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Non-Isolated High Gain DC-DC Converters for Fuel Cell Application – A Comparative Study

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Abstract: This paper evaluates different topologies of non-isolated high gain DC-DC converter for fuel cell application. These converters transmit the low dc voltage of fuel cell to high dc voltage in DC link. In this learning, ripple content of both input current and output voltage were evaluated and discussed. In addition to that current and voltage stress are computed and compared. A comparison and discussion of the efficiency and losses are also presented in this paper. Study conceded out on this paper intends to choose the most excellent converter for fuel cell application. The selected converter has high conversion ratio, reduced voltage and current stresses on the power semiconductor switches when contrasted to the conventional boost converter. The analyzed converter can be applied to fuel cell system and also other renewable energy systems. Simulation is conducted over MATLAB/Simulink.

Keyword: Fuel cell, High gain, DC-DC converter, Ripples, Voltage and current stress.

1. INTRODUCTION

In the present day, energy catastrophe is due to the raise in demand. As a result, the utilization of non-renewable resources is also increased. This lead to the acceptance of renewable resources. Among them, hybrid vehicles is a promising technology. The hybrid vehicles use storage batteries for the locomotive purpose. Fuel cells are extensively being used nowadays as a source for the hybrid vehicle. A fuel cell is a device that employs hydrogen and oxygen to create electricity. These are more energy efficient than combustion engine and the hydrogen used to power them can drawn from variety of sources.

There are five types of fuel cells. Among these Polymer Electrolyte Membrane (PEM) fuel cells utilized in automobiles and also called Proton Exchange Membrane fuel cell which uses hydrogen fuel and oxygen from the air to produce electricity. Fig1 shows how a PEM fuel cell works. Most fuel cells intended for use in vehicles generate less than 1.16 volts of electricity. Therefore, multiple cells must be accumulated into a fuel cell stack. The power generated by a fuel cell stack depends on the number and size of the individual fuel cells that encompass the stack and the surface area of the PEM.

The future is electric, so great innovations are appreciated to develop battery operated vehicles. Many fuel cell vehicles are emerging in the market such as Honda FCX clarity, Mercedes-Benz F-Cell and so on. High-efficiency conversions, high power density, quieter operation, renewable are the notable advantages of the fuel cell. The main disadvantages of the fuel cell are high costs compared to other energy systems technology; operation requires replicable fuel supply, and output is very low. Thus it requires a DC-DC converter with the high gain ratio. Major concerns related with the DC-DC Converter are cost, efficiency, reliability, ripple current, transient response, Electromagnetic interference (EMI) emission. The selection of DC-DC-converter for fuel cell applications must fit into the constraints such as high conversion ratio, high stability of the output voltage during the variations of the output current and the input voltage, low number of components, high efficiency, low cost, low current or voltage stresses of the semiconductors, low ripple input current [1-2]. The major challenges in high step-up DC/DC converters are the following [4].

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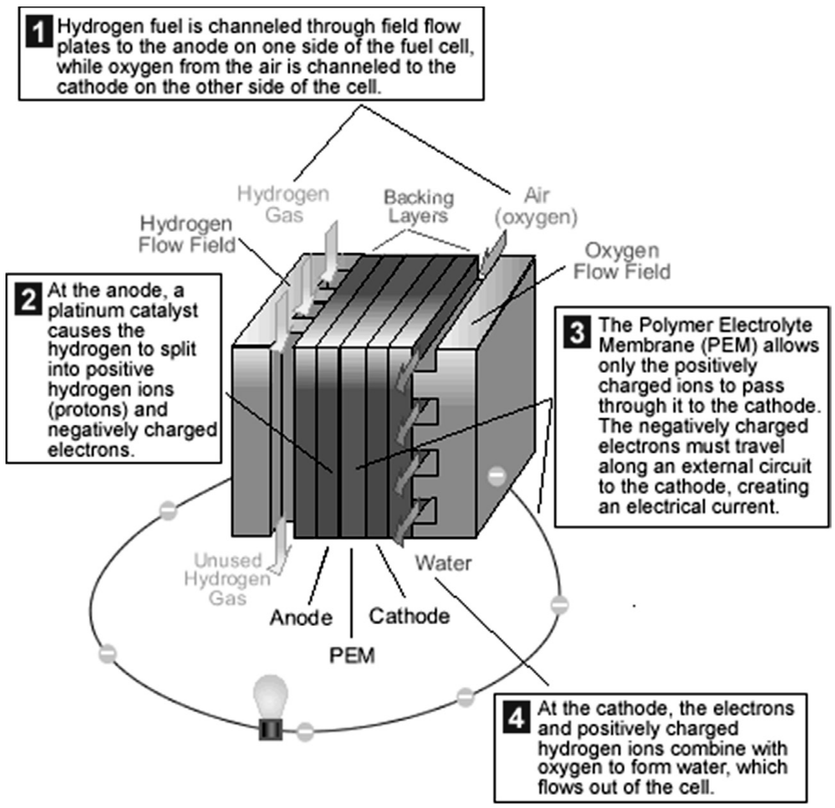


