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Simulation and Implementation of Soft-Switched Interleaved DC-DC Boost Converter for Fuel Cell Systems

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Abstract

In this paper, a soft-switched Interleaved DC-DC Boost Converter (IBC) for fuel cell is simulated and implemented. The proposed two-phase IBC circuit consists of two identical boost converter connected in parallel and are controlled by interleaved switching signals. But in the conventional IBC switching loss increases with the number of switching devices. To solve this problem, this paper has proposed a soft switched IBC. Detailed analysis has been done to investigate the benefits of soft-switched IBC compared to that of conventional uncoupled and directly coupled IBC. The converter circuit is constructed using power MOSFET as power switch. The PWM is generated by PIC18F4450 microcontroller. In this paper, the analysis of the converter is presented which is verified by the results of simulation and experimentation.

Keywords: *soft-switching, IBC, PWM*

1. Introduction

For designing high efficiency fuel cell power systems, a suitable DC-DC converter is required. Among the various topologies, IBC is considered as a better solution for fuel cell systems, due to improved electrical performance, reduced weight and size [1,2 & 3]. However, the switching loss of an IBC increases with the number of switching devices. To overcome this, soft-switching is adopted. This paper utilizes two phase IBC since the ripple content reduces with increase in the number of phases. The proposed converter can reduce the switching loss because the switches are turned on and off with Zero Current Switching (ZCS) and Zero Voltage Switching (ZVS) respectively [4]. Mathematical analysis of overall current ripple and the design equations for soft-switched IBC has been presented. The proposed IBC is compared with the conventional IBC. Hardware prototype has been built to validate the results.

2. Soft-Switched Interleaved Boost Converter

In order to improve the efficiency of the proposed converter, a two-phase interleaved boost converter integrated with soft switch cells is used [5]. All the switching devices in the proposed converter achieve ZVS and ZCS. The converter has a high efficiency characteristic due to low switching losses. It has the advantage of both interleaving topology and soft switching strategy. Figure 1. shows the circuit diagram of two-phase soft-switched IBC. The design equations of soft switched IBC are presented in this section. IBC design involves the selection of the number of phases, the inductors, the output capacitor, power switches and the output diodes. Both the inductors and diodes should be identical in all the channels of an interleaved design. In order to select these components, it is necessary to know the duty cycle range and peak currents [6, 7].

Since the output power is channeled through ‘n’ power paths where ‘n’ is the number of phases, a good starting point is to design the power path components using 1/n times the output power. Basically, the design starts with a single boost converter operating at 1/n times the power. The design procedure is as follows [8,9]:

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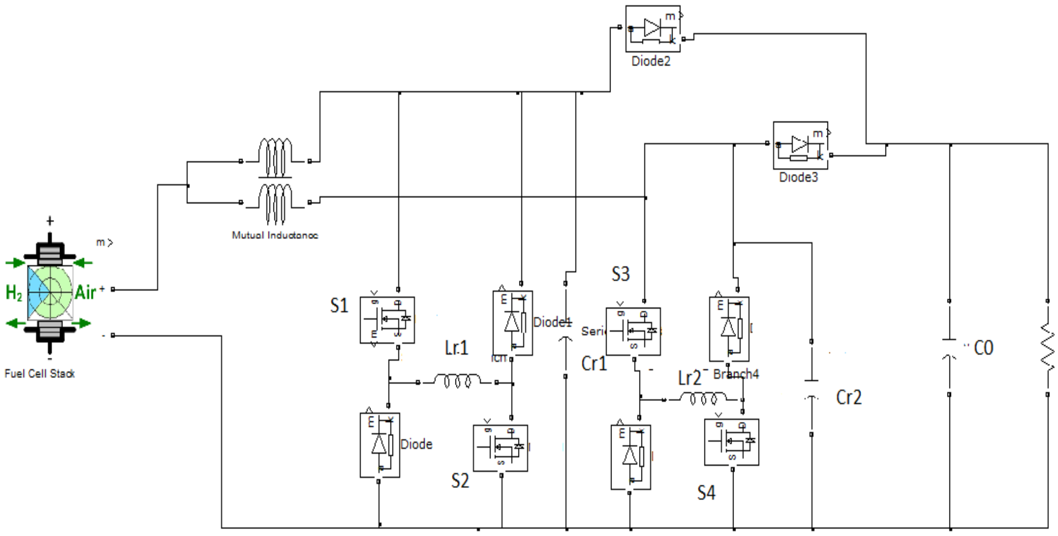


