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An interleaved step-up/step-down converter for fuel cell vehicle applications

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ABSTRACT

Fuel cells have received considerable attention as one of the most promising candidates for green power sources in vehicles. The voltages of fuel cells vary widely depending on the operating conditions. Furthermore, the output power of the fuel cell in a vehicular powertrain should be controlled in accordance with some energy management strategies. For these reasons, the fuel cell must be interfaced with other components by means of a DC/DC converter in fuel cell vehicle applications. A step-up/step-down converter for fuel cell vehicle applications, which effectively operates in step-up or step-down mode when the fuel cell voltage is lower or higher than the output voltage of high-voltage direct current bus, is proposed in this paper. To reduce the current ripple, the interleaved circuit structure is used for the proposed converter. The proportional-integral regulator for the fuel cell current control is achieved by a digital signal processor to improve the reliability and flexibility of the converter. Smooth transition between step-up and step-down modes is realized using average current method for the converter. The principle of operation and theoretical analysis of the converter are given. Experimental results of a prototype are provided to evaluate the performance of the proposed scheme.

Introduction

Fuel cell (FC) is currently considered to be a promising candidate for green power generation. In particular, proton exchange membrane fuel cells (PEMFCs), which can be characterized by their rapid start-up, low working temperature, high efficiency, high specific power, high specific energy, low noise and no emission, become competitive as a power source for vehicle applications [1]. To reduce the cost and improve the durability of a PEMFC, the hybridization of power sources is a promising solution by using a PEMFC and other energy storage systems (ESS), such as the lithium-ion battery system or the ultra-capacitor system [2]. The powertrain configurations and control strategies for FC/battery [3–5], FC/ultra-capacitor [6] and FC/battery/ultra-capacitor [7] vehicles have been studied. Due to the wide variation in FC's terminal voltage depending on operating conditions, a DC/DC converter is required as the interfacing circuit between FC and other components in a fuel cell hybrid powertrain. The converter can also control the output power according to energy management strategies, resulting in energy or power distribution among the power sources, which will enable efficient operation of the whole powertrain [2,5,8].

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A typical fuel cell powertrain of a vehicle, as shown in Fig. 1 [4,5], consists of fuel cell, DC/DC converter, ESS (battery in this case) and a driving system. Unlike other components, a fuel cell is indirectly connected to the high-voltage direct current bus (HV DC BUS) via a DC/DC converter which acts as a power conditioning to match and stabilize the HV DC BUS voltage, so the input voltage of DC/DC converter is equal to that of the fuel cell and the output voltage of DC/DC converter is equal to that of the HV DC BUS (i.e., voltage of battery). A second-order low-pass filter (L_{fc}, C_{fc}) is used to filter the high frequency ripple generated at the converter input in order for the FC current ripple to become nearly negligible, which contributes to improved FC durability. In addition, a diode D_{fc} is used to protect FC from the faults of the converter or loads [4,9].

In general, DC/DC converters fall into three categories: step-up, step-down and step-up/step-down, depending on the difference of the FC voltage and HV DC BUS voltage [10,11]. Fig. 2 shows the selection of converter category according to the FC voltage and the HV DC BUS voltage. When the HV DC BUS voltage range is within the FC voltage range, a step-up/step-down converter is required. These converters are able to not only convert the wide FC voltage into an expected value, but they also have additional merits, such as high power density, high efficiency, high reliability and so on, for vehicle applications [12]. For a complicated powertrain with more than two power sources, power sources and loads can be connected by a multi-port converter, which can be seen as a combination of several two-port converters [13].