Figure 1: Fuel cell stack

- To widen the voltage gain and also evade the extreme duty cycle to reduce the conduction losses.
- To lessen the switch voltage to make use of low voltage MOSFETs.
- To realize soft switching to diminish the switching losses.
- To alleviate the output diode reverse-recovery problem.
- To boost the power level easily and reduce the passive component dimension.

The first hinders are taken, and they were examined to choose the finest converter for the fuel cell. Especially designing a converter with an inductor in series with the input and interleaved topology is essential for the fuel cell application system. Hence this paper is mainly based on the ripple analysis of input current of the different converter employed for the fuel cell application system.

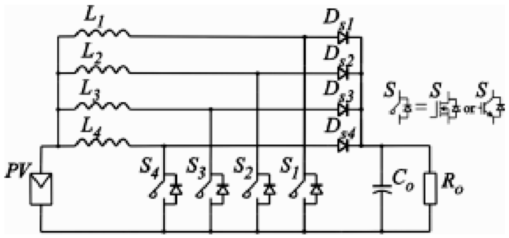
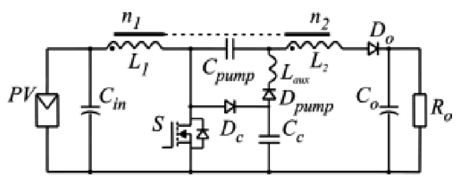
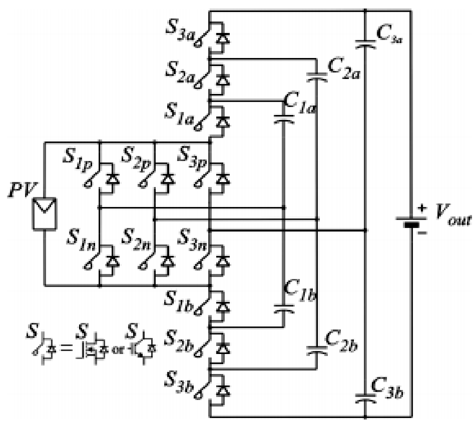
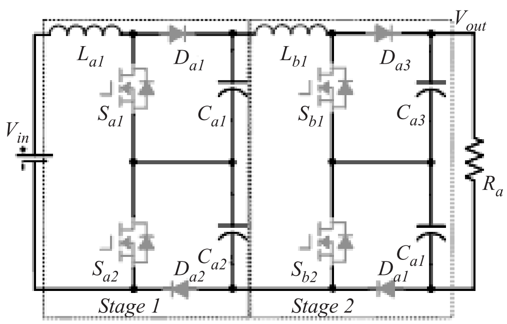
2. HIGH STEP-UP DC-DC CONVERTER – A REVIEW