Figure 1. Soft Switched Two-phase Interleaved Boost Converter

A. Choosing the number of phases

A two-phase IBC has been chosen for this work as the ripple reduces to 12% compared to a conventional boost converter If the number of phases is increased further, without much decrease in ripple content, the complexity of the circuit increases thereby increasing the implementation cost. Hence, as a tradeoff between the ripple content, cost and complexity, the number of phases is chosen as two [10]. The number of inductors, switches and diodes are same as the number of phases and switching frequency is same for all the switches.

B. Selection of Duty Ratio

The decision of duty cycle is based on the number of phases. This is because depending upon the number of phases, the ripple is minimum at a certain duty ratio. For two-phase IBC, the duty ratio value is chosen as 0.45 as the ripple is minimum at this value.

C. Selection of Capacitance

The selection of capacitance is done using the formulae [10,11].

$$C = VoDF/R\Delta Vo \qquad (1)$$

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

D. Selection of Inductance

The coupled inductor is designed with a single pair of ferrite EE core. The design specifications required for the core are obtained using the software by the micro metals corporation. The minimum equivalent inductance L_{eq} is calculated as [12,13]

$$L_{eq} = \frac{Vin\,DT}{\Delta I_{phase}} \qquad (2)$$

with a coupling coefficient of 0.61, the minimum self –inductance of the coupled inductor is found as

$$L = \frac{1+\alpha\frac{D}{1-D}}{1+\alpha-2\,\alpha^{2}}L_{eq} \qquad (3)$$

The value of the mutual inductance (L_m) and leakage inductance L_k is calculated as

$$L_m = \alpha.L \tag{4}$$

$$L_k = (1-\alpha)L \tag{5}$$

Using equations (1) to (5), the inductance value is calculated.

E. Selection of Power Devices

The power devices chosen for constructing the proposed IBC are IRFP460 MOSFET and fast recovery diode. The maximum voltage across the switching devices is given by

$$Vs_1, s_2 = V_{in} \frac{1}{1-D} \tag{6}$$

where V_{in} is the input voltage, D is the duty ratio of the converter.

3. Simulation Results

Two-phase soft-switched IBC with fuel cell as power source is simulated in MATLAB with the parameters as shown in Table-I. Figure 2 shows the gating signals, voltage waveforms and inductor current waveforms of IBC.

Table 1. Simulation Parameters for 2-phase soft- switched IBC

Parameters	Values
Input Voltage (PEM fuel cell)	29.15 V
Output Voltage	56.53V
Switching Frequency	10kHz
Duty Ratio	0.45
Inductance, L	7.95mH
Coupling coefficient	0.61
Mutual Inductance	4.85mH
Resonant Inductor (Lr)	40uH
Capacitance	2000uF
Resonant Capacitor (Cr)	20nF

