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Design, Simulation and Hardware Implementation of a Multi Device Interleaved Boost Converter for Fuel Cell Applications

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ABSTRACT

This paper presents the analysis and implementation of a two-phase Multi Device Interleaved Boost Converter (MDIBC). Among the various DC-DC topologies, Multi device Interleaved converter is considered as a better solution for fuel cell hybrid vehicles as it reduces the input current ripple, output voltage ripple and the size of passive components. Detailed analysis has been done to investigate the benefits of Multi device Interleaved boost converter by comparing it with the conventional Interleaved boost converter topology. Moreover, in this paper, power loss analysis (switching loss, conduction loss, inductor loss) of the proposed converter has been performed. Simulation study of Multi device interleaved converter has been studied using MATLAB/SIMULINK. Hardware prototype is built to validate the results.

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1. INTRODUCTION

Fuel Cell is a promising alternative source of energy. The major challenge involved in designing a fuelc ell system is to choose a proper boost DC-DC converter to handle the high current at the input and high voltage at the output. An interleaved boost DC-DC converter seems to be a suitable candidate for current sharing and stepping up the voltage [1]-[2]. The main objective of this paper is to propose a multi device boost converter with interleaved control which reduces the input current and output voltage ripple. Multi device Interleaved boost converter has been proposed to reduce the size and weight of the passive components such as the inductor, capacitor and input/output electromagnetic interference (EMI) filter. Also, the input current and output voltage ripple can be minimized with high efficiency and reliability. Furthermore, the proposed converter will be compared with the conventional interleaved boost converter to investigate its characteristics. Mathematical analysis of the current ripple and the design parameters are included in this study. Simulation studies have been carried out to investigate the power losses of the proposed converter. A prototype of the two-phase MDIBC has been built to validate the simulation results.

2. OPERATION OF MULTIDEVICE INTERLEAVED BOOST CONVERTER

The proposed structure of multi device IBC consists of two-phase interleaved with two switches and two diodes connected in parallel per phase [3]. Figure 1 shows the circuit diagram of MDIBC. One of the way to reduce the size of the passive components namely the size of the inductor, capacitor and input/output filter is by increasing the frequency of the inductor current and the output voltage ripple. To achieve the above mentioned control strategy the phase-shift interleaved control is proposed. This strategy will give a doubled ripple frequency in inductor current at the same switching frequency, which provides a higher system bandwidth. The reason for higher bandwidth is that a faster dynamic response is achieved and also the size of the passive component reduces.

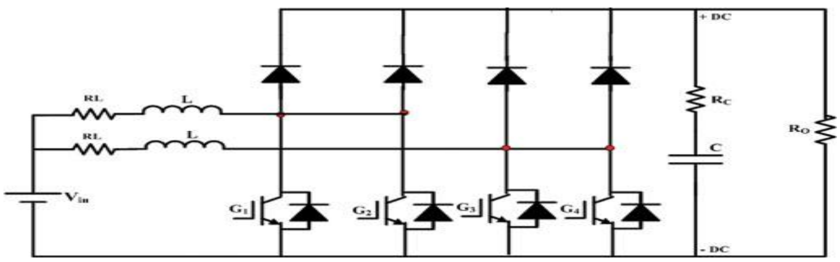

Figure 1. Circuit diagram of MDIBC

Also, the sequence of the driving signals is very important which provides a double ripple frequency in inductor current at the same switching frequency and to achieve the interleaved control. With the help of this strategy, the switching pattern is shifted by 360°/($n \times m$),where m is the number of parallel power switches per channel, while n is the number of channels or phases. The input current ripple is ($n \times m$) times of the switching frequency. Similarly, the output voltage ripple is ($n \times m$) times of the switching frequency .As a result, the size of the passive components will be reduced by m times compared with the n-phase interleaved dc/dc converters. In this proposed converter structure, m is selected to be 2, while n is chosen to be 2. Figure 2 shows the gating pattern for interleaved boost converter. It is also assumed that the proposed converter operates in the continuous conduction mode (CCM). All switches have identical duty cycles which means $d_1 = d_2 = d_3 = d_4 = d$.