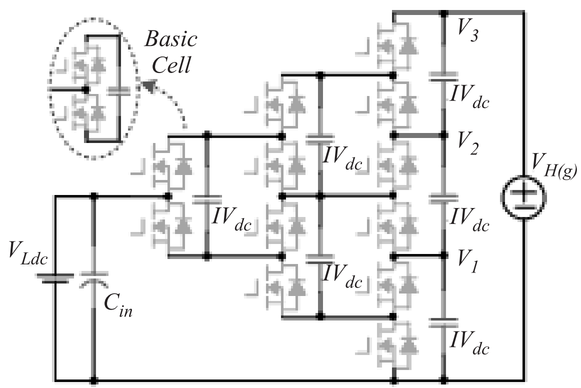
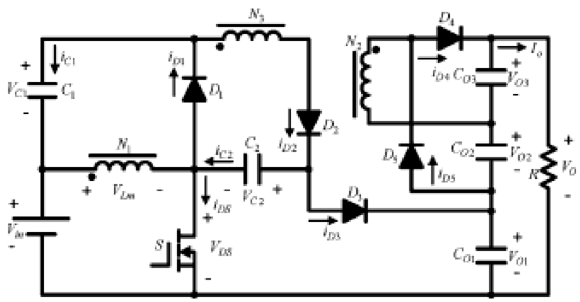
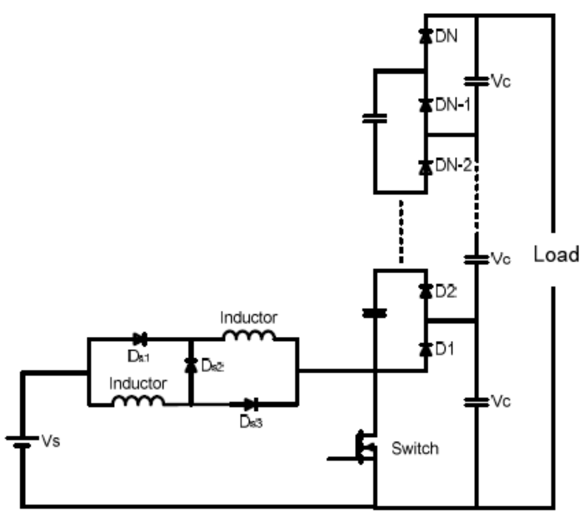
Table 1 gives the comparison of different types of the high step-up DC-DC converter mentioned in the literature. Their advantage and disadvantage are also discussed.

3. HIGH CONVERSION RATIO DC-DC CONVERTER:

Figure 2 furnishes the fundamental circuit diagram of two-phase interleaved boost converter. The interleaved boost DC-DC converter consists of two parallel joined boost converters, which are controlled by a phase-shifted switching function. The input current is the summation of the two inductor currents, I_{L1} and I_{L2}. Since the inductor's ripple currents are out of phase, they rescind each other out and reduce the input current ripple. The best input-inductor-ripple-current cancellation occurs at 50% duty cycle. The output-capacitor current is the sum of the two diode currents, I_1+I_2, minus the dc-output current, which reduces the output-capacitor ripple, as a function of duty cycle. [12].

Table 1
Comparison of different high step-up DC-DC converter

DC-DC Converter	*Topology*	*Advantage*	*Disadvantage*	*Reference*
Interleaved Boost Converter		Low input current ripple.	(i) small voltage gain (ii)The current ripples of the switches and the output diodes are huge. (iii)The switch voltage stress is equal to the output voltage, which is large in high output voltage applications.	[6][5]
Coupled Inductor Step-up Converter with Charge Pump		Wide input voltage range, high conversion ratio and cheaper.	At high power level the power dissipation within the components becomes a vital concern especially in case of the inductive elements.	[7][5]
Multilevel switched capacitor DC/DC Converter		High efficiency and capacity to work in elevated temperatures	Owing to capacitive load the switches are exposed to high current stress.	[11][5]
Cascade three-level boost converter.		Current ripple is decreased.	The cascade converter requires two sets of power devices, magnetic cores and control circuits, which is difficult and increases the circuit price.	[4][9]

DC-DC Converter	Topology	Advantage	Disadvantage	Reference
High step-up converter with the general multi-level cell.		High efficiency, High power density	A lot of power MOSFETs are necessary to realize a high voltage gain, and the gate driver circuit is complex, which increases the cost.	[4][10]
Boost converter with three winding coupled inductor and voltage doubler		(i) Energy stored in the leakage inductor is recycled to increase efficiency (ii) Voltage stress on the active switch is clamped; thus, a power switch with a low voltage rating can be adopted.	Ripples are high	[8]
Switched inductor multilevel boost converter		(i) The voltage stress on the switch is very smaller than the voltage stress on the switching conventional boost converter (ii) The efficiency of this converter is large	Input current, and output voltage ripples are high	[16]