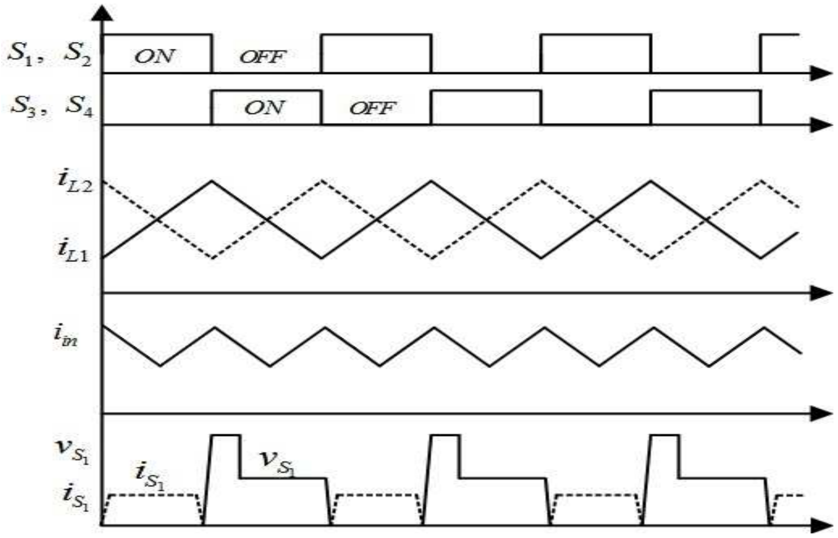


Figure 2. Switching pattern, current and voltage waveforms of IBC

The fuel cell output is given to two phase interleaved boost converter with coupled inductors. The gating pulses are phase shifted by 180 degrees. The output is given to resistive load. Filter capacitor is included to reduce the output ripple. Figs. 3& 4 gives the simulated output voltage and input current ripple of soft -switched IBC interfaced with fuel cells.

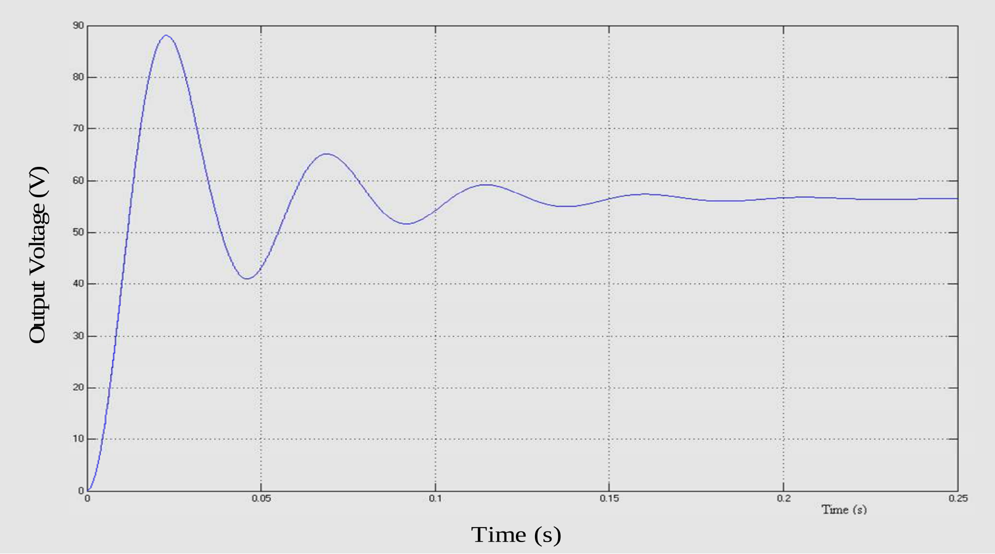


Figure 3. Output voltage of IBC with coupled inductors and soft switch interfaced with FC

