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Design and Simulation of Fuel Cell Based Interleaved Boost Converter for Vehicular Application

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Abstract— **This paper presents design and simulation three-phase interleaved boost converter suitable for fuel cell used in electrical vehicle. The interleaved boost converter (IBC) serve several applications which require boost in output voltage such as fuel cells, photovoltaic cells and batteries etc., Because it has advantages of related to the conventional boost converter are low input current ripple, high efficiency, faster transient response, reduced electromagnetic emission and improved reliability. The multiphase boost topology comprises parallel combination of a number of boost converters with same phase shift and switching frequency. The waveforms of input, inductor current ripple and output voltage ripple are achieved using MATLAB / SIMULINK.**

Keywords— **Interleaved boost converter (IBC), fuel cell, Electrical Vehicle.**

I. INTRODUCTION

Fuel cells have recently become more and more alluring for power generating in both stationary and embarked applications. Among the existing technologies, we can mention the proton exchange membrane fuel cell known as the Proton Exchange Membrane Fuel Cell (PEMFC), they are considered as the most encouraging technologies for power generating in automotive applications thanks to a high energy density and a low functioning temperature and enable easily speedy start [1] [2]. However, some issues are still arising mainly because of the low voltage produced at the fuel cell output. Subsequently, a DC / DC converter becomes essential to rise up this voltage to the suitable level of the DC bus voltage [3]. BOOST DC-to-DC converters have very good source interface properties. The input inductor makes the source current smooth and hence these converters provide very good EMI performance. On account of this good property, the boost converter is also the preferred converter for off-line unity-power-factor (UPF) rectifiers. One of the issues of concern in these converters is the large size of the storage capacitor on the dc link. The boost converter suffers from the disadvantage of discontinuous current injected to the load. The size of the capacitor is therefore large. Further, the ripple current in the capacitor is as much as the load current; hence the Externally Supported Roof (ESR) specification of the tank capacitor is quite demanding. This is especially so in the emerging application areas of automotive power conversion, where the input voltage is low (typically 30V) and large voltage boost (4 to 5 times) are desired [4]. To be so optimal, the DC / DC converters have to meet many requirements in fuel cell electric vehicle applications, namely:

1) Low mass and small volume;
2) High energy efficiency;
3) High power density;
4) Low cost;
5) Low electromagnetic disturbance (perturbation);
6) Reduced current ripple in order to lengthen the life of the fuel cell.

The poly-phase operation of boost converter to overcome the disadvantages of large size storage capacitor in boost converter and off-line UPF rectifiers and a small signal analysis of N converters in parallel to an equivalent second order system in such converters. In designing DC converters, parameters such as ratio of energy stored in inductor and capacitor to energy delivered to load in one period, maximum current in the switch and the value of the RMS current in the output capacitor have great importance. Analysis of N converters in parallel to an equivalent second order system in such converters. In designing DC converters, parameters such as ratio of energy stored in inductor and capacitor to energy delivered to load in one period, maximum current in the switch and the value of the RMS current in the output capacitor have great importance. [4]

The interleaved boost converter has high voltage step up, reduced output voltage ripple, low switching loss, faster transient response. Also, the steady-state voltage ripples at the output capacitors of IBC are reduced.

Although IBC topology has more inductors increasing the complexity of the converter correlated to the classical boost

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converter it is chosen because of the low ripple content in the input and output sides. [1] [5] [6]

One such invention is the Interleaved Boost Converter (IBC) that has the boost and current sharing capability on high power application. It can be configured with many phases that allow the input current sharing and heat dissipation. Even though there are a number of DC boost converters that are available for the fuel cell applications, they have objectionable level of ripples. In addition to the minimization of the ripples, it has higher modularity, reliability and power capability at the cost of additional inductors, diodes and switching devices. In this paper, the three phase IBC can be used so as to get reduced current ripple that comes out of the fuel cell. [7] [8] [9]