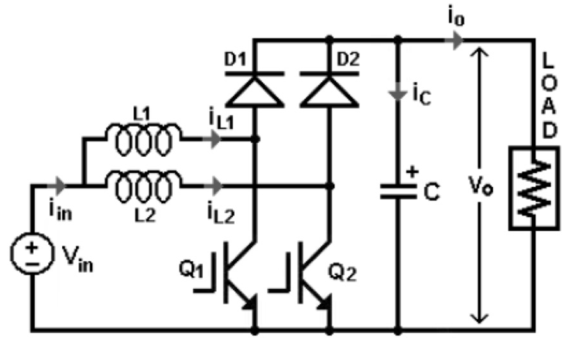


Figure 2: Interleaved boost converter

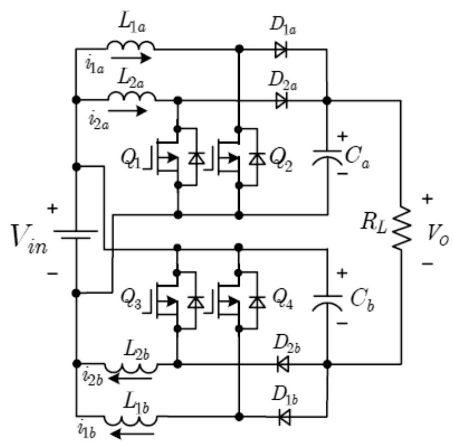


Figure 3: Double dual interleaved boost converter

Figure 3 presents the design of four phase double dual interleaved boost converter. This configuration is compiled of two conventional boosts with the input coupled inversely. The advantages of DDIBC converter compared with a conventional boost converter are high gain properties, low input current ripple, and high power applications. Besides, the ratings of the components are less than the output voltage [13].

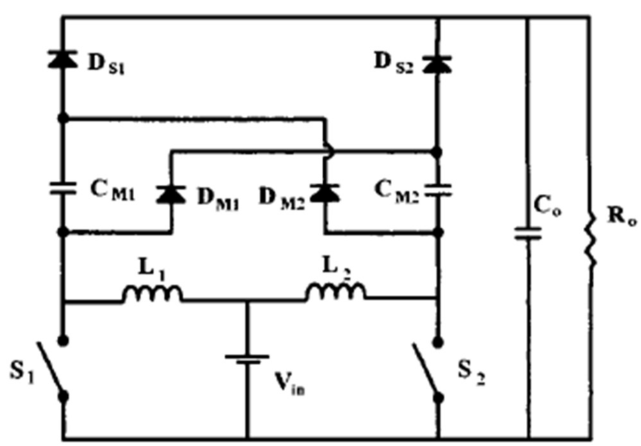


Figure 4: Interleaved Voltage Multiplier Boost converter

A common construction of the interleaved boost converter with voltage multiplier cell is given in Figure 4. This converter is based on the interleaved boost converter, integrated with voltage multiplier (VM) cell. VM cell consists of capacitor and diodes and used to obtain high gain. The number of parallel stages is represented by the parameter "P" for interleaved operation**,** and the number of VM stages is represented by the parameter "M", that are described by the number of the capacitor and diode combination connected in series with each switch [14].