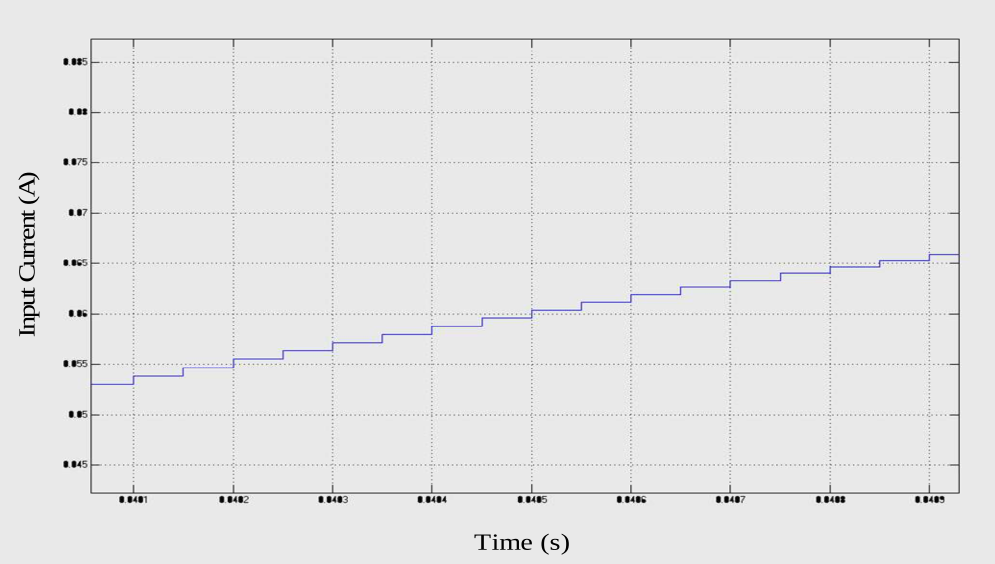


Figure 4 Input current ripple of IBC with coupled inductors and soft switch interfaced with FC

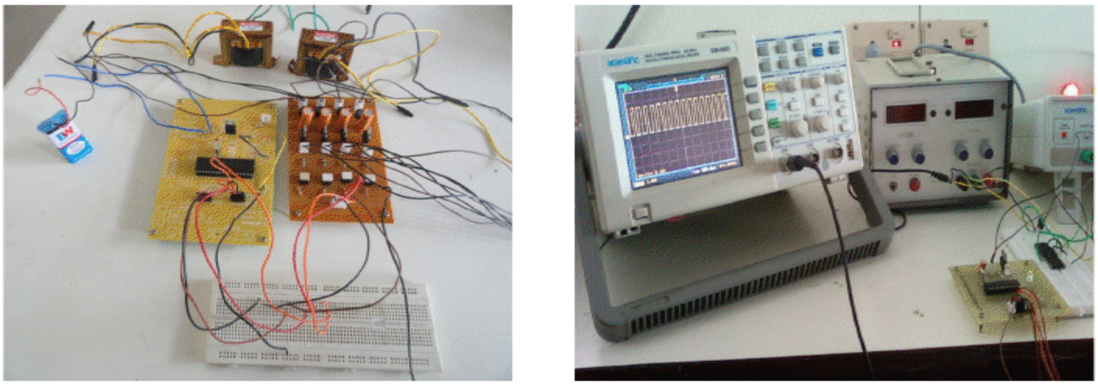
The ripple content of output voltage, input current and inductor current are calculated for IBC with uncoupled inductors, coupled inductors and for IBC with coupled inductors with soft switching and the results are compared. The comparisons are shown in Table 2. From Table 2, it is found that the soft switched IBC gives a reduced current ripple compared to conventional uncoupled and directly coupled IBC. Therefore, soft switched IBC is highly suited for fuel cell applications.

Table 2. Simulation Results

Parameters	Uncoupled IBC (%)	Coupled IBC (%)	Soft switch based IBC (%)
Input current ripple	5.17×10^{-3}	3.49×10^{-3}	3.3×10^{-4}
Inductor current ripple	5.30×10^{-3}	1.72×10^{-3}	5.734×10^{-4}
Output voltage ripple	3.53×10^{-3}	1.32×10^{-3}	3.53×10^{-3}

4. Experimental Results

The prototype of soft switch based two-phase IBC circuit has been developed in which the inductors are wound in a Ferrite EE core. The diode is a fast recovery diode. Heat sinks are attached to each of the four IRFP460 MOSFET switches and the PIC microcontroller has been used for generating pulses. The power supply and pulse generation circuit is shown in Figure 5. Figure 6 shows the hardware circuit for soft-switched IBC.