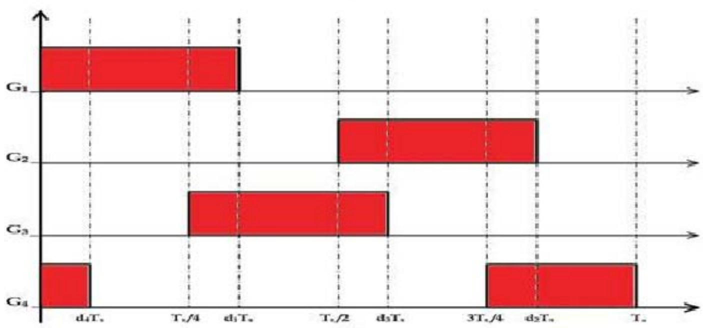

Figure 2. Sequence of the driving gate signals for MDIBC switches for d ≥ Ts/4

The design aspects of MDIBC are discussed in this section [4]-[5]:

a. Boost ratio

The voltage gain of the converter is a function of the duty ratio and it is defined as:

$$\frac{V_{dc}}{V_{in}} = \frac{1}{1-D} \quad (1)$$

Where V_{dc} is the output voltage,V_{in} is the input voltage and D is the duty ratio.

b. Input current

The input current can be calculated by the input power and the input voltage

$$I_{in} = \frac{P_{in}}{V_{in}} \quad (2)$$

Where P_{in} is the input power, V_{in} is the input voltage.

c. Inductor current ripple peak-to-peak amplitude:

The inductor current ripple peak-peak amplitude is given by:

$$\Delta I_{l1,l2} = \frac{V_{in}D}{f_{sw}L} \tag{3}$$

Where f_{sw} is the switching frequency, D is the duty cycle, V_{in} is the input voltage and L is the inductance.

d. Relationship between input current ripple peak-to-peak amplitude and inductor current ripple peak-to-peak amplitude

Mostly the minimum input ripple occurs at a duty ratio of 0.5 due to the 180 degree phase shifted gating signals between the devices. There are two operating modes which can be defined by the inductor [6]-[7]:

(i) Mode 1, D>0.5: over a particular period of time the current in both the inductors rises.
(ii) Mode2, D<0.5: over a specified period of time both the inductors discharge.

Hence the input current ripple peak-to –peak amplitude is given by,

$$\Delta I_{in} = \frac{V_{dc}-2\cdot V_{in}}{f_{sw}\cdot L}\begin{Bmatrix} -D & if\ D \leq 0.5 \\ 1-D & if\ D \geq 0.5 \end{Bmatrix} \tag{4}$$

The design of IBC and MDIBC involves selection of inductor, output capacitor, number of phases, device selection and the freewheeling diodes. The inductors and diodes have to be same in all the parallel paths of an IBC and MDIBC.

e. *Selection of inductor and capacitor:*

Nowadays in the power electronic systems the magnetic components play a major role for energy storage and filtering.The value of the inductor can be found out by the following formulae [8]:

$$L = \frac{V_s D}{\Delta i_L F} \tag{5}$$

Where Vs represents the source voltage and Δi_L represents the inductor current ripple, D represents the duty ratio. The value of the capacitor is given by the formulae:

$$C = \frac{V_o DF}{R\Delta V_o} \tag{6}$$

Where Vo represents the output voltage (V), D represents the duty ratio, F represents the frequency, R represents the resistance and ΔVo represents the change in the output voltage (V).

f. Choosing the number of phases:

The factor which decides in choosing the number of phases is that the ripple content reduces with the increases in the number of phases. There is a restriction to the increase in number of phases because if the number of phases is increased further without much reduction in ripple content the size of the components increases and hence increases the cost of performance [9]. It is to be noted that the number of inductor switches and diodes are same as the number of phases and the switching frequency should be same for all the phases.

g. Duty ratio:

The duty ratio selection is based on the number of phases, the ripple is minimum at a certain duty ratio. Here in the ripple is minimum at duty ratio in the range of 0.45.

h. Selection of the devices:

The device which is chosen for the multidevice interleaved boost converter is power MOSFET because of its high commutation speed and high efficiency at low voltages.

3. SIMULATION RESULTS

Based on the design equations, the proposed interleaved boost converter is designed and the simulation parameters are shown in Table 1.

Table 1. Simulation Parameters Of Multidevice Boost Converter At 0.45 Duty Ratio

PARAMETERS	MULTIDEVICE IBC
Vin	24V
Vout	43.63V
Switching frequency	25khz
Output voltage ripple	3.63%
Input current ripple	0.055%
Inductor current ripple	0.1246%
Input current ripple frequency	100khz
Inductor current ripple frequency	50khz

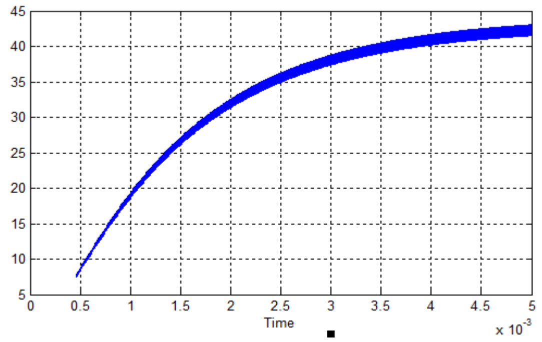

Figure 3. Steady and transient response of MDIBC

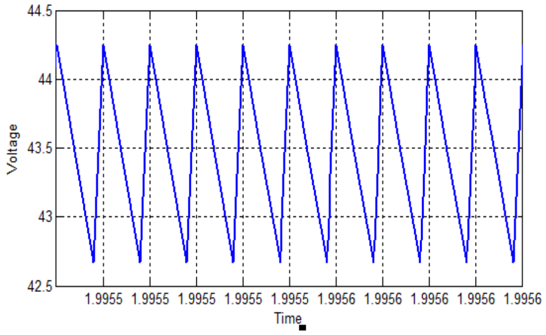

Figure 4. Output voltage ripple of MDIBC

The steady and transient response of multi device interleaved boost converter is shown in Figure 3. The output voltage ripple waveform of multi device interleaved boost converter is shown in Figure 4.