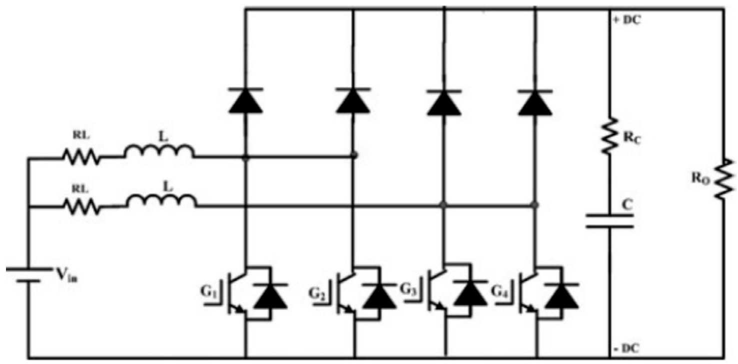


Figure 5: Multi-device interleaved boost converter

Multi-device interleaved boost converter (MDIBC) has been considered and investigated to decrease the size and heaviness of the passive components, such as the inductor, capacitor. The advantages of the Multi-device interleaved boost converter are low input current ripple and output voltage ripple, high efficiency and reliability. This structure consists of two-phase interleaved with two switches and two diodes connected in parallel per phase. Here the switches are fixed in parallel with a single storage element. Thus with m switches, the size of the passive components will be reduced by m times compared with the n-phase interleaved boost converter. In this converter structure, m is selected to be 2 to make the analyses simple. The switching pattern is quite complicated to achieve high gain in this converter. The switches in this converter operate with same duty cycle.

4. VOLTAGE GAIN ANALYSIS:

Table 2
Voltage Gain, Input current, Inductor current of high step-up DC-DC converter

High gain DC-DC converter	*Voltage Gain* (V_o/V_{in})	*Input Current* (I_{in})	*Inductor current* (I_L)
Interleaved Boost converter (IBC)	$1/(1 - D)$	$NI_o/(1 - D)$	$I_o/(1 - D)$
Double dual interleaved boost converter (DDIBC)	$(1 + D)/(1 - D)$	$I_o(1 + D)/(1 - D)$	$I_o/(1 - D)$
Interleaved voltage multiplier Boost converter (IVMBC)	$M + 1/(1 - D)$	$NI_o/(1 - D)$	$I_o/(1 - D)$
Multi device Interleaved Boost converter (MDIBC)	$1/(1 - mD)$	$V_o/(1 - m)R_o$	$V_o/n(1 - m)R_o$

Table3
Output Voltage for Different duty cycle

DC-DC converter	*0.3*	*0.5*	*0.7*
Interleaved Boost converter (IBC)	50	70	116
Double dual interleaved boost converter (DDIBC)	65	105	140
Interleaved voltage multiplier Boost converter (IVMBC)	100	198	233
Multi device Interleaved Boost converter (MDIBC)	88	---	---

Table 3 gives the formula for voltage gain, inductor current, and input current. Figure 6 explains the behaviour of gain concerning duty cycle for the different high step- up DC-DC converter. IVMBC voltage gain is twice that of the IBC. Even the gain of IVMBC can be increased by increasing M (Voltage Multiplier cell).

In custom, the elevated values of D are disadvantageous because of high current and low efficiency. Thus MDIBC can be used because it works for the D<0.5. But its ripple content and stresses across the switch gets increased for the duty cycle greater than 0.3 and less than 0.5.

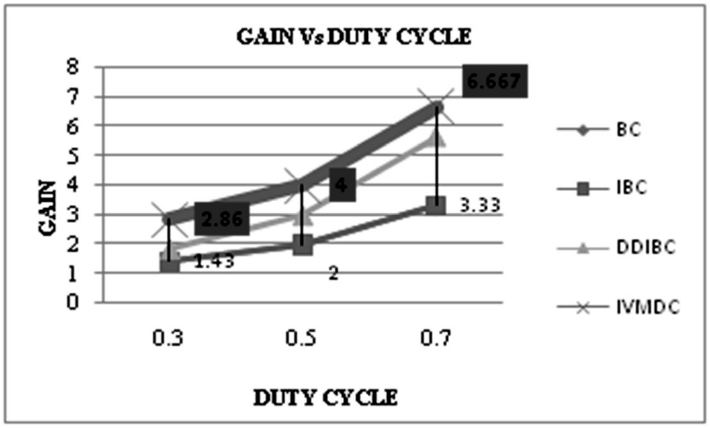


Figure 6: Gain Vs Duty cycle

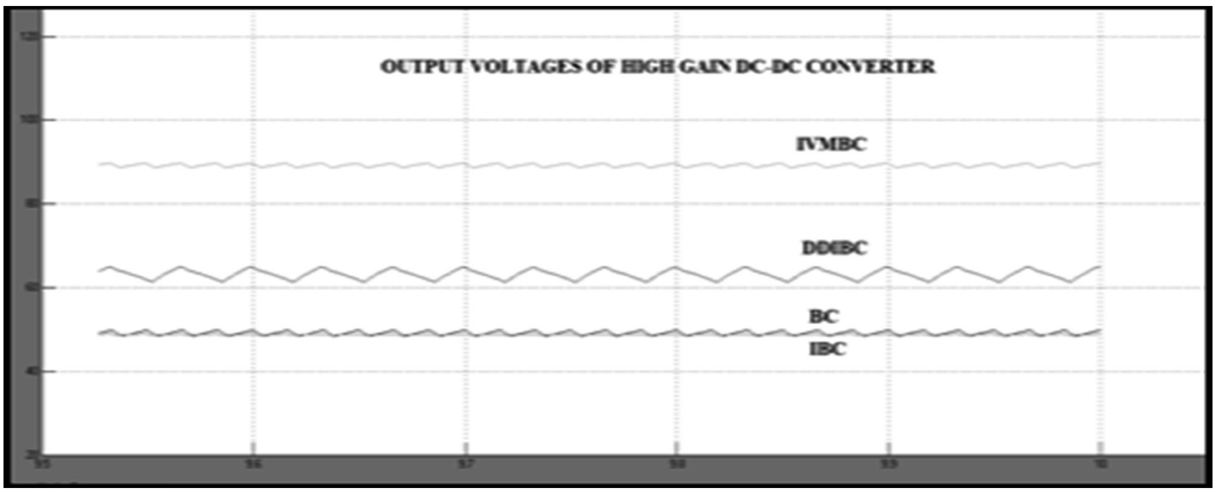


Figure 7: Simulated Output Voltage of High step up Dc-Dc converter (D<0.5)

5. RIPPLE AND STRESS ANALYSIS

Table 4
Design values of L and C

DC-DC converter	*Value of L(uH)*	*Value of C(uF)*
Interleaved boost converter (IBC)	833	16.66
Double dual interleaved boost converter (DDIBC)	416.5	16.66
Interleaved voltage multiplier Boost converter (IVMBC)	416.5	16.66
Multi device Interleaved Boost converter (MDIBC)	416.5	16.66

Table 5
Comparison of MDIBC (0 < D < 1)

MDIBC	*D = 0.25*	*D = 0.3*	*D = 0.45*
Output Voltage	70	88	350
Input Current	14	22	350
Input current Ripple	0.002	0.56	2.1
Output Voltage Ripple	0.465	3.6	28
Voltage Stress on switches	70	88	350
Current stress on switches	7	12	170

Table 6
Comparison of IVMBC (0 < D < 1)

IVMBC	*D = 0.3*	*D = 0.5*	*D = 0.7*
Output Voltage	100	140	233
Input Current	23.65	56	155
Input current Ripple	0.36	0.47	0.75
Output Voltage Ripple	0.96	0.061	2.5
Voltage Stress on switches	65	76	125
Current stress on switches	6.6	15	41

Table 7
Comparison of DDIBC (0 < D < 1)

DDMBC	*D = 0.3*	*D = 0.5*	*D = 0.7*
Output Voltage	65	105	198
Input Current	12	32	110
Input current Ripple	0.66	0.42	3.1
Output Voltage Ripple	3.7	0.43	30
Voltage Stress on switches	50	65	140
Current stress on switches	8	20	60

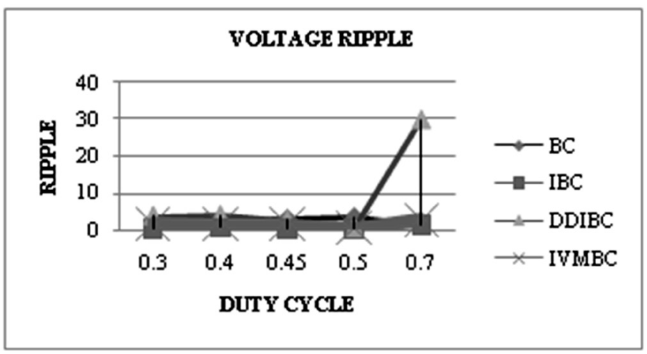


Figure 8: Voltage ripple analysis of high step-up DC-DC converter (0 < D < 1)

