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Optimal power management for fuel cell–battery full hybrid powertrain on a test station

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ABSTRACT

In this study, a test station of fuel cell–battery hybrid powertrain is established for validating the control strategy and system components as a Hardware-in-the-Loop test platform. Firstly, a fuel cell and $LiFeO_4$ battery pack full hybrid powertrain is presented and the structure and methods of the module-based test station are described. Secondly, a power management strategy is proposed for the hybrid powertrain, aiming to minimize the hydrogen consumption of the fuel cell stack with a limited power rising rate and meanwhile to obtain a given depleting value for the state of charge (SOC) of the battery pack over the ECE driving cycle. The strategy has been implemented in the Matlab/Simulink software and its effectiveness is evaluated by the simulation results and experimental data from the test station. Finally, it is deduced that the proposed fuel cell–battery full hybrid powertrain can bring about greater improvements in driving range than pure battery electric vehicle. Thus, it is confirmed that the full hybrid structure and optimal control scheme can be used to achieve specific objectives for fuel cell–battery hybrid powertrains.

1. Introduction

A PEMFC (Proton Exchange Membrane Fuel Cell) is a device that converts the chemical energy from hydrogen gas into electricity through a chemical reaction with oxygen or other oxidizing agent [1–4]. PEMFC is different from rechargeable batteries in that it requires a constant source of hydrogen and oxygen to run, but it can produce electricity continually for as long as these inputs are supplied [2,3].

To date, PEMFC has been developed and applied in many fields, such as portable power supplies, back-up power sources, distributed generation systems, PV/Wind/PEMFC hybrid power systems, urban cars, buses, light trams, tramways, locomotives, and aircrafts [4–8]. For different applications, the requirements for fuel cell lifetime vary significantly, ranging from 7000 h for cars to 20,000 h for buses and 40,000 h of continuous operation for stationary applications [9–11]. Although the lifetime target for automobiles is lower than those for stationary applications, the operating conditions of dynamic load cycling, startup/shutdown, and freeze/thaw make this goal very challenging for current fuel cell technologies. The work of Pei et al. [12] concluded that 56% of the fuel cell deterioration is due to load-change cycling and 33% due to start-stop cycling.

Therefore, a fuel cell (FC) system combined with an energy storage system (ESS) with high power density can perform better for automotive applications [13,14]. And the additional ESS can power-assist the FC system and recover braking energy, such as batteries (Lead-acid, Ni-MH, Li-ion), and ultracapacitors [15]. Nowadays, the mild hybrid structure dominates the FC/ESS hybrid electric vehicle, i.e. FC is the primary energy source and ESS is the auxiliary energy source. The power ratio (the maximum output power of FC/the maximum output power of ESS) is greater than 2 [16–18].

In this study, we propose a full hybrid structure for FC/ESS hybrid electric vehicle, with a lithium iron phosphate ($LiFeO_4$) battery pack as the ESS, because it has a longer life, better power density and is inherently safer to operate than other lithium-ion batteries. As a full hybrid powertrain, the power ratio between the FC and the battery pack is less than 1. It can introduce more benefits compared with the mild hybrid structure by downsizing the FC and upsizing the battery pack, especially in reducing the FC cost, in making it more steadily, and in promoting its lifetime. Specifically, WUT (Wuhan University of Technology) new energy company provides the atmospheric pressure and low temperature FC system in this study.

Since the powertrain is hybrid, a power management strategy is needed to split power between the FC and the battery pack [16–22]. Depending on how the necessary power is obtained, a minimization of hydrogen consumption can be achieved: the PMS (Power Management Strategy) is a set of algorithm which determines at each sampling time power generation split between

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the FC and the battery pack in order to fulfill the power balance between the load demand and the hybrid energy sources.

The PMS for FC/Battery hybrid electric vehicle is an open and kernel issue, with some different approaches in existing literature. Fuzzy logic controllers have been the common methods used in the case of the rule based approach. This can be seen in the work of Caux et al. [19], Kisacikoglu et al. [20], Li et al. [22], Kim et al. [23], Li et al. [4] and Ryu et al. [24]. Caux proposed an on-line fuzzy energy management strategy for reducing the hydrogen consumption via minimizing the system losses. Ryu designed an optimized fuzzy controller using genetic algorithm and proposed an adaptive membership function based on a stochastic approach. The main difficulty with fuzzy logic controllers is that they require enough training data and experience expertise in order to correctly form membership functions and sets of “if–then” rules that dictate the output of controller.

There are also some rule-based approaches. Thounthong et al. [25] and Wang and Cai [26] proposed a DC link voltage optimized control scheme through the control of power converters respectively, and used a different model and focus view, but do not deal with the fuel consumption and system efficiency. Fernandez et al. [27] proposed a suitable state machine control architecture and scheme for the fuel cell–battery hybrid system, its objective being to provide demanded power over the driving cycle, optimizing the energy generated. However, the switching stability among the eight states of state machine control strategy should be considered.

