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CPU-FPGA based real-time simulation of fuel cell electric vehicle

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ABSTRACT

Proton exchange membrane fuel cell (PEMFC) has been considered as one of the promising renewable power technologies for the vehicular application. This paper proposes a fuel cell electric vehicle (FCEV) power system model that can be implemented in the hardware-in-the-loop (HIL) emulation for real-time execution on field-programmable gate arrays (FPGAs). The FCEV model comprises three parts: a PEMFC, a Z-source inverter and a squirrel cage motor. To achieve an accurate and efficient FPGA resources' utilization, the PEMFC model is implemented by CPU whereas the models of the DC-AC inverter and the electrical motor are built in FPGA. For the validation of the proposed power system, the real-time simulation tests are conducted with a high accuracy. The developed hybrid system model can reach a simulation time step of 100 ns for FPGA and 500 µs for CPU under the co-simulation mode. Moreover, the simulation under various system operating conditions indicates that the high performance can be reached by the hybrid system computed in real-time. The proposed real-time model can be used to design the on-line diagnostic and model predictive control method, which can help to test the FCEV before the commercial applications.

1. Introduction

Proton Exchange Membrane fuel cells (PEMFCs) can transform the chemical energy stored in hydrogen fuel into electricity directly without pollution, which have received significant research attention in both laboratory and industrial field. Along with the depletion of traditional fossil fuel, the conventional oil and diesel vehicles need to find a replaced fuel for propulsion. Thanks to the advancement of the fuel cell material in recent years, the power of PEMFC can meet the requirement of vehicular applications. Thus, the research attention has been refocused on the modeling of the fuel cells. Conventional fuel cell models can be classified by the modeling dimension and the modeling domain. Different models may vary from zero-dimensional (0D) to three-dimensional (3D), which can couple electrochemical, fluidic and thermal domains. A complex fuel cell model accounts for a higher accuracy, whereas for the vehicular applications, the basic equivalent circuit models are usually adopted due to the simplicity.

Fuel cell models proposed in literature [1–6] give the basic equivalent circuit models for the PEMFC, which can be applied for fuel cell electric vehicle (FCEV) modeling and simulation. These models can be used for verifying the polarization characteristics of the fuel cell, whereas the modeling approach may lose some accuracy. For improving the accuracy of the fuel cell model, literature [7–12] are focused on the multi-physical approach. These models are useful for analyzing the fuel cell operating in the vehicular applications, especially for the degradation phenomenon since the fuel cell temperature can vary a lot when a larger load is required. As it is known, the lifespan can be a key factor for the fuel cell electric vehicle (FCEV). The temperature variation can influence the fuel cell performance seriously by decreasing the lifespan. In order to better control and investigate the fuel cell degradation on FCEVs, multi-physical model including thermal phenomenon should be considered during the modeling of FCEV.

Aside of the fuel cell model, the modeling of the power converter is also very important since the efficiency and stability can greatly influence the performance of the EV system. Modeling works [13–18] on FCEV contribute to the developing and analyzing of the power converter before FCEV's mass commercial implementation. Das et al. [13] gives a comprehensive conclusion of the latest power conditioning units and topologies of the fuel cell hybrid electric vehicles. Different types of power converters are analyzed and compared in the paper, leading to different control techniques applied to different power stage demands. Articles [14–16] give the stabilization and energy management analysis

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of the power converter for FCEV system. The test of dynamic load variation is discussed, and the converter can maintain the power output in an effectively way. However, the fuel cell models used are constrained to the equivalent circuit model, which will certainly lose some accuracy of the modeling system. Literature [17,18] are all related to interleaved DC-DC converter for fuel cell vehicle applications. The proposed converters work under different control algorithms to maintain the power supply of the machine and can decrease the input current ripple for improving the efficiency and reliability. However, none of the proposed models can be applied directly to the real-time simulation due to the utilization of the simulation modules in the commercial software.

Hardware-in-the-loop (HIL) applications can provide a time-saving and safe way for designing the on-line control method, which can be used to evaluate FCEV performance before its commercial spreading around the world. However, few researches [19–22] are focused on the real-time simulation of the FCEV. Since a typical FCEV system couples a high non-linear characteristic, and the multi-physical fuel cell dynamic performance among different domains can make the system hard to be executed in real-time. Moreover, CPU-based simulation might suffer from the high I/O latency and thus make the power electronic system in FCEV hard to keep accurate and stable due to the multi-switch events introduced by the PWM control strategy. Literature [19] contributes to the analysis of two real-time optimization strategies for a PEMFC system, which is used as the power source of the hybrid FCEV. The control and management algorithms are discussed in detail in the paper, whereas the converter and the machine are not discussed. A PEMFC vehicle real-time platform has been built using dSPACE simulator in [20]. The developed real-time model for FCEV can operate under constant load conditions, and the simulation results are validated by the experiment, whereas the fuel cell model is still of an equivalent circuit one. For better applying the power management strategy, a real-time fuzzy logic power management strategy for a fuel cell vehicle is proposed in [21]. The paper analyzes and evaluates the performance of the three operating parts including a fuel cell, a battery and a super capacitor, whereas the fuel cell model in the proposed system takes into consideration only the electrochemical domain. Research [22] tests the real-time performance of the fuel cell model and power converter on the FCEV, whereas the system involves no electrical part and is not capable to assess the overall performance of FCEV.

