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Continuous input-current buck-boost DC-DC converter for PEM fuel cell applications

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ABSTRACT

This paper proposes a buck-boost converter topology with continuous input-current capability for proton exchange fuel cells (PEMFC) systems. The continuous input-current feature of the converter contributes to maintain the PEMFC life-time, which is in sharp contrast with traditional buck-boost converters whose input currents damage the PEMFC and reduce the efficiency. Moreover, this converter offers the main advantages found in traditional topologies, such as the Cuk or the SEPIC converters, using a reduced number of electronic components. In particular, the topology features buck-boost conversion range capability, low input-current ripple, and a simple low-cost structure. A detailed analysis that encompasses steady state analysis, dynamic modelling, stability analysis, control and experimental results are provided.

Introduction

One of the main challenges in the design of power conditioning systems for PEMFCs, consists in achieving a well regulated voltage from a variable one, while draining a non-pulsating current with a small ripple from the voltage sources, e.g. a fuel cell (FC). Traditional technologies of FCs provide DC voltages that vary between 50 and 100% of its nominal value [1,2], which is usually very low; consequently, boost converters are usually implemented. Recently, nominal voltages provided by FCs over 100 V have become very common and such a current trend aims at achieving even higher nominal voltages in the future [1,2]. Hence, buck-boost topologies are required when the input-to-output voltage characteristics of the converter falls short with respect to the required range of operation of the FC generation devices [2,3].

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Traditional buck-boost converter topologies drain a pulsating current from the input power source [4]. This issue induces an accelerated aging rate of the electrodes [5,6]. Usually, power converter topologies with input inductors are used in order to reduce the PEMFCs current ripple, since in this way the inductor provides a trade-off between input current ripple and the converter dynamic response. According to this situation, Cuk and Sepic converters can be used to induce a non-pulsating current from the FC; however, these converters require a higher number of electronic components witch is detrimental for the cost of the implementation [3]. Other topologies that display plausible performance results have been also reported in the literature, see e.g. Refs. [7–9]; however, such configurations also require an increased number of electronic components.

In order to overcome these challenges, we propose the use of a single-inductor continuous input-current buck-boost converter for applications in FCs. It is the only converter found in the literature with a single inductor and capable of either increasing or reducing the input voltage. This converter has been studied in Refs. [10,11], without addressing and specific application. In this work a DC-DC buck-boost converter topology with continuous input current (CICBB) is applied to a FC generation system, even though it is also suitable for implementations involving photovoltaic cells and electric vehicles (see e.g. Refs. [8,12]).

The main aims of this paper are: *(i)* showing the main features of the continuous input-current buck-boost DC-DC converter topology, such as ripple characteristics and overall steady state analysis; *(ii)* introducing the proposed application in PEMFCs; *(iii)* showing a detailed compendium of experimental results to validate the theoretical analysis; *(iv)* studying the dynamics of the converter for control purposes; *(v)* implementing a current-mode controller for an experimental prototype.

Proposed topology

The proposed continuous input current buck-boost converter is shown in Fig. 1 (b) while the traditional buck-boost converter is depicted in Fig. 1(a).

Though both topologies in Fig. 1 are similar, the converter in Fig. 1(b) has a special capacitor connection that, instead of being grounded, is connected to the positive terminal of the input voltage. When the switch closes the inductor is charged with a positive current (positive with respect to the sign defined in Fig. 1) and when the switch is open, the inductor

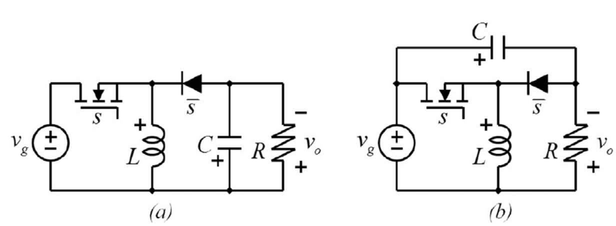

Fig. 1 – (a) Traditional buck-boost converter, (b) Continuous input current buck-boost converter.

current closes the diode in order to charge the capacitor with a positive voltage (with respect to the specified signs). When the switch is closed, the diode is open because of the capacitor terminals coincide with the those of the diode.

Steady state operation in continuous conduction mode (CCM)

Fig. 2 shows the equivalent circuits that correspond to the switching states of the converter, as well as some relevant waveforms in continuous conduction mode (CCM).

By defining D as the duty cycle, which corresponds the portion of time when the switch is closed with respect to the switching period T_s, and by using the *small ripple approximation* [4], the average voltage across the inductor in steady state can be expressed as

$$\langle v_L(t)\rangle := DV_g + (1-D)(V_g - V_c), \tag{1}$$

where the (average) DC component of the voltage across the capacitor and the input voltage are denoted by V_c and V_g respectively. During steady state, the average voltage across the inductor is equal zero, then

$$DV_g + (1-D)(V_g - V_c) = 0 \Rightarrow V_c = V_g\frac{1}{1-D}. \tag{2}$$

Note that the voltage across the capacitor has the same steady state gain as that of the traditional boost converter. However, in this case the output voltage is given by the sum of the capacitor voltage and the input voltage, i.e. the input voltage is in series with the capacitor voltage. Hence, considering the signs defined in Figs. 1 and 2, the output voltage can be expressed as

$$V_o = V_c - V_g = V_g\frac{1}{1-D} - V_g = V_g\frac{D}{1-D}. \tag{3}$$

The continuous input current converter has the same conversion ratio as in the traditional buck-boost converter. The main advantage of the proposed converter can be seen in Figs. 1 and 2, the input voltage is connected to the reference node with the inductor and the load, both the inductor and the load drain a continuous current and then the input current is continuous.

We now derive the DC current through the inductor. By using the small ripple approximation, the average current through the capacitor can be expressed as

$$\begin{aligned}\langle i_C(t)\rangle &:= D\left(-\frac{V_c - V_g}{R}\right) + (1-D)\left(I_L - \frac{V_c - V_g}{R}\right)\\ &= -\frac{V_c - V_g}{R} + (1-D)I_L.\end{aligned} \tag{4}$$

where I_L denotes the current through the inductor. During the steady state, the average current through the capacitor is equal zero, then the current through the inductor can be expressed as

$$I_L = \frac{V_c - V_g}{(1-D)R}. \tag{5}$$

By substituting (2) in (5) the DC current through the inductor is expressed as

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