Table 2 shows the comparison between conventional boost converter and multi device interleaved boost converter at 0.45 duty ratio.

Table 2. Comparison between conventional interleaved boost converter and MDIBC for 0.45 duty ratio

PARAMETERS	IBC	MDIBC
Input Voltage	24V	24V
Output Voltage	42.2128V	44.25V
Input Current Ripple	3.28%	0.055%
Inductor Current Ripple	36.095%	0.1246%
Switching Frequency	25Khz	25Khz
Output Voltage Ripple Frequency	50Khz	100Khz
Input current Ripple Frequency	50Khz	100Khz
Inductor Current Ripple Frequency	25Khz	50Khz

From the results, it is found that the input current and output voltage ripple are reduced in the proposed interleaved boost converter compared to the conventional topology.

4. POWER LOSS ANALYSIS

The power loss analysis of the converter includes power loss of the MOSFETs, diodes and main inductor used in the converter circuit. The switching losses, conduction losses and inductor losses are calculated and the results are tabulated. The power loss of MOSFET consists of the switching loss (PSW(MOSFET)) and the conduction loss (PCOND(MOSFET)) [10]-[11]. The drain current waveform of MOSFET obtained as a result of MATLAB simulation is considered for calculating conduction loss. The MOSFET current during each time interval as shown in Figure 5 is used in calculating the rms value of drain current.

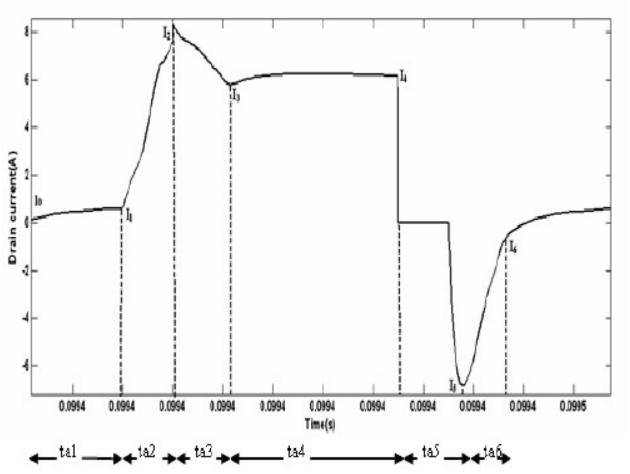

Figure 5. Drain current waveform of MOSFET

The PSW(MOSFET) is calculated on the basis of the overlap area of the drain-source voltage (VDS) and drain current (IDrain) as shown in Figure 6. The switching frequency used is 20kHz.

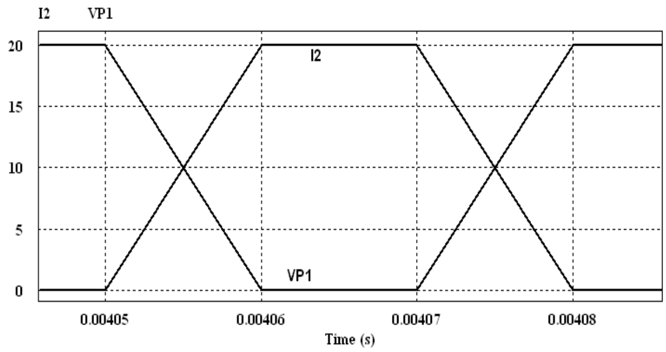

Figure 6. Switching characteristics of Power MOSFET

Table 3. Switching and Conduction Loss of Power MOSFET for MultiDevice interleaved boost converter

POWER LOSS PARAMETER	VALUE
Psw(MOSFET)×4	15.947W
PCOND(MOSFET) ×4	16.3772W
PMOSFET×4	32.3242W

A fast recovery diode was used as the main diode. The reverse recovery current is almost zero. Thus, although the fsw is increased, the switching loss is not increased. The power loss of the diode (PDIODE) consists of the reverse recovery loss (Ptrr(DIODE)) and the conduction loss (PCOND(DIODE)).

Table 4. Power Loss Of Diodes Of Multi Device Interleaved Boost Converter

POWER LOSS PARAMETER	VALUE
(Ptrr) *4	0 W
(PRD)*4	84.8mW
(PVF)*4	1.79876W
(PSW(DIODE))*4	1.08W
(PCOND(DIODE)) *4	4.2W
PM DIODE	7.16356W

The power losses of the main inductor (PML) consist of the core losses (PMfe) and the copper losses (PMcu).

Table 5. Power Loss of Main Inductor

INDUCTOR POWER LOSS	VALUE
(PMfe)×2	0.0594W
(PMcu)×2	6.114W

Therefore, the total loss of main inductor is found to be PML = 6.1734 W. Hence the power loss of interleaved boost converter and multi device interleaved boost converter are calculated and tabulated as shown in Table 6.

Table 6. Comparison of power loss between IBC and MDIBC

DEVICES	IBC	MDIBC
MOSFET	38.1815W	32.3252W
DIODES	7.01844W	7.16356W
INDUCTORS	6.539W	6.539W
TOTAL	51.7389W	46.0298W

From the above table, it is obvious that the power loss for multi device interleaved boost converter are less than the conventional IBC. Hence multi device interleaved boost converter is implemented for practical purposes.

5. HARDWARE IMPLEMENTATION

The hardware implementation of Multidevice interleaved boost converter basically consists of power supply circuit, gating circuit and the proposed interleaved boost converter. The power supply to the 4N35 optocoupler is supplied by developing a power supply board consisting of 12V, 1mA transformer, Bridge rectifier and a 12V regulator. To reduce the switching losses [12], IRFP460 power MOSFET is employed as the main switch and FR-107 is used as freewheeling diodes. The gating pulses are generated by PIC controller 18F4550 and given as input to optocoupler. The pulse generation from PIC circuit for firing MDIBC switches is shown in Figure 8.

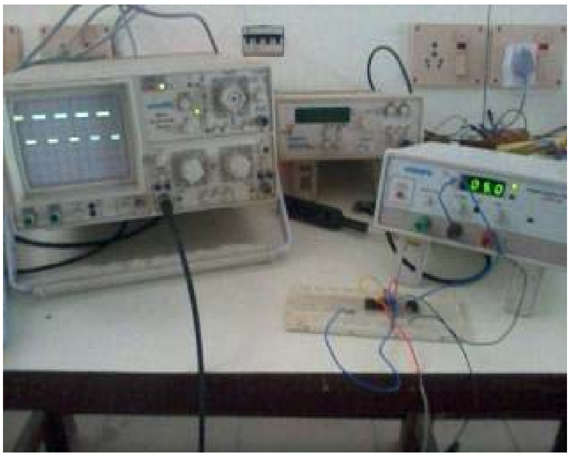

Figure 7. Output obtained from PIC circuit for firing MDIBC

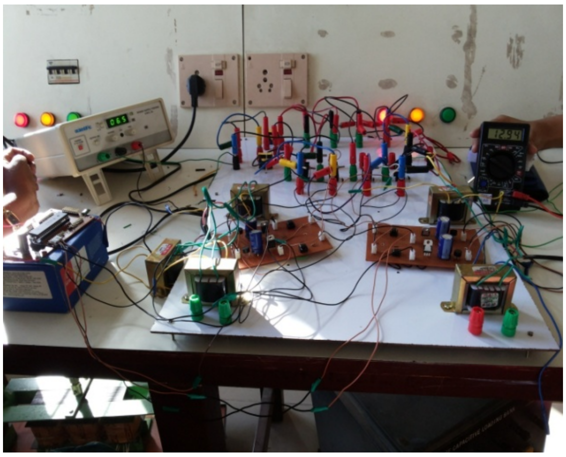

Figure 8. A Prototype of Multi device Interleaved Boost converter with optocouplers and PIC circuit

Figure 8 shows that for an input voltage of 6.5V, an output of 12.94V is obtained as per the design and the simulation results are verified. Figure 9 shows the output voltage of 11.42V for an input of 6.12V measured using PQ analyzer.

Figure 9. Output voltage of MDIBC measured using PQ analyzer

6. CONCLUSION

In this paper, a novel Multi Device Interleaved Boost Converter has been designed for fuel cell applications. The simulation and experimental results have demonstrated that the inductor size and the capacitor size of the MDIBC are reduced by two times compared to the conventional IBC. Moreover, the current and voltage ripples are reduced by two times compared with the IBC topology. The power losses of the proposed boost converter have been analyzed and the results were tabulated. The power loss results shows that switching and conduction losses are less for MDIBC compared to the conventional IBC. The maximum efficiency of the proposed interleaved converter is found to be 96.4%. Therefore, the proposed converter seems to be very promising for high-power fuel cell systems to extend their lifespan as well as battery systems. It is important to point out that the proposed converter can improve efficiency and reduce the size of the passive components, leading to high reliability compared with other dc/dc converter topologies.

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