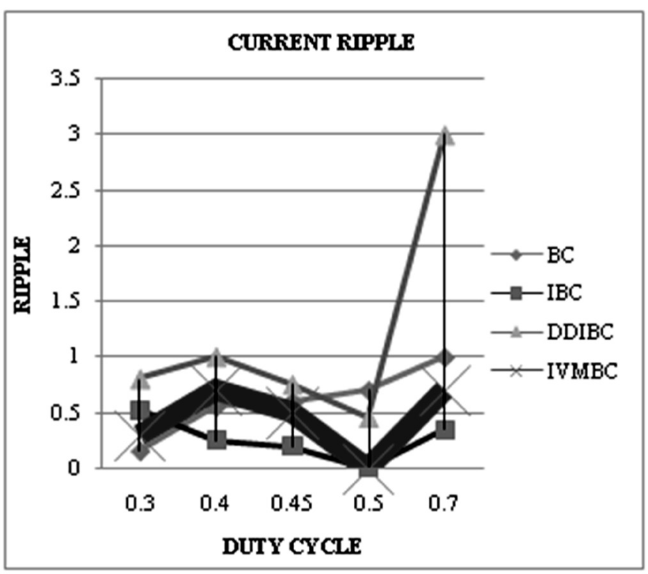


Figure 9: Current ripple analysis of high step-up DC-DC converter (0 < D < 1)

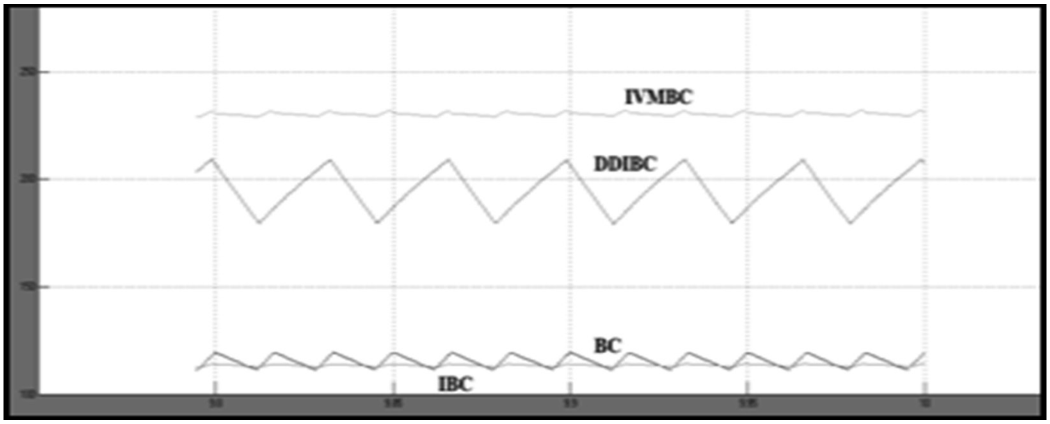


Figure 10: Simulated Input current waveform of high step-up DC-DC converter (D = 0.7)

Table 8
Voltage stress analysis between DDIBC & IVMBC

Duty cycle	*DDIBC*	*IVMBC*
0.3	50	65
0.5	65	76
0.7	140	125

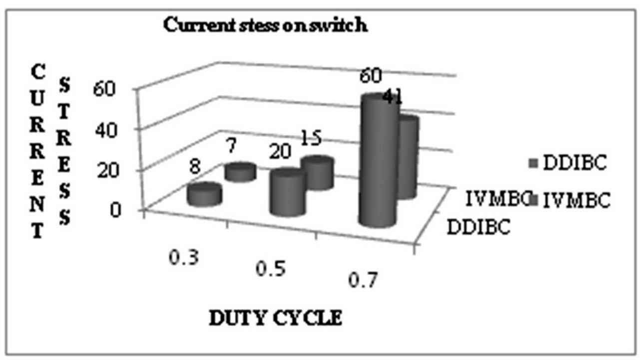


Figure 11: Voltage Stress-Comparison (0 < D < 1)

