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Interactions between a polymer electrolyte membrane fuel cell and boost converter utilizing a multiscale model

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HIGHLIGHTS

- A multiscale model for a fuel cell system and boost converter is presented.
- Mass transport process and high frequent switching operations are simulated.
- Influences of high frequent switching on mass transport states are analyzed.
- Stabilities of the fuel cell stack under different control modes are studied.

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ABSTRACT

In a fuel cell vehicle, a direct current boost converter (DCC) is required to link a polymer electrolyte membrane fuel cell system (FCS) and lithium battery packages. The DCC is installed to regulate the output power of the FCS, and can be controlled in different ways, via current, voltage, or power modes. Interactions between a DCC and FCS have attracted growing interests in recent years, because they affect dynamic and stable performances of the entire system. This paper outlines a simulation study on interactions between high-frequency switching operations of a DCC and internal states of an FCS based on a multiscale model. Results are as follows. (1) High-frequency switching operations have a major influence on the cathode overpotential, voltage ohmic loss and water transport through the membrane, whereas the influence on the partial pressures of gas species inside the stack is slight. (2) The FCS is more stable in the case of membrane dehydration than in that of water flooding. DCC's control mode has a greater influence on the FCS when water flooding occurs than membrane dehydration. The power control mode is the most unstable of the three, whereas the current control mode is the most stable.

1. Introduction

Polymer electrolyte membrane (PEM) fuel cell systems (FCSs) are highly efficient, make little noise, emit zero emissions and are considered a viable candidate for vehicular power sources in the future. FCS technologies have been under development for decades. However, there are still bottlenecks that hinder the commercialization of this technology, e.g., high costs and short lifetimes [1–3]. One method of prolonging the working lifetime of a vehicular FCS, is to hybridize it with batteries. In this case, the power required by the whole vehicle is decoupled from the output power of the FCS. The battery provides dynamic power when the vehicle accelerates and recycles braking energy when it decelerates. The fuel cell operation loads can be optimized to obtain high levels efficiency and durability [4–16].

A direct current converter (DCC) is an essential component in a fuel cell system for stabilizing the output voltage and regulating the output power [17–19]. In general, boost, buck and bidirectional converters are featured. Because a high bus voltage is preferred in electric vehicles for promoting powertrain efficiency in the high-speed operations and for reducing ohmic losses within the electrical components, a boost converter is often utilized in fuel cell vehicles to increase the fuel cell's output voltage to the level of the bus voltage [17]. There are different types of boost converters according to electric topologies: non-isolated boost converters, push pull converters, isolated half/full bridge converters, etc. [20] [21]. Non-isolated boost converters are preferred in fuel cell systems owing to their relatively higher efficiency, fewer

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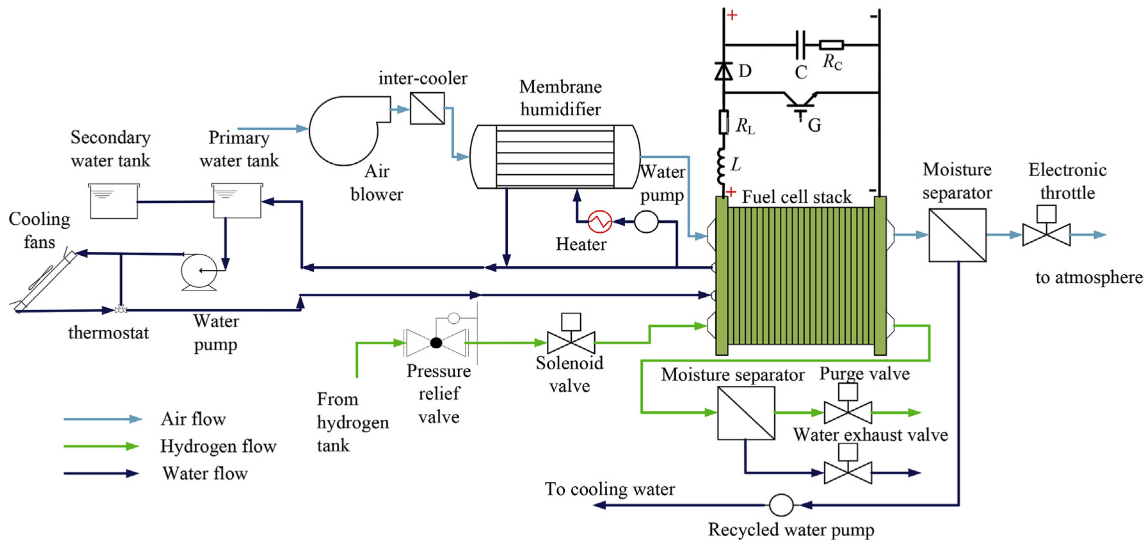

Fig. 1. A schematic of an FCS with a non-isolated boost DCC.

components and greater simplicity of control [20]. The highly frequent switching operations of a boost DCC affect the internal states of the fuel cell stack. Interactions between a converter and an FCS affect the performance of the whole system, and these interactions have gained the interest of researchers in recent years.