In recent years, a new category of real time algorithms based on the exploitation of optimal control algorithms has been widely investigated [28–32]. Another popular approach is Equivalent Consumption Minimization Strategy [33–38]. These strategies are derived from the minimum principle, and always focus on a charge-sustaining (CS) task for the ESS with a specific optimal object. To utilize the battery pack more fully on the proposed full hybrid powertrain, we will introduce a charge-depleting (CD) mode and design an optimal objective to obtain a given depleting value for the charge-state of the battery pack over the whole driving cycle with the cost of minimizing the hydrogen consumption. As a result, the proposed power management strategy of this paper will become an optimization problem with specific constraint conditions.

To validate the power management strategy, we have established a test station for the fuel cell–battery hybrid powertrain on the basis of stand-alone module. The real-time data can be transferred to the test management system managing the whole test station via CAN bus.

The organization of this paper is as follows. In Section 2, the fuel cell and $LiFeO_4$ battery full hybrid powertrain is proposed. In Section 3, the test station of hybrid powertrain is established showing the system structure and test methods. Then, the simulation model is described in Section 4 and the proposed power management strategy is introduced and implemented in Section 5. In Section 6, the simulation and test results are presented and discussed. The conclusions of the work are in Section 7.

2. Configuration of a fuel cell–battery full hybrid powertrain

The schematic diagram of a fuel cell and battery full hybrid powertrain is shown in Fig. 1. In this paper, the technical specifications of the hybrid powertrain are listed in Table 1, including the Fuel cell system, the $LiFeO_4$ battery pack, the DC/DC converter and the traction motor system. From Table 1, the rated power of the FC stack is 10 kW, thus its rated energy is 10 kW h with sufficient fuel. The $LiFeO_4$ battery pack capacity is 40 A h, and the cell number is 90, thus the total energy is 11.52 kW h ($90 \times 3.2 \times 40 = 11.52$). As a result, the energy ratio ($10/11.52 = 0.868$) between the FC stack and the battery pack is nearly 1, moreover, it can be found that the power ratio between the FC and the battery pack is less than 1 based on the test results as a full hybrid powertrain.

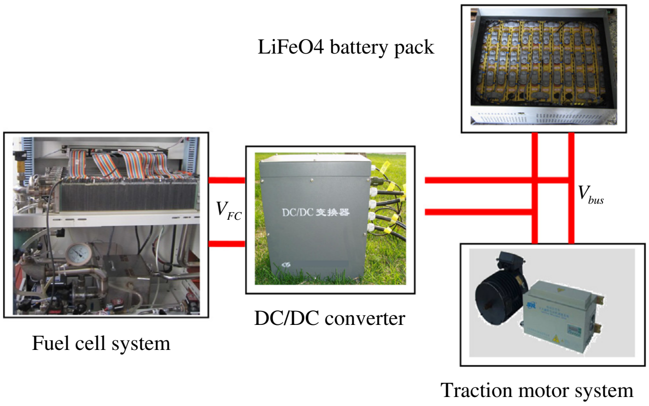

Fig. 1. Simplified schematic of the hybrid powertrain.

Table 1
Technical specifications of the hybrid powertrain.

Fuel cell system:	
Rated stack power	10 kW
Number of cells	180
Output voltage horizon	100–180 V
Compressor	Vortex blower
Controller for FC system	Self-designed
Battery pack system:	
Battery type	$LiFeO_4$ battery
Rated capacity	40 A h
Number of cells	90
Nominal voltage	288 V
BMS	Commercial
Traction motor system:	
Motor type	Brushless DC motor
Rated power	10 kW
Rated voltage	300 V
Rated torque	50 N m
Rated speed	2500 rpm
Maximum torque	100 N m
Controller for motor	Commercial
DC/DC converter:	
Convert rated power	10 kW
Input voltage horizon	100–200 V
Output voltage horizon	250–350 V

Because the DC bus voltage V_{bus} (250–350 V, Table 1) is higher than the FC stack voltage V_{FC} (100–180 V, Table 1), the FC stack is linked to the DC bus by a boost DC/DC converter, which delivers a directional current from the FC stack to the DC bus. We use the permanent magnet brushless DC motor and a commercial controller as the traction motor system of the hybrid powertrain.

3. Test station for the fuel cell–battery hybrid powertrain

3.1. Hardware-in-the-Loop test platform

To validate the proposed full hybrid powertrain, a test station was established as a Hardware-in-the-Loop test platform, which is shown in Fig. 2. Fig. 3 depicts the scheme of the hybrid powertrain on the test station. All module-based components in Fig. 1 were put into relevant cabinets, and then, we utilize an AC asynchronous electrical dynamometer to simulate a dynamic driving cycle as the vehicle load. The maximum absorbed power of the