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An interleaved, FPGA-controlled, multi-phase and multi-switch synchronous boost converter for fuel cell applications

*Fernando Sobrino-Manzanares, Ausias Garrigós**

Industrial Electronics Group, University Miguel Hernández, 03202 Elche, Alicante, Spain

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form
9 July 2015
Accepted 15 July 2015
Available online xxx

Keywords:
Multi-phase
Multi-switch
Boost converter
Interleaving
FPGA
Fuel cell

ABSTRACT

This work describes the practical implementation of an interleaved multi-phase, multi-switch boost converter for fuel cell applications. The paper aims to validate the concept of digitally-controlled Multi-Interleaving Boost Converter (MIBC) for fuel cell applications, from two-phase, four-legs per phase, synchronous boost converter, abbreviated as 2-4-MIBC. Compared with the Interleaved Boost Converter (IBC), MIBC exhibits interesting performance in terms of magnetics, input and output current ripple, part count and distributed power losses. A potential field of application is indeed medium and higher power fuel cell front-end converters, where minimizing input current ripple is significant but also redundancy and reliability are crucial. Actually, this approach covers all these aspects since provide module and device redundancy with real-time and flexible digital control reconfiguration. Relevant aspects related to design, modeling, simulation and experimental verification of 1 kW, FPGA-controlled, 2-4-MIBC are treated in this paper.

Introduction

In the range from few hundred watts to several kilowatts, fuel cell (FC) stacks and modules are generally sized up to 100 V DC and 500 A DC [1–3,25]. Hence, modular power processing is usually considered to accommodate different power levels from the same power converter basis. Some major advantages of this approach include reusability, expandability, power loss distribution, standardization, flexibility and redundancy [4,5].

Among different options available, the Interleaved Boost Converter (IBC) is a common choice for FC front-end power conditioning [6–9], because its simplicity, high efficiency, step-up voltage ratio, low input current ripple, modularity, good dynamic response and redundancy.

Recently, the Multi-Interleaving Boost Converter (MIBC), as shown in Fig. 1, has also been proposed as an alternative to IBC to optimize fuel cell converter performance [10,11,26]. The underlying idea of the MIBC is to create a two-level interleaved structure by two different means, sequentially operation of the power switches within the power converter module (phase) and interleaving operation of different phases. At module (phase) level, Distributed Driving Scheme (DDS) [11] performs sequential operation of the m half-bridge legs, as depicted in Fig. 2. Considering this multi-switch driving pattern, inductor frequency is m times higher than switching

* *Corresponding author*. Industrial Electronics Group, Dpt. Materials Science, Optics and Electronics Technology, Building "Torrevaillo", 1D6, University Miguel Hernandez, Av. Universidad s/n, 03202 Elche, Spain. Tel.: +34 96 665 8892; fax: +34 96 665 8497.
E-mail address: augarsir@umh.es (A. Garrigós).

http://dx.doi.org/10.1016/j.ijhydene.2015.07.078
0360-3199/

Nomenclature

CCM	continuous conduction mode
DCM	discontinuous conduction mode
DDS	distributed driving scheme
ESR	equivalent series resistance (capacitor)
FC	fuel cell
IBC	interleaved boost converter
MIBC	multi-interleaved boost converter
PWM	pulse width modulation

frequency. As a result, the number of half-bridge legs becomes an important variable and adds a new degree of freedom for the converter design process. Other interesting features of this multi-switch approach include enhanced current capabilities, power losses distribution and elimination of switch current sharing issues. Since there is only one power semiconductor conducting at a given time, switch current sharing problems are avoided [12–14] and thermal management alleviated by proper selection of the number of half-bridge legs. Using this power conversion technique, there are two ways to reduce input current ripple, at module level, inductor ripple is driven by the number of legs, switching frequency and inductance value and, on the other hand, input current ripple can be reduced by increasing the number of phases of the converter due to input current cancellation. On account of this, MIBC is an interesting option for medium and high power DC/DC conversion with stringent input/output current ripple and thermal requirements [15–18].

An important difference respect previous multi-phase, multi-switch converters published works [10,11] is the use of bidirectional half-bridge legs, instead of unidirectional boost power cells composed of controlled power switch plus power diode. Bidirectional current capabilities report several benefits. First, bidirectional structures could operate in Continuous Conduction Mode (CCM) or Discontinuous Conduction Mode (DCM) just selecting properly the gate driving scheme. Some authors have employed DCM to eliminate current sensing and inner current control loops [19–21]; however DCM also have some drawbacks mostly due to higher peak inductor current and parasitic ringing; which in turn impacts on converter efficiency and electromagnetic compatibility [22]. Conversely, complementary driving scheme for each half-bridge leg allows CCM operation [23]. In this case, inductor current flows from positive to negative and back forth while the average inductor current sets the average power flow direction. Further, the addition of displaced inductor currents, due to phase interleaving, reduces input current ripple and keeps unidirectional current for an extended range. Apart of eliminating the parasitic ringing issue, CCM operation simplifies control loop design (only CCM model is required) and provides soft-switching transitions for low-side and high-side switches.

An FPGA control system has been devised to implement the Distributed Driving Scheme, the Digital Pulse Width Modulated (DPWM) signals for each power semiconductor and the converter control loops. Some advantages of digitally controlled systems are high-accuracy PWM signal generation (including dead-time generation), reconfigurability, control loop design versatility, noise immunity and system expandability.

To conclude this section, the paper is structured as follows. Introduction is given in Section Introduction; MIBC power section design is covered in Section 2-4-MIBC: power section; converter modeling and control loop design are detailed in Section 2-4-MIBC: converter modeling and control loop design; simulation and experimental validation are given in Section 2-4-MIBC: simulation and experimental validation and conclusions summarized in Section Conclusions.

2-4-MIBC: power section

Since this work aims to validate the MIBC for medium and high power fuel cells, some typical specifications have been considered as baseline for converter design: input voltage range 75–90 V, output voltage 100 V and input current 16 A.

One of the most interesting characteristics of the MIBC converter is that inductor frequency remains higher than

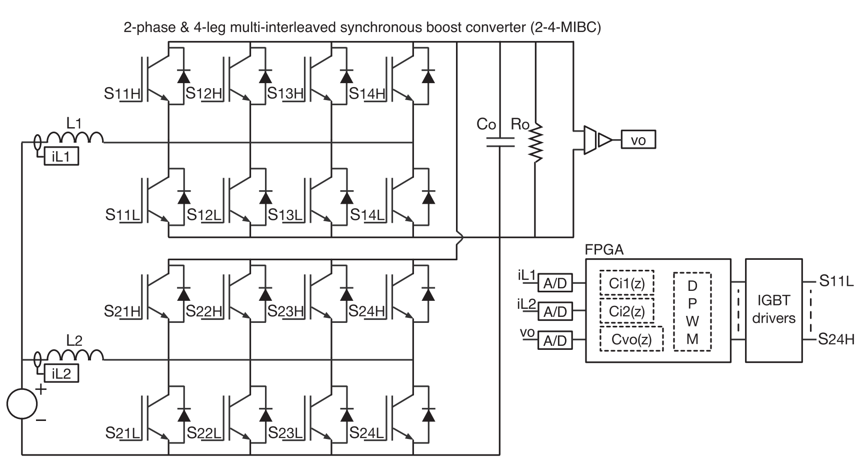

Fig. 1 – Schematic of the proposed 2-phase and 4-leg multi-interleaved synchronous boost converter, named 2-4-MIBC.

Please cite this article in press as: Sobrino-Manzanares F, Garrigós A, An interleaved, FPGA-controlled, multi-phase and multi-switch synchronous boost converter for fuel cell applications, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.07.078