1.Power supply circuit:

2. Pulse generation using PIC

Figure 5. Power supply and pulse generation circuit for soft-switched IBC

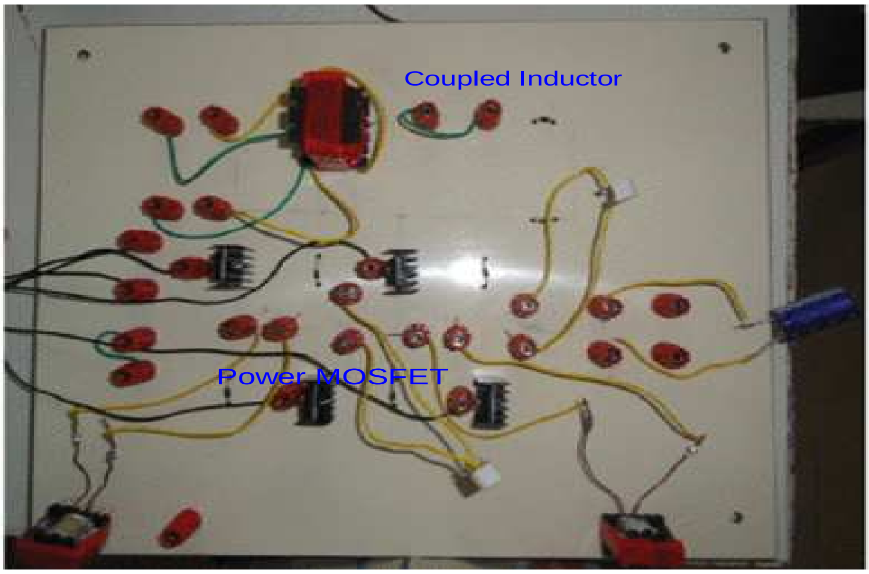
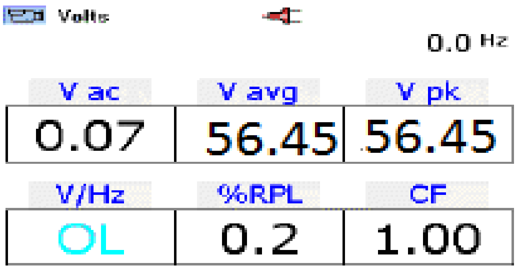


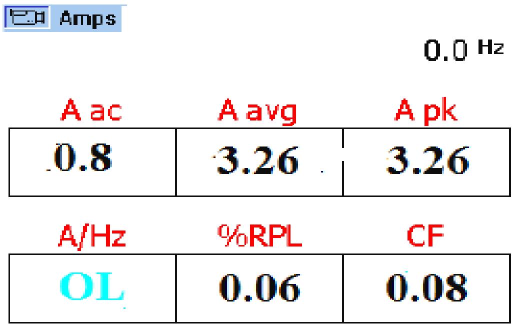
Figure 6 Soft- switched Two-phase Interleaved Boost Converter circuit

The experimental results for the output voltage ripple and input current ripple of soft-switched IBC is shown in Figures 7 and 8.



V ac	V avg	V pk
0.07	56.45	56.45
V/Hz	**%RPL**	**CF**
OL	0.2	1.00

Figure 7 Output voltage ripple for Soft-switched IBC



A ac	A avg	A pk
0.8	3.26	3.26
A/Hz	**%RPL**	**CF**
OL	0.06	0.08

Figure 8 Input current ripple of soft-switched IBC

5. Conclusion

This paper has presented the significance of soft-switching in interleaved DC-DC boost converter. Simulation studies has been carried out using MATLAB/SIMULINK for the proposed IBC to analyze the current ripple characteristics .It is found that soft-switched coupled IBC gives a reduce current ripple compared to the conventional one. A prototype of two-phase soft-switched IBC has been built and the simulation results have been verified experimentally. Therefore, from the results, soft-switched IBC proves to be a promising topology for fuel cell applications.

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