The high-frequency potential cycle induced by a switching power converter leads to Pt/C catalyst degradation. Uno et al. [22] note that when the cycle frequency is less than 100 Hz, obvious reductions in the electrochemical surface area (ECA) can be found. To reduce the influence of switching operations on fuel cell performance, researchers pay attention to multiphase interleaved boost DCCs. When the phase number increases, the input ripple current decreases; however, the complexities of the electric topology and control algorithm increase. Currently, the most popular topologies are single- [23–28], two- [29] [30], and three-legged [31] [32] interleaved boost converters.

The following are typical examples of the modeling and control of DCCs for an FCS. Control algorithms are usually designed such that the ripple current and converter losses can be reduced, and faults can be rapidly detected. Bjazic et al. [23] propose a control-oriented nonlinear model for an FCS and a single-phase boost converter, with the model utilized in the design of fault diagnosis and control algorithms. Tahri et al. [24] consider a nonlinear adaptive voltage controller based on the Lyapunov approach for a single-phase boost converter. Meanwhile, Ghanes et al. [25] propose a nonlinear voltage controller for a single-phase boost converter based on a singular perturbation approach. The convergence of the controller under converter losses was proved by applying Lyapunov theory. Wang et al. [26] designed a time delay controller (TDC) for the pulse width modulation (PWM) control function of both a boost and buck converter. Giaouris et al. [27] studied the bifurcation patterns of the system based on Filippov's theory for an FCS, combined with a single-phase boost converter. A high-frequency sinusoidal signal was injected into the system to ensure it remained stable. Wang et al. [28] propose a conventional proportional-integral (PI) feedback controller for a boost controller, with four typical load cases simulated, namely heavy load, light load, load following and fault handling. Somkun et al. [29] designed a two-phase interleaved boost converter and its controller, which verified that low fuel cell stack ripple currents can be guaranteed by optimizing the control parameters. Thammasiriroj et al. [30] propose a nonlinear control algorithm based on the differential flatness concept for a two-phase interleaved boost converter. Guilbert et al. [31] [32] designed a fault diagnosis and tolerant control algorithm for a three-legged interleaved DCC boost converter used in an FCS. Experimental results show that the algorithm can detect and quickly handle the open-circuit fault and thereby avoid irreversible damage to the fuel cell stack.

From the above analysis, it is apparent that most recent studies relate to the interactions between an FCS and a converter focused on the modeling and control of the DCC. However, the internal mass transport processes within an FCS are rarely considered. This work provides a study on interactions between an FCS and a boost converter based on a multiscale model. The contributions of this paper are as follows:

(1) A control-oriented two-phase flow model of the gas diffusion layer (GDL) in the membrane electrolyte assembly (MEA) is developed based on a one-dimensional model.
(2) A multiscale model for the combined system of an FCS and a boost DCC is presented. The model includes the highly frequent switching operations of a DCC, and two sub-models for the DCC are presented, corresponding to high-frequency and low-frequency domains.
(3) The influence of the highly frequent switching operations of the DCC on the internal states of the fuel cell stack, as well as of DCC control modes on the performance of the FCS, are presented and analyzed.

The paper is organized as follows. In Section 2, a system composed of an FCS with a boost DCC is described and modeled, with the model verified using experimental data. An introduction to three control modes of the converter, namely the current, voltage, and power control modes, is provided in Section 3. Section 4 analyzes the influences of the DCC operations on the FCS performance. The internal states of the fuel cell stack are emphasized in the high-frequency domain, whereas the stability of the FCS is the focus in the low-frequency domain. Section 5 presents the conclusions.

2. A multiscale model of an FCS and a boost converter

2.1. System description

The schematic of an FCS with a non-isolated boost DCC is illustrated in Fig. 1. The fuel cell system is composed of a fuel cell stack and the balance of plant (BOP), which includes a water cooling/heating system, an air supply system and a hydrogen supply system. The water cooling system has two circuits, one for cooling and the other for heating. The air supply system, meanwhile, has three important components: an air compressor for regulating the airflow, a membrane humidifier for regulating air humidity and an electronic throttle at the output port of the cathode side (which can also be called the backup pressure valve)