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Energy management for fuel cell hybrid vehicles based on a stiffness coefficient model

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ABSTRACT

In this paper, a novel stiffness coefficient model (SCM) is proposed for power flow distribution between two power sources, fuel cell system and battery. Then the energy management strategy is developed based on the SCM for a prototype FCHV. The power flow distribution in different power sources could be dynamically adjusted by the proposed strategy according to the logic relationship between the power demand and the fuel cell output power at peak efficiency point, and the fuel economy of the FCHV could be improved as much as possible by making the fuel cell system work in high-efficiency area. The designed control strategy is verified by the simulation and the practical test. In the test, for a combined cycle which includes three typical driving cycles, the fuel economy of the FCHV with the proposed control strategy is increased averagely by 5.18% with maintaining power balance and stable control.

Introduction

Fuel cell vehicles (FCVs) are one of the most important trends of new energy vehicles. For their advantages of high energy conversion efficiency and zero emission, FCVs have attracted widespread attentions among academic and industrial circles. Since the end of the 20th century, huge investments have been poured into the development of prototype FCV by the world major automobile enterprises, such as “*Sequel*” of GM, “*FCHV*” of Toyota, and “*Hypower*” of Volkswagen etc. [1,2].

However, fuel cell usually has a hysteresis characteristic, which fails to meet the power demand of the vehicles. Hence an auxiliary storage device is usually applied in FCV power train. This is so-called fuel cell hybrid vehicles. As for such a complex dynamic system with two power sources, the difficulty and key for power control mainly lies in coordinating the power flow among fuel cell system, auxiliary storage device and electric-drive system according to the rapidly changing vehicle load, and the basic goal of power control is to improve vehicle efficiency while maintaining the power balance of the vehicle under different working conditions.

Active studies have been conducted on power flow management of FCHV power train. Kim and Peng [3] designed a power distribution algorithm based on Markov Decision Programming. Li and Liu [4], Kisacikoglu et al. [5] and Hanane et al. [6] proposed the control strategy for fuel cell hybrid power system based on Fuzzy Logic. Xu et al. [7–9] designed an optimal vehicle control strategy based on the time-triggered controller area network, the multi-mode control,

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Nomenclature

Ee	average-error between simulation and test data
Eer	average-error-rate between simulation and test data
I_m	motor current
I_{dcf}	fuel cell system current
I_b	battery current
U_{bus}	battery voltage
SOC	battery state of charge
P_{fset}	fuel cell power setting
P_{demand}	power demand
P_{peak}	fuel cell power at peak efficiency point
$K_{discharge}$	dynamic discharging coefficient
a	calculating constant of $K_{discharge}$
$k1$	stiffness coefficient of discharging
SOC_{min}	working lower limit of the battery SOC
K_{charge}	dynamic charging coefficient
b	calculating constant of K_{charge}
$k2$	stiffness coefficient of charging
SOC_{max}	working upper limit of the battery SOC

List of abbreviations

SCM	stiffness coefficient model
FC	fuel cell
FCV	fuel cell vehicle
FCHV	fuel cell hybrid vehicle
PEMFC	proton exchange membrane fuel cell
J1015	Japan 1015 city driving cycle
UDDS	Urban Dynamometer Driving Schedule of America Cycle
ECE-EUDC	Economic Commission for Europe and Extra-Urban Driving Cycle
FAST	city FAST driving cycle
DC/DC	direct current/direct current converter

and the determined dynamic programming (DDP) for FCHVs respectively in their studies. Ryua et al. [10] designed different energy distribution strategies according to the driving mode of motor. Zheng et al. [11] proposed an optimal control scheme based on the Minimum Principle for fuel cell hybrid vehicles. Mehdi et al. [12] proposed an optimal solution to the energy management problem in fuel cell hybrid vehicles with dual storage buffer for fuel economy in a standard driving cycle using multi-dimensional dynamic programming. Geng et al. [13] developed a multi-objective particle swarm optimization algorithm for a fuel cell/battery hybrid vehicle. Branislav et al. [14] developed a model predictive control system for a hybrid battery-ultracapacitor power source and experimentally verified it in their paper. In addition, several studies paid attention to modeling and simulation of fuel cell hybrid vehicles. Chan et al. [15] focused on architectures and modeling for energy management. They used a systemic modeling approach which allows better understanding of the interaction between the subsystems. Hwang et al. [16] developed a model by MATLAB/Simulink software and used it to analyze the dynamic performance and power distribution for a fuel cell HEV. Mallouh et al. [17] built a model of hybrid fuel cell/battery vehicle based on a validated ICE vehicle model. Simmonsa et al. [18] developed an energy-based simulator for a fuel cell/battery hybrid passenger bus.

To sum up, it could be concluded that recent studies mainly focused on the stability control and function implementation of the power system. A few studies discussed optimal energy distribution strategy using offline simulation. But the strategies proposed in these studies were not verified by practical vehicle driving test. In this paper, a SCM is proposed for energy management for FCHV, which simulate the compression/stretching characteristics of spring. This SCM-based energy management not only achieves proper control of power balance, but also improves fuel economy of the FCHV power train as much as possible.

According to Ref. [19,20], the internal resistance of the battery is so small that the power loss of battery charging/discharging is not the foremost factor influencing the vehicle efficiency. At the same time, the efficiency curve of the fuel cell system in Refs. [21–23] indicates that the fuel cell system efficiency is remarkably affected by the power load. Besides, statistics collected from the practical test of the typical driving cycle show that the time when FC worked in low-efficiency area almost accounted for 20%–40% of the entire driving cycle. Therefore, how to make FC work in the high-efficiency area as much as possible, this is a very important problem for energy management of FCHV. In this paper, a prototype FCHV "*ROEWE*" from China Shanghai Motor Company (SAIC MOTOR) is used as the test object of the study, a SCM-based energy management strategy is developed and applied in the hybrid power train (fuel cell + battery) of *ROEWE*, which achieves the stable and efficient operation of the hybrid power train by optimizing the distribution of energy flow in each power source.

Dynamic simulation model of the FCHV

Fig. 1 shows the power train topological structure of the FCHV prototype vehicle *ROEWE*. A lithium-ion battery pack, as the auxiliary power source, is in parallel connection with a fuel cell system (FC). A direct current/direct current converter (DC/DC) is placed between a proton exchange membrane fuel cell (PEMFC) and the motor controller. Its purpose is to compensate for the over soft output characteristic of the fuel cell and protect it. The output power of the fuel cell can be controlled by regulating the output power of the DC/DC. The wheels are driven by the electric-driven system through deceleration/differential module, and the four-quadrant working mode of the motor's forward/reverse drive and brake can be realized by variable frequency vector control of the motor controller. Table 1 gives the specification and the main parameters of the *ROEWE*.

In our previous study [24], a dynamic simulation model of FCHV (FCHV-SIM) has been constructed as showed in Fig. 2.

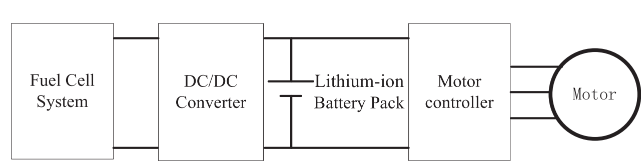

Fig. 1 – Schematic of the *ROEWE* power train.