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Hybrid-mode interleaved boost converter design for fuel cell electric vehicles

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ABSTRACT

For Fuel Cell Electric Vehicles, DC-DC power converters are essential to provide energy storage buffers between fuel cell stacks and the traction system because fuel cells show characteristics of low-voltage high-current output and wide output voltage variation. This paper presents a hybrid-mode two-phase interleaved boost converter for fuel cell electric vehicle application in order to improve the power density, minimize the input current ripple, and enhance the system efficiency. Two operation modes are adopted in the practical design: mode I and mode II are used with each boost converter operating in continuous conduction mode and discontinuous conduction mode. The operation, design and control of the interleaved boost converter for different operating modes are discussed with their equivalent circuits. The boundary conditions are distinguished with respect to switching duty ratio and load conditions. Transitions between continuous conduction mode and discontinuous conduction mode are illustrated for the whole duty ratio range. The expressions for inductor current ripple, input current ripple and output voltage ripple are derived and verified by simulation and experimental tests. The efficiency and power density improvements are illustrated to verify the effectiveness of the proposed design scheme.

1. Introduction

Due to the growing concerns of environmental pollution and energy crisis, Electric Vehicles (EV), such as pure EV, hybrid EV, Fuel Cell Electric Vehicles (FCEV) and their charging stations have gained significant advances [1]. For instance, a plug-in hybrid EV is used as one important resource for the future distribution networks operation [2]. Supplied by photovoltaic solar panels and batteries, a grid-connected EV charging station is discussed in [3]. The smart charging of EVs is analyzed in [4] in order to increase export capacity and integration with renewable energy. Among these EVs, thanks to zero CO_2 emission or ultra-low emission, high-density current output ability, and high energy efficiency of the proton exchange membrane fuel cell (PEMFC), FCEVs are widely regarded as an ideal alternative to replace the internal combustion engines [5]. Firstly certified in 2002, Honda FCX can achieve a driving range of 210 miles and 1 mile per kilogram energy efficiency [6]. In China, a 30 kW PEMFC-powered EV driving system was developed by Chinese academy of sciences under the support of the ministry of sciences and technology of China [7].

Some technical challenges arise when the fuel cell energy sources are integrated into the EV drive train. One of them is the lack of energy storage capability to absorb the regenerated energy fed back by the electric machine [8]. Thus, auxiliary energy storage devices (ESD) such as batteries and supercapacitors are required during transient and instantaneous peak power demands [9]. Most importantly, since fuel cells show characteristics of low-voltage high-current output and wide output voltage variation [10], a DC-DC power converter is essential to provide an energy storage buffer between fuel cell and the traction system [11]. Fig. 1 shows the system configuration of the FCEV, including the main power source FC, high power dc-dc connecting FC with high-voltage dc bus, auxiliary power source connecting to dc bus via a bidirectional dc-dc converter, inverter, and motor. The power flow in the power train of EVs is given by

$$P_{DC} = P_{FC} + P_{ESD} \quad (1)$$

where P_{DC}, P_{FC}, and P_{ESD} represent the power flow of the EV dc bus, fuel cell, and energy storage device, respectively. As one of the most important components in a FCEV system, the high-power DC-DC converter may adopt different topologies and their performances

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Nomenclature

P_{DC}	power flow of the EV dc bus	d	voltage conversion ratio
P_{FC}	power flow of the fuel cell	D	pulse width of the gate drive signal
P_{ESD}	power flow of other energy storage device	i_{in}	input current of the interleaved boost converter
$L_{i(i=1,2)}$	input inductor of each boost converter	k_{IBC}	mode boundary for the interleaved boost converter
C_o	output capacitor	k_{CBC}	mode boundary for the conventional boost converter
L_s	inductance of each boost converter		

are compared in terms of their component count, current ripple, and control [11]. Although some topologies including the buck-boost converter, full-bridge converter, and push-pull converter are presented for EV application [12–14], nonisolated DC-DC converter is preferred as the power interface between the FCs and the powertrain of EVs considering the increasingly demands in power density. For instance, according to the FreedomCAR and Vehicle Technologies (FCVT) program, with the latest power devices and integration design techniques, the volume power density of EV converters has been increased from 2.03 kW/L to 8.80 kW/L [15] and will be further increased to 14.1 kW/L in 2020 [16].

A typical Volt-Ampere characteristic of 1.26 kW PEMFC stack that is made up of 42 cells is illustrated in Fig. 2, which shows that the output voltage of fuel cell stack will change continuously with the output current for different operation regions such as low-torque region and high-torque region. For low-torque region, the output voltage of fuel cell stack is higher than that in high-torque region. Thus, a nonisolated dc-dc converter is required to provide smooth output voltage for motor driving system and regulate the power flow in EV system.

Among nonisolated dc-dc topologies, the conventional boost converter (CBC) is commonly used. One application of CBC is to act as the power interface of the proton exchange membrane fuel cell stacks [17]. Other application such as a fuel cell power conditioning system with a seamless control algorithm is reported in [18]. For EVs, CBC is also a good candidate topology in connecting low-voltage energy source with high voltage dc bus due to its simple construction, and high conversion efficiency. However, large output capacitor banks must be used in order to reduce the output voltage ripple especially for high current conditions. Thus, both the power density and the dynamic performance of CBC are deteriorated accordingly [19]. To address this issue, an interleaved boost converter (IBC) is proposed by operating boost converters with a phase shift between their gate driving signals with aim to improving the power density and transient response [20]. Compared with CBC, due to interleaving operation, IBC exhibits lower input current ripple and lower output voltage ripple simultaneously [21]. The power density is improved since the size of inductor and filter capacitor is reduced. Furthermore, IBC can enhance the dynamic performance since the effect of right half plane zero point is minimized [22].

Previous works on the interleaved boost converter are also focused on the following subjects:

(1) Control strategies and digital implementation: digital adaptive current source driver method for PFC converter application [23]; sliding-mode control [24]; and master-slave interleaving control method [25].
(2) Soft-switching operation: a simple passive auxiliary circuit can be used and arranged between two phases of IBC to realize zero-voltage-switching (ZVS) operation [26]; the conventional PWM technique and ZCS technique are combined to improve the switching performance [21]; a built-in transformer voltage doubler cell is added to achieve ZVS operation for all active switches [27].
(3) Magnetic Integration: interleaved winding-coupled boost converter [28]; two boost inductors are integrated into a single magnetic component [29]; the integration of two discontinuous-current-mode (DCM) converters for ballast application [30].

The previous works are mainly focused on a 1 kW power level [20,21] or even lower power applications [22]. For a 150 kW high power FCEV application, the design and optimization of the IBC are different. For instance, the inductor current in FCEV application is high up to 600 A for a 150 kW system, thus, coupled inductor discussed in [28–30] is difficult to manufacture and the cost will also be significantly increased. With soft-switching techniques, the switching losses of boost converters are reduced [21,26,27]. But the additional auxiliary circuits are added, which will bring extra losses and lower the system reliability considering the increased components number. In this study, a two-phase IBC is selected for a 150 kW FCEV application since further increasing the interleaving phase number will make the system too complex and significantly increase the system cost [20–22]. Although some control strategies are discussed [23–25], the effectiveness of these methods is mainly for low power applications. These control methods are seldom used for a high power FCEV system considering its complexity in practical implementation. Furthermore, key design issues for the two-phase IBC considering the FCEV applications including operation modes, input current ripple, output voltage ripple, and efficiency, have not been discussed comprehensively in prior works [20–30]. Thus, this paper will address these key practical design issues through simulation and experimental tests. In order to improve the power density and efficiency, a hybrid-mode scheme is used in IBC, where Mode I and mode II are used with each boost converter operating in continuous conduction mode and discontinuous conduction mode. The boundaries between different operating modes are distinguished with respect to switching duty ratio and load conditions. In the whole duty ratio range, the transitions between CCM and DCM for each boost converter are discussed. The expressions for inductor current ripple, input current ripple and output voltage ripple are derived according the detailed analysis and they are also verified by simulation and experimental results.

This paper is organized as follows. The operation principle of IBC and the equivalent circuits are discussed in Section 2. Section 3 presents the steady-state power characteristics of IBC under two operation modes which their boundary determination. The input current ripple and output current ripple with the proposed scheme are discussed and compared with the conventional design. In Section 4, the experimental results are provided to verify the analysis. In Section 5, the conclusions are given.

2. Operating principle of IBC

Fig. 3 shows the topology of the two-phase IBC, where boost converter (BC) I includes inductor L_1, diode D_{11}, IGBT Q_{12}, and BC II operates in parallel includes L_2, diode D_{12}, IGBT Q_{22}. For the steady state operation, the voltage conversion ratio d can be defined as