Boost and Buck converters with non-isolated single-switch circuit structure, as basic step-up converter and step-down converter for fuel cell vehicle powertrains can be found in many publications [14–18]. Although there exist several non-isolated single-switch step-up/step-down converters, such as Sepic, Cuk, Buck-Boost and Zeta, they are not suitable for fuel cell vehicle applications because of the demands for high power and wide range of FC voltage [19]. Isolated converters can easily perform step-up/step-down functions, but they cannot achieve high efficiency due to the existence of transformers [20,21]. A buck-boost converter based on Cuk is presented in Ref. [22], and the main disadvantage of the converter is that energy must be transferred via a capacitor, which limits higher power transmission. In addition, the converter is composed of many elements, which can affect the reliability of the converter. A combination converter of Buck and half-bridge isolated converters is reported in Ref. [23], the combinational converter can transit smoothly between the step-up and step-down modes because of the complete decoupling of buck and half-bridge modules. However, the converter topology is very complicated and half-bridge part cannot operate with high efficiency. Buck-boost cascaded converter with only one inductor [24], or boost-buck cascaded converter with two independent [25] or coupled inductors [26], is a popular choice with high efficiency and low component stresses. Oscillations or slow dynamic response may occur during the step-up/step-down transition because the cascaded structure has a coupling feature between the pre- and post-stage circuit. In Ref. [26], a damping network is employed to improve the dynamic performance of the cascaded converter, but the complicated structure leads to increased costs and decreased efficiency.

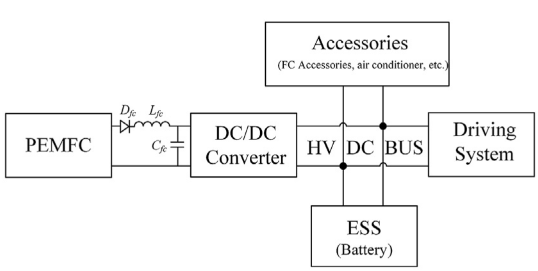

Fig. 1 – A typical fuel cell powertrain of vehicle.

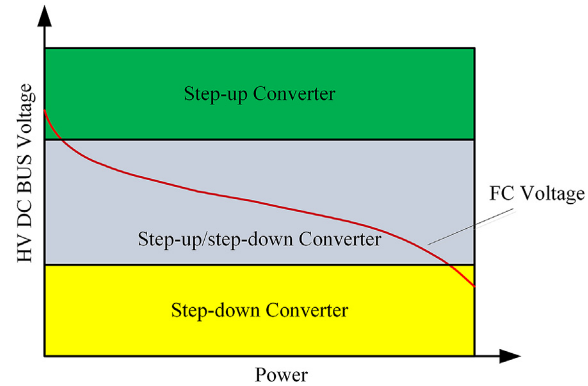

Fig. 2 – Selection of DC/DC converter.

Another problem with the converter for fuel cell vehicle applications is high-frequency ripple components in the fuel cell current created by converters or loads, which can lower durability of membranes and degrade the stack output power [27]. Merely employing a low-pass filter between the FC and the converter is not enough to filter the high-frequency ripple. For the most non-interleaved converters, the increasing of the switching frequency of power device is helpful to mitigate current ripple, but the higher switching frequency can increase the switching losses. Interleaved techniques can be used to drastically reduce the fuel cell ripple current. This technique has several advantages for high power converters. The power losses of each converter are reduced because the fuel cell output power is processed by multiple converters. Moreover, using a smaller inductor with the high ripple current for each converter leads to less distorted waveforms in the fuel cell current and better transient response [28]. Also Refs. [29,30] show that the interleaved converter is more reliable in case of power switch faults in comparison to the non-interleaved converters.

It may be difficult to meet the needs of high reliability and data communications in a fuel cell vehicle by using analogue devices, which are applied in the control system of a multi-phase interleaved converter. Digital signal processors (DSP) designed for power electronic applications are a better option for the control core of DC/DC converters in a fuel cell vehicle powertrain because of its ability to perform complex mathematical computations within a minimum amount of time and with less effort [9]. Furthermore, the digital controller is flexible and reliable because the implementation involves only software instructions and is independent of the converter structure and devices [31].

In this paper, a novel interleaved non-isolated converter is proposed to fulfil step-up and step-down requirements. The