Additional components such as inductors, diodes and power switching devices are needed for interleaving thereby increasing the cost of the system; however, the power converter's efficiency, size, electromagnetic emission and transient response are improved [4]. The interleaved boost converter is suitable for high power applications due to ripple cancellation in the input current and the output voltage greatly reducing the switching losses, size and losses of the output filter. Power electronic converters such as the boost, buck-boost series resonant full bridge and push pull converters are not efficient because they add high input current ripples to the current flowing out of renewable energy sources such as fuel cells. [7] [10]

Furthermore, for high-power applications, multiphase interleaved converters have been proposed for use in electric vehicle applications. [11] [12]

The fuel cell hybrid electric vehicle (FCHEV), as shown in Fig.1, utilizes an FC (fuel cell) as the main power source and the ESS (e.g., batteries and super capacitors) as the auxiliary power source to assist the propulsion of the vehicle during transients and to recuperate energy during regenerative braking. In this configuration, the FC is connected to the dc bus through a boost converter, whereas the ESS is connected to the dc bus via a bidirectional dc/dc converter. [3] [7]

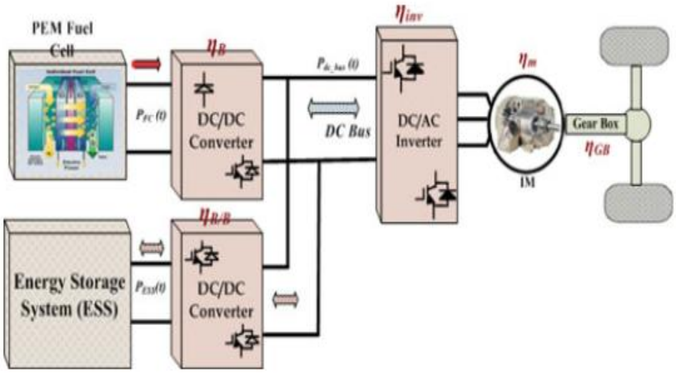

Fig. 1: Electrical vehicle structure

Actually, this paper is organized as the followings. Section 2 is devoted for a detailed description of the interleaved boost converter. In Section 3, we present the dynamic model of the fuel cell. While the design of the DC-DC converter is introduced in section 4. Eventually, the simulation results based on the interleaved boost converter for high-voltage application are described in section 5. The final part is dedicated to the paper conclusion.

II. INTERLIVED BOOST CONVERTER

A. Boost Converter

A boost converter (step-up converter) is a power converter with an output DC voltage greater than its input DC voltage. It is a class of switching-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple.

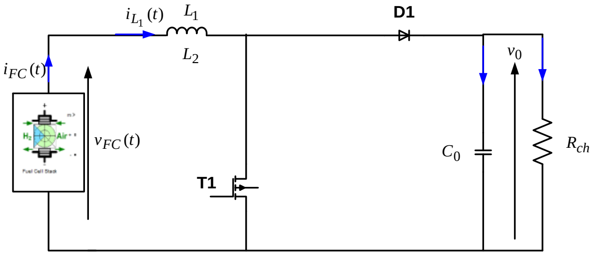

Fig. 2: Basic boost Converter

The circuit that models the basic operation of the boost converter is shown in Fig. 1. The input voltage in series with the inductor acts as a current source. The energy stored in the inductor builds up when the switch is closed. When the switch is opened, current continues to flow through the inductor to the load. Since the source and the discharging inductor are both providing energy with the switch open, the effect is to boost the voltage across the load. The load consists of a resistor in parallel with a filter capacitor. The capacitor voltage is larger than the input voltage. The capacitor is large to keep a constant output voltage and acts to reduce the ripple in the output voltage.

B. Need for Poly Phase Operation

In designing DC converters, parameters such as ratio of energy stored in inductor and capacitor to energy delivered to load in one period, maximum current in the switch and the value of the RMS current in the output capacitor have great importance and it is necessary to be considered.