Table 9
Current stress analysis between DDIBC & IVMBC

Duty cycle	*DDIBC*	*IVMBC*
0.3	8	7
0.5	20	15
0.7	60	41

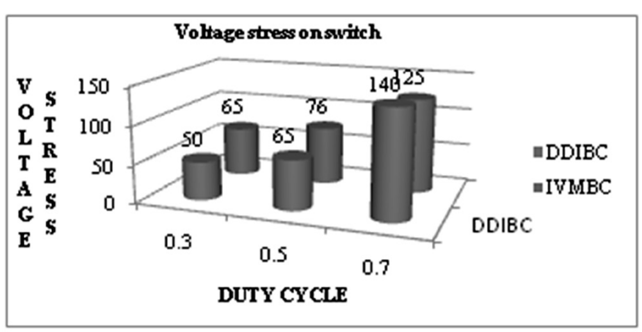


Figure 12: Current Stress-Comparison (0 < D < 1)

The ripples in the Input current of DC-DC converter can be reduced by

(i) Increasing fs.

(ii) Increase L value

The First condition increases the losses in the converter (Switching loss) which consecutively reduces the efficiency of the converter. The second condition increases the weight and quantity of the converter. A simple way to lessen the dimension of the inductor and capacitor is by raising the frequency of the inductor current ripple and the output voltage ripple.

The phase shifted interleaved control strategy doubles ripple frequency in inductor current at the unchanged switching frequency. If the ripple frequency is augmented, a bandwidth increase which in turn leads to quick dynamic response for the converter and the size of the passive components are reduced. Therefore the value of inductance used for DDIBC, IVMBC and MDIBC is just half of IBC.

Table 6, 7, 8 gives the comparison of different performance measures of DDIBC,IVMBC,MDIBC. Figure 8, 9 gives the comparison graph of ripples of different converters. From the graph, IVMBC is the best converter for different value of duty cycle, but MDIBC is the best converter for the duty cycle less than 0.5.

Figure 10 gives the simulated waveform of the input current which shows the ripple content of the current waveform for the duty cycle 0.7. Figure 11, 12 gives the comparison of voltage and current stresses of DDIBC and IVMBC. Voltage stress is quite high in IVMBC compared to DDIBC whereas current stress is less compared to other topologies. The voltage stress across the switch can be cut down by implementing the soft switching technique in IVMBC.

6. CONCLUSION

Table 10
Comparison between DDIBC & IVMBC

DC-DC converter	*Input current & output voltage Ripples*	*Voltage stress*	*Current stress*	*No of switches*	*No of diodes*	*No of passive elements*
Double dual interleaved boost converter (DDIBC)	High	Less	High	4	4	6(4L,2C)
Interleaved voltage multiplier Boost converter (IVMBC)	Less	High	Less	4	8	9 (4L,5C)

Table 11
Comparison between DDIBC & IVMBC & MDIBC

DC-DC converter	*Input current & Output Voltage Ripples*	*Voltage Stress*	*Current Stress*	*No of Switches*	*No of passive elements*
Double dual interleaved boost converter (DDIBC)	High	Very less	Less	2	4(2L,2C)
Interleaved voltage multiplier Boost converter (IVMBC)	Less	Less	Very less	2	5(2L, 3C)
Multi device Interleaved Boost converter (MDIBC)	Very less	High	High	4	3(2L,1C)

To make a choice of a topology among the topologies discussed for the fuel cell application is very difficult task, Double dual interleaved boost converter (DDIBC), interleaved voltage multiplier Boost converter (IVMBC) and Multi device Interleaved Boost converter (MDIBC) are compared. The Voltage and current ripples of these converters are analysed. Stresses on the switches are also analysed and compared.

For a duty cycle<0.5, MDIBC is the best converter for fuel cell application. For greater than 0.5 duty cycle, IVMBC is the best converter but its voltage stress is high and their current stress is low compared to other converters. Voltage stress can be reduced by implementing any soft switching technique.

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