The main objects of this paper focus on building a hardware-in-the-loop (HIL) simulation platform to evaluate the overall FCEV performance. As it can be seen from Fig. 1, the simplified FCEV power system contains three parts [13]: the fuel cell as the input power source, the Z source inverter as the power transmission and the three-phase AC machine as the load. By combining the fuel cell model, the power converter and the AC machine together, a basic FCEV power system can be formulated to verify the overall system performance. In order to verify the power converter stability, dynamic inputs through the multi-physical fuel cell model under various operating conditions are conducted. Moreover, the proposed FCEV model can operate under co-simulation mode through the FPGA and CPU. By deploying the CPU to solve the high-order equations in the fuel cell model, we can study the different physical characteristics of fuel cell under the influence power electronic converter. With the power electronic system implemented in the FPGA, we can get a high-speed calculation model with consideration of fuel cell model. Meanwhile, the developed model can be used to monitor the fuel cell operating performance and design the on-line diagnostic control methods of the FCEV. The model can also provide insights to the converter and electrical motor control strategy research. The principle contributions of this paper include:

1. A multi-physical fuel cell model including electrochemical, fluidic and thermal domains is developed for FCEV to operate under various operating conditions;
2. The implementation of power converter associating with an asynchronous motor in the FPGA could provide the controller a low I/O latency;
3. Real-time simulation for a FCEV powertrain system is conducted with a time step of 50 ns for FPGA and a time step of 500 μs for CPU, which can help to develop the on-line diagnostic and control method.

The following of this paper are organized as follows: Section 2 gives the multi-physical fuel cell model, which takes into consideration the electrochemical, fluidic and thermal domains. The converter and electric machine models are developed in Section 3. In Section 4, the algorithms for the hybrid system are discussed and analyzed. Section 5 gives the simulation results for the proposed power model. A conclusion section is finally presented in Section 6.

2. Multi-physical fuel cell modeling

In this section, the multi-physical PEMFC model will be demonstrated in electrochemical, fluidic and thermal domains, respectively. During the operating of the fuel cell, the degradation occurs and the overall performance of the fuel cell system can be influenced. In most cases, degradation mechanisms in PEMFC for transportation applications are: carbon corrosion, catalyst sintering and membrane degradation. As indicated by the reviewer, these degradation mechanisms can be highly influenced and accelerated by the operating conditions such as load cycling, thermal cycling and start-stop conditions. For this topic, the degradation related phenomenon for fuel cell has been discussed in our previous related works [33–35]. Since this work our main contribution is the realization of the real-time capable model and HIL simulation for the fuel cell electric vehicle applications using separate

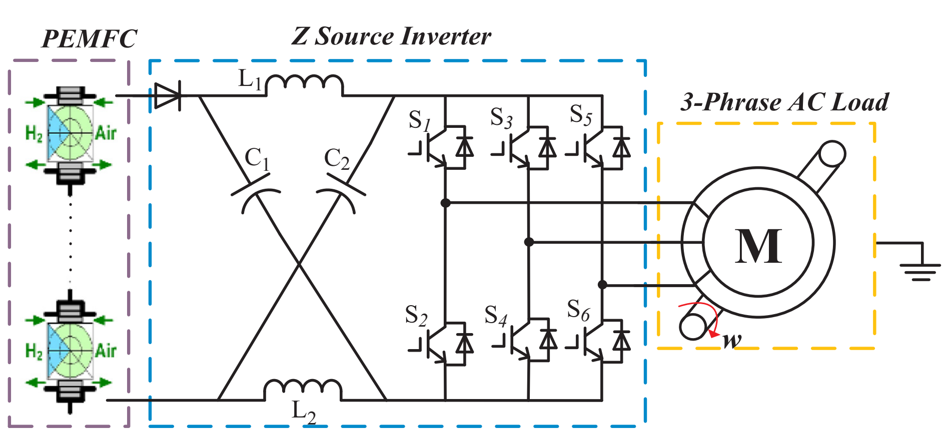

Fig. 1. FCEV power system with Z Source inverter.

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