One-way of reducing the storage requirement is increasing the switching frequency however this is not practicable in all instances. During the on state of the switch, the capacitor has to supply the entire load current in the boost converter; this discontinuity of current in the capacitor increases the RMS value of current and also increases the amount of capacitor which is needed to keep the ripple voltage low. The power dissipation in the ESR of the capacitor is also high. In standard designs it is not uncommon to see tank capacitors one or two orders of magnitude higher than the ideally required capacitance A way to overcome this problem is using poly-phase operation with appropriate phase shift in the control circuit of main switches.

C. Proposed Converter

Fig. 2 shows the basic 3-phase boost converter. One advantage that is evident from the figure is that the multiphase configuration allows the combination of output capacitor from each individual boost into just a single capacitor C0. Due to the frequency multiplication property of the multiphase, the output voltage will actually have ripple component three ice the operating switching frequency of each individual boost converter. This may further reduce the output filtering requirement. The frequency multiplication effect also occurs at the input side of the boost and hence reducing the input filtering requirement as well as improving the quality of the input current. In turns, three input and output sides of the multiphase boost will emit less dv/dt and di/dt noises back to the system connected to them. The control switching is adjusted by Ts/3 where is the switching period. Fig. 3 shows the operation converter C1, C2 and C3 denotes respectively the controls signal of the MOSFETs T1, T2 and T3. d denotes the controlled duty ratio.

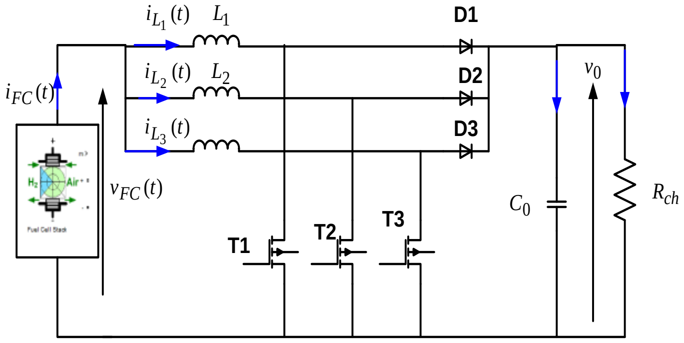

Fig. 2 Multiphase boost topology

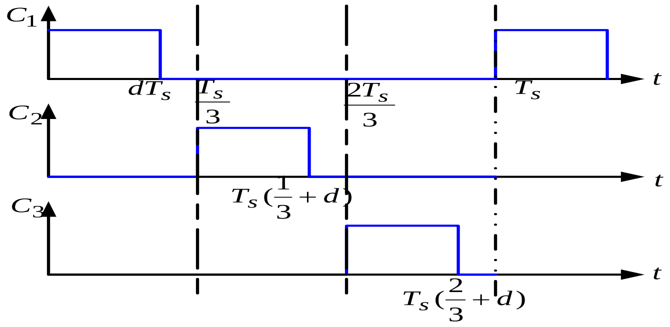

Fig. 3 Control signals

III. DYNAMIC MODELING OF FUEL CELL

A fuel cell is an energy conversion system that converts chemical energy into electrical energy without any thermal or mechanical process. The operating principle of a fuel cell is described by a chemical reaction that reacted hydrogen and oxygen to produce electricity, heat and water, according to the chemical reaction given by equation (1)

$$\begin{cases} 2H_2 \rightarrow 4H^+ + 4e^- \\ O_2 + 4H^+ + e^- \rightarrow 2H_2O \\ 2H_2 + O_2 \rightarrow 2H_2O + electricity + heat \end{cases} \tag{1}$$

There are many fuel cell models; each model has its own specificities and benefits, according to the phenomena studied. The chosen model should be simple and accurate.

Indeed, this work presents an electrochemical model which can be used to predict the fuel cell behavior in static and dynamic conditions. [7]

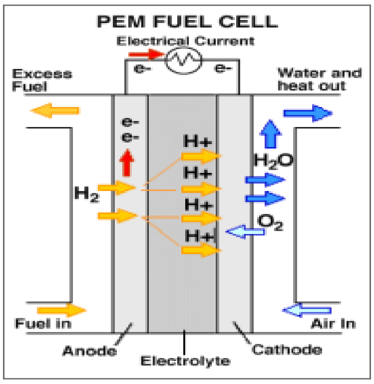

Fig. 4 Illustration of a typical fuel cell structure

The fuel cell voltage depends on the partial pressures of hydrogen and oxygen, the chemical reaction temperature of the membrane hydration and the output current. It is defined by the following equation.

