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A novel equivalent consumption minimization strategy for hybrid electric vehicle powered by fuel cell, battery and supercapacitor

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HIGHLIGHTS

- Novel SECMS strategy for FCHEV with three power sources.
- Solving two degrees of freedom energy management problem.
- Experimental validation of designed SECMS strategy through test bench.

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ABSTRACT

The aim of this paper is to present a sequential quadratic programming (SQP) based equivalent consumption minimum strategy (ECMS) (SECMS) for fuel cell hybrid electric vehicle (FCHEV) powered by fuel cell, battery and supercapacitor. In order to decrease hydrogen consumption and increase the durability of power sources, fuel cell is chosen as the main power source and supplies steady current, battery is designed as the main energy buffer and the replacement of fuel cell failure and supercapacitor is operated to supply peak power. Low energy density of supercpacitor lets its equivalent hydrogen consumption be taken as zero for many ECMS researches. This simplification leads to suboptimal fuel economy and complex of control system. SECMS considers hydrogen consumption of three power sources into objective function to solve this problem. A rule based control strategy (RBCS) and an hybrid ECMS operating mