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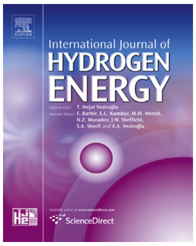

Interleaved multi-phase and multi-switch boost converter for fuel cell applications

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ABSTRACT

This work describes an interleaved multi-phase, multi-switch boost converter for fuel cell applications. Different options of PWM switching patterns are detailed with special emphasis in those that pursue input current ripple minimization and part reduction. The topology studied contains *n* power modules (phases) with *m* switches per module. From the different available configurations, the multi-phase, multi-switch boost converter operating in interleaving mode, so-called multi-interleaved boost converter (MIBC), performs remarkably in terms of magnetics, input and output current ripple and part count. MIBC description, modeling and simulation are provided in this paper. Finally, a comparative trade-off analysis is performed between the interleaved multi-phase, multi-switch boost converter and the traditional interleaved boost converter for a stand-alone, battery backed-up, 1 kW fuel cell power system.

Introduction

Fuel Cells (FCs) are clean power sources which provide a compact and lightweight solution for a large number of applications. Nowadays, they are present for primary or back-up power in industrial [1–4], electrical mobility [5–10], residential [11–14] or portable electronics [15–18] among other applications.

Since FCs are non-regulated Direct Current (DC) power sources, they usually require power electronic interfaces to adapt input–output voltage levels and protect both, the source and the load. This power electronic interface normally has step-up voltage characteristic due to low DC voltage of the fuel cell [19–23].

For low-power FCs, the power electronic interface could be a single converter including two switches (e.g. boost converter). For high power levels a single converter module might be not adequate due to several reasons, e.g. limited current handling capabilities, concentration of losses, thermal management issues and problems associated to magnetic design. Therefore a different approach is required to address this problem. Parallelization of several power switches (multiple-switch approach) is traditionally employed when a single switch is not able to handle the required current. Parallelization of several power modules (multi-module or multi-phase approach) is also a typical solution to alleviate electrical stresses in all components while providing greater modularity. In both cases, power and current sharing are major

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Nomenclature

CCM	continuous conduction mode
DCM	discontinuous conduction mode
DC	direct current
DDS	distributed driving scheme
EMI	electro-magnetic interference
FC	fuel cell
IBC	interleaved boost converter
MIBC	multi-interleaved boost converter
PDS	parallel driving scheme
PFC	power factor correction
PWM	pulse width modulation
SDS	sequential driving scheme
VRM	voltage regulation modules

issues to avoid heat dissipation problems derived from any imbalance.

On top of this, it exists another important concern for FC's converters regarding the input current ripple. As a result of the connection of cascaded DC/DC and DC/AC converters, FC's are subjected to current harmonics in high-frequency (in the kHz range) and low-frequency (in the hundred Hz range) which have an important impact on system performance degradation and reliability [24–26]. To mitigate such effects different investigations are aimed to develop converters with very low input current ripple [27–29]. In this sense, the Interleaved Boost Converter (IBC) is typical choice [30–32] because offers step-up voltage ratio, simplicity, modularity and reduced input current ripple. The selection of the number of phases is a critical aspect during IBC design since impacts directly on magnetics, power semiconductors and associated control circuitry, e.g. current sensors, driving circuits, etc.; which in turn, translates into converter size and cost. Hence, any improvement in this direction would contribute to power converter optimization for fuel cell applications.

In this context, the present paper explores the combined use of multi-phase and multi-switch approach with different Pulse Width Modulation (PWM) switching patterns to optimize the boost converter used as an FC front-end power interface.

The converter described here has been reported previously in the literature [33,34], but in this work the analysis is extended to any number of phases-switches and it quantifies the most important characteristics to assess converter performance and compare with other options.

To conclude this section, the paper is structured as follows. Introduction is given in Section Introduction; multi-switch and multi-phase boost converters are described in Section Multi-switch, multi-phase boost converters; modeling of the proposed converter is covered in Section MIBC converter analysis; converter simulation and comparative study with IBC converter is performed in Section Fuel cell converter simulation: 4-IBC vs 2-2-MIBC, optimization of an existing FC IBC converter [35] is treated in Section Fuel cell converter evaluation: 4-IBC vs 2-2-MIBC and the conclusions summarized in Section Conclusions.

Multi-switch, multi-phase boost converters

Multi-switch boost converters: driving scheme options

An arrangement that comprises several paralleled power switches, please refer to Fig. 1, is normally adopted if the single switch boost converter is not an adequate solution. Reasons to consider such approach are various and include insufficient power switch current handling capabilities, excessive power switch dissipation, complicate thermal management or power switch redundancy. Multi-switch boost converters could admit different driving schemes with different levels of complexity and performance.

Driving all switches simultaneously, here named Parallel Driving Scheme (PDS) please refer to Fig. 2, is probably the most common technique employed because of simplicity, i.e. only one driving signal is required for all switches; but two other driving options can be considered, Sequential Driving Scheme (SDS) and Distributed Driving Scheme (DDS), please refer to Fig. 3 and Fig. 4 respectively. The SDS divides the equivalent ton into m time intervals which drive sequentially each power switch. The PDS is similar to the previous scheme but the equivalent toff is also divided into m intervals. Driving signals sequentially start at $k \cdot Ts/m$, where $k = 1,2,\ldots,(m-1)$.

The main features of driving schemes, divided into pros and cons, are gathered in Table 1. PDS is the easiest way to drive the multi-switch boost but has some limitations concerning current sharing, especially critical for negative temperature coefficient power semiconductors like IGBTs; and to some extent it also applies for positive temperature coefficient power switches like MOSFETs [36–38]. SDS could overcome that issue since only one switch conducts at a given time, but the penalty will be higher peak and RMS currents in the power switches. DDS avoids the problem of current sharing between switches in the same way that SDS, but also modifies the inductor frequency. The latter represents a new design parameter for converter design. For instance, keeping the same switching frequency for all three driving schemes, DDS might offer some advantage in terms of inductor design and input current ripple. Conversely, if the inductor frequency is the same for all three, then switching frequency on DDS has to be reduced, which impacts on switching losses and thermal management.

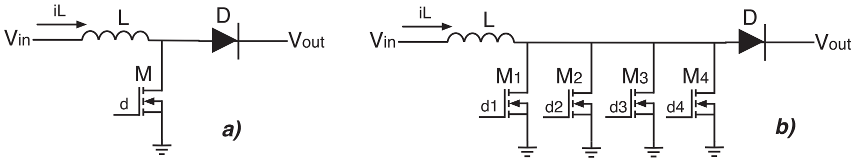

Fig. 1 – a) single-switch boost converter; b) multi-switch boost converter (paralleled switches, m = 4).