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohm} - V_{con} \tag{2}$$

Where:

$$E_{Nernst} = 1.229 + \frac{RT}{n_e F} ln\left(\frac{PH_2 \sqrt{PO_2}}{PH_2O} \right) \tag{3}$$

$$\Delta V_{Act} = \frac{RT}{n_e F} ln\left(\frac{i_{FC}}{i_0} \right) \tag{4}$$

$$\Delta V_{Ohm} = R_{FC} i_{FC} \tag{5}$$

$$\Delta V_{Con} = -\frac{RT}{\alpha n_e F} ln\left(1 - \frac{i_{FC}}{i_l} \right) \tag{6}$$

E_{Nernst}: the average thermodynamic potential of each unit cell.

V_{Act}: the activation voltage drop.
V_{Ohm}: the Ohmic voltage drop.
V_{Con}: the concentration voltage drop.

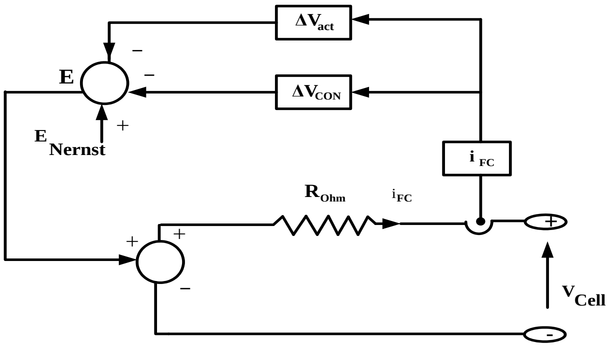

Fig. 5 The electrical model of a fuel cell

The polarization curve of a fuel cell is that which represents the battery voltage as a function of current output. This curve is presented for different temperature values. Fuel cell polarization curves increase with increasing of operating temperature such as shown in Fig. 6.

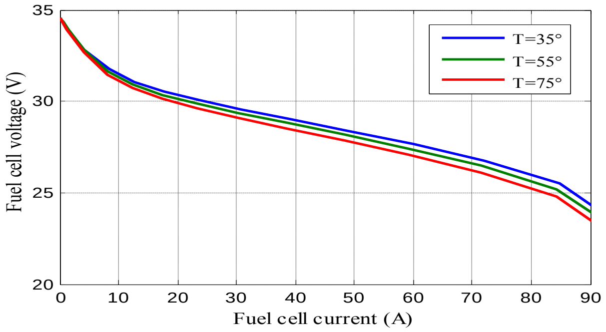

Fig. 6 Polarization curve at different temperatures.

IV. DESIGN OF INTERLIVED BOOST CONVERTER

In this paragraph, a design procedure uses the schematic diagram in Fig. 2 as a reference. While the interleaved boost converter with 100V/1000W output has been selected as a design example, the design specifications are listed in the following table.

TABLE I. IBC SPECIFICATIONS

Parameters		Values
Input voltage	V_e	30V
Output voltage	V_0	100V
Output power	**P**	1000W
Switching frequency	f_s	10Khz

The proposed design procedure can be outlined in the followings steps:

- Selection of inductor values
- Decision of duty ratio
- Design of output filter

