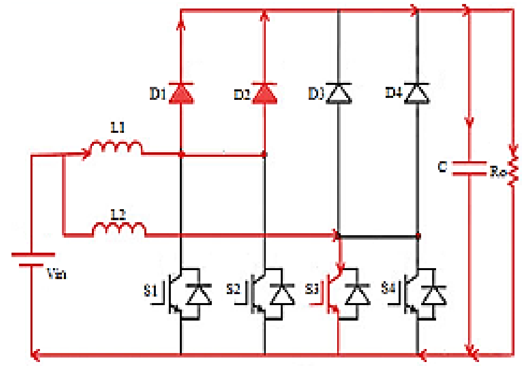

Figure 4(d): Mode 4

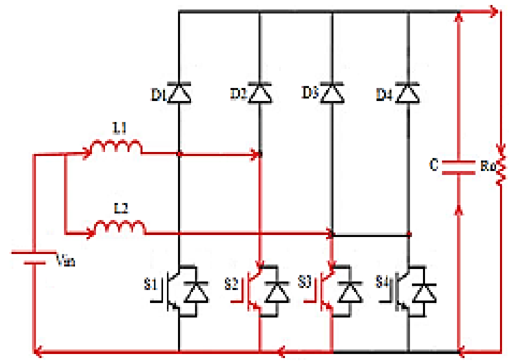

Figure 4(e): Mode 5

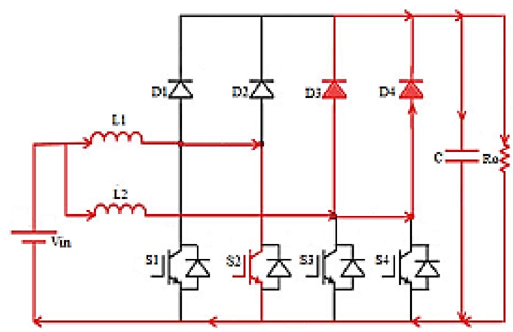

Figure 4(f): Mode 6

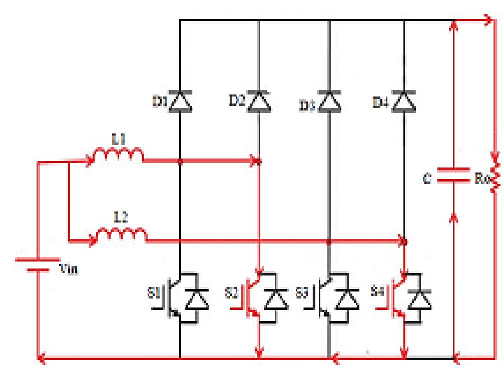

Figure 4(g): Mode 7

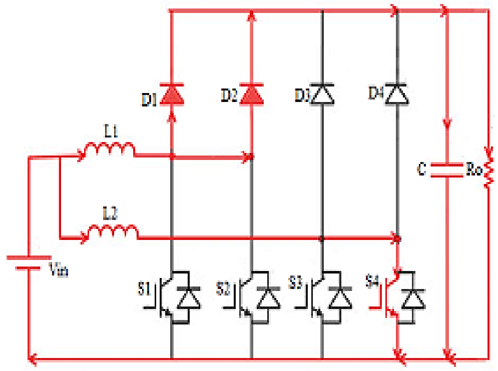

Figure 4 (h) Mode 8

Figure 4 (a),(b),(c),(d),(e),(f),(g),(h): Equivalent circuit for the converter in 8 mode operation

III. MDIBC SIMULATIONS

In this section, MDIBC and IBC converter are designed and simulated in MATLAB/Simulink. The converters performed under the parameters shown in Table II. The value for R_C and R_L can be neglected.

Table 2
IBC and MDIBC Parameters

Item	L1/L2(μH)	C(μF)	R(Ω)	[n m]
IBC	375	320	100	[2 1]
MDIBC	187.5	160	100	[2 2]

The DC voltage source is representing the fuel cell stacks. The IBC consists of two switches in two parallel paths per phase shown in Figure 5 and the switching status as in Figure 6. The MDIBC consist of four switches in two parallel paths per phase shown in Figure 7. Figure 8 shows the switching status for the MDIBC.

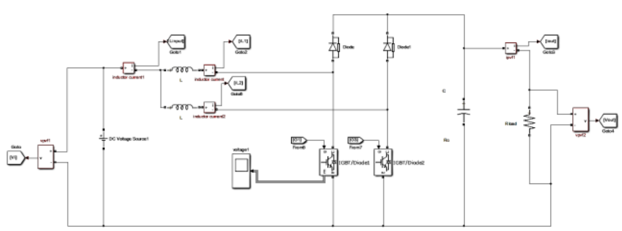

Figure 5: Simulation model for IBC

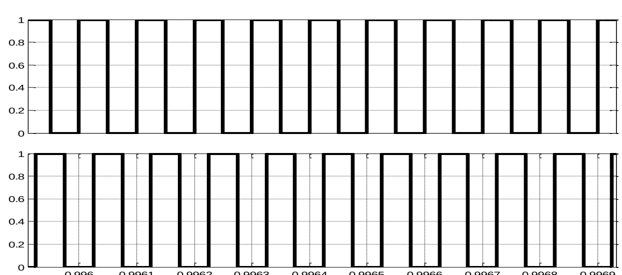

Figure 6: Switching status for IBC

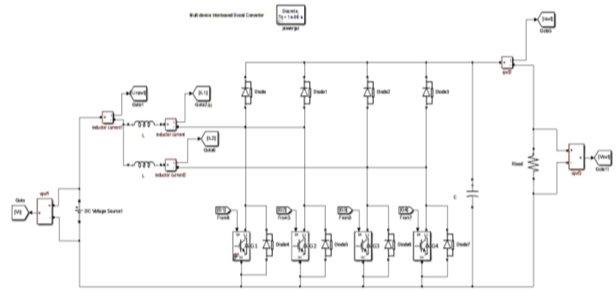

Figure 7: Simulation model for MDIBC

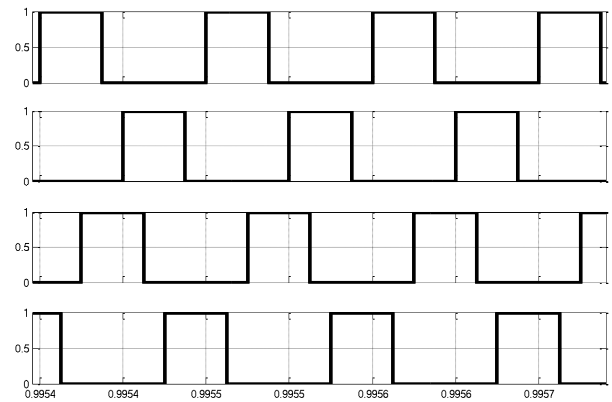

Figure 8: Switching status for MDIBC

Figure 9 shows the output voltage range in 72V for IBC. The ripple from the output voltage is 0.14V. The ripple produced is small and the output voltage is stepped up to be used in high voltage applications.

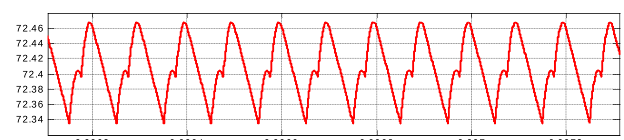

Figure 9 Output ripple voltage of the IBC

Figure 10 shows the output voltage range in 100V for MDIBC. The ripple for the output voltage is around 0.12V. The ripple is also lower compared to IBC's.

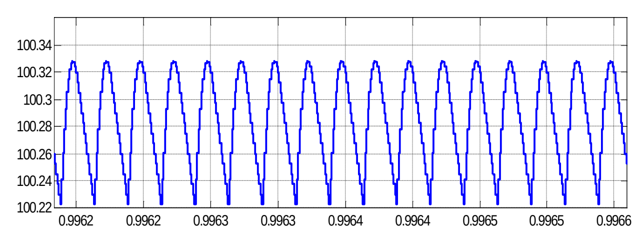

Figure 10 Output ripple voltage of the MDIBC

Figure 11 shows the waveforms of input current ripple for IBC. Referring to the Figure 11, the ripple of the input current in IBC is 5A.

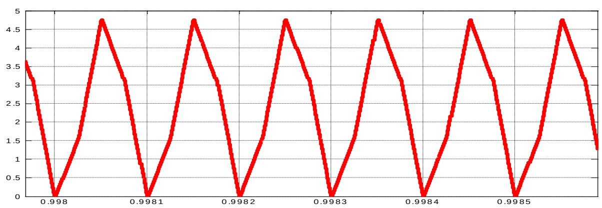

Figure 11 Waveforms of input current ripple of the IBC

As shown in Figure 12, the input current ripple frequency in MDIBC is almost doubled compared to IBC. The ripple at input current is 3A.

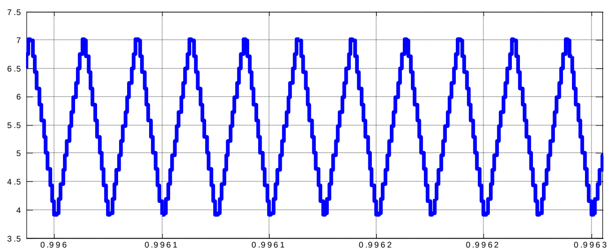

Figure 12 Waveforms of input current ripple of the MDIBC

The performance of different the DC-DC converter topologies are studied and analysed. Waveforms of converter output voltage and inductor input current are obtained using MATLAB/Simulink. Inductor input current with different ripple values is obtained for different converter topologies.

Table 3
Converters results of comparisons

Items	Output voltage ripple	Inductor current ripple	Switching frequency	Input current ripple frequency	Efficiency
IBC	0.14V	5A	10kHz	10kHz	93%
MDIBC	0.12V	3A	10kHz	40kHz	97%

Table III shows the comparisons between IBC and MDIBC based on simulation results. The efficiencies are calculated from the Eq (6). It is noticed that the proposed converter, MDIBC can improve the efficiency, reduced the component sizes and also reduced the ripple produced. Based on the results, the size of the passive components (inductor and capacitor) in MDIBC is reduced by half compared to IBC. As seen in Table III, the input current ripple frequency increase as a way to reduce the size of passive components. Phase-shift interleaved control is present to give doubled ripple frequency in inductor current at the same switching frequency. This provides a higher system bandwidth as it needed in faster dynamic response achievement. Furthermore, the MDIBC also reduced the ripple in input current ripple and output voltage. The converter could give much contribution in fuel cell system as it avoid from the damages to the fuel cell stacks as the ripple reduced. The advantages of the proposed converter can be summarized as below:

1. The sizes of the passive component are reduced.
2. The ripple in the input current waveforms also reduced.
3. Reliability or the efficiency of the converter is increased.

IV. Conclusion

In this paper, a MDIBC is recommended for fuel cell systems in order to improve the performances in the systems. The simulation results have shown that the inductor size and the capacitor size of the MDIBC are reduced 50% compared to the IBC. Therefore, the MDIBC converter seems to be suitable to use in high-power FC systems, as a method to extend the lifespan of the fuel cell. It is important to focus that the converter can improve system's efficiency due to low input current and output voltage ripple, reduced the passive component sizes and lead to higher reliability compared to other than IBC.

Acknowledgment

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