Step 1: Determine the inductance value

The interlacing concept does not only permit to increase the current ripple at each phase but also to decrease the inductance value and volume. In fact, decreasing both the inductance value and the current results in the reduction of the volume, the weight, the cost and the maximum of stored energy.The inductance value is given as:

$$L = \frac{V_{FC} D}{\Delta i_0 f_s} \tag{7}$$

Where D is the duty ratio of the converter. In addition, the value of L was determined at the nominal voltage (Vfc = 30V) of the fuel cell and for a switching frequency (fs = 10 kHz). In order to guarantee a conduction mode Continuous, the current ripple in a phase inductance must satisfy the following condition:

$$\Delta i_L \leq \frac{i_{FC}}{N} \tag{8}$$

Where N is the phase number of the converter. The ripple in a phase inductance, Δi_L is given by the following expression:

$$\Delta i_L = \frac{V_0 D (1-D)}{L f_s} \tag{9}$$

Step 2: selection of duty ratio and number of phases

For a specific input and output voltages and power rating of the converter, the duty ratio is calculated as

$$D = \frac{V_0 - V_{FC}}{V_0} \tag{10}$$

Therefore, the duty ratio is chosen as 0.7 and the number of phases for IBC as three so as get reduced input current ripple and keep the inductor current ripple and inversely coupled inductor, the current ripple is reduced for directly coupled interleaved boost converter.

Step 3: A capacitor filter is needed at the output to limit the peak to peak ripple of the output voltage. The capacitance of the output filter is function of the duty cycle, frequency and minimum load resistance during maximum load. The value of the capacitance is given by the formula:

$$C = \frac{V_0 D}{R f_s \Delta V_0} \tag{11}$$

Using the above equations, the values of the components interleaved boost converter are:

$$\begin{cases} L_1 = L_2 = L_3 = 2.1mH \\ C = 350\ \mu F \end{cases}$$

VI. SIMULATION RESULTS

Simulation studies are carried out using MATLAB/SIMULINK and the simulation circuit of interleaved boost converter for an input of 30V is shown in Fig. 2.

The proposed converter necessities a phase-shift of 120° between the cells to generate the three-switching control signal which are used to drive the three active IGBT switching devices of the converter system. Fig. 7 shows the three phase control signal waveforms respectively C1, C2 and C3.

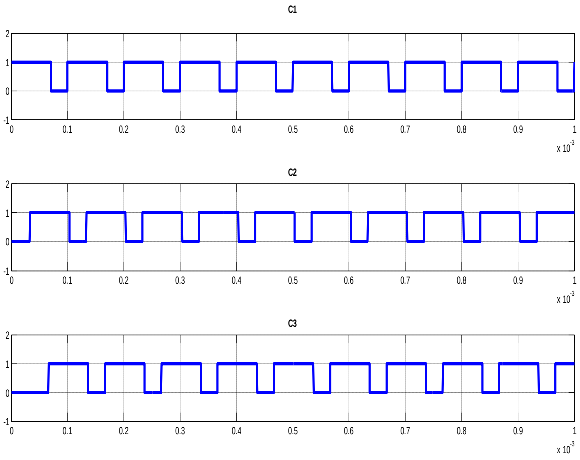

Fig. 7 Driving pulse of switches T1, T2 and T3 wavefroms

Fig. 8 shows the currents flowing through the inductors (L1, L2 and L3). The shape shows the ripple of the inductor current is equal to 1.35A.

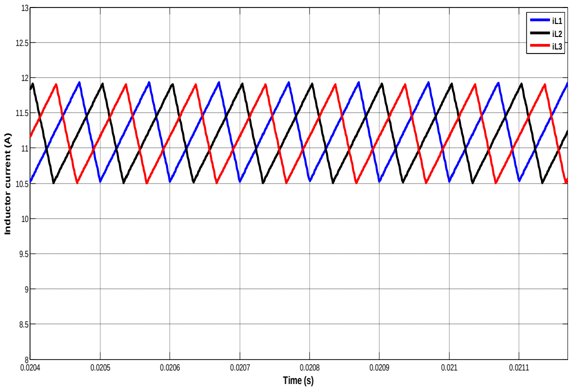

Fig. 8 Inductor currents ripples IBC

It can be seen from Fig. 9 and Fig. 10 that the ripple of output voltage for boost converter is 6.4V and ripple of output voltage for interleaved boost converter is 0.35V.

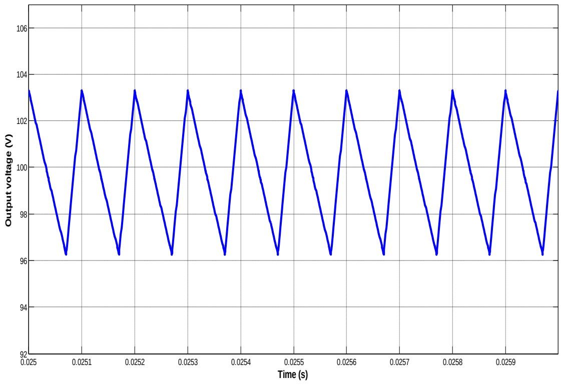

Fig. 9 Output voltages ripples of the BC

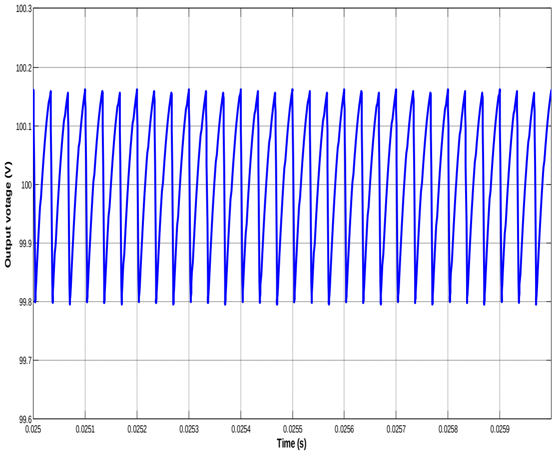

Fig. 10 Output voltages ripples of the IBC

Fig. 11 and Fig. 12 show that the ripple of output current for boost converter is 0.66A and ripple of output current for interleaved boost converter is 0.035A.

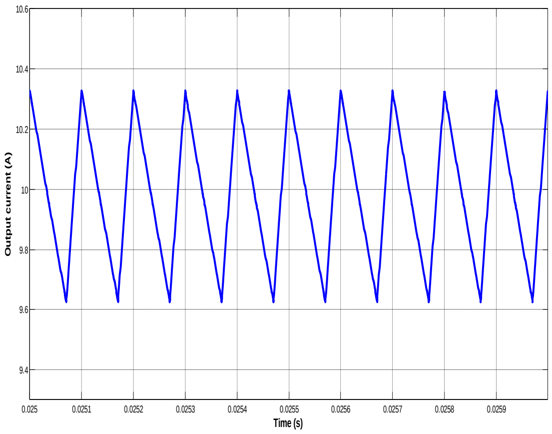

Fig. 11 Output current ripples of the BC

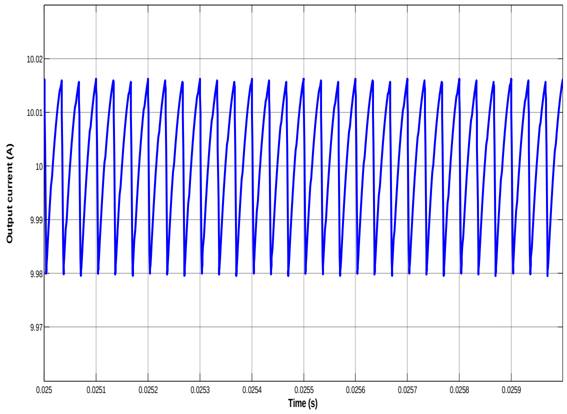

Fig. 12 Output current ripples of the IBC

VII. CONCLUSION

In this paper, analysis, design and simulation of 30V/100V interleaved three-phase dc/dc boost converter system with one kilowatt output power is presented. This system is a part of the dual voltage architecture that will be used in future passenger car power system. Based on the simulation results, the performance of the dc-to-dc boost converter system provides a number of features that do not exist in today's electrical systems. All the advantages of interleaving, such as higher efficiency and reduced input and output ripple for voltage/current, are also Achieved in the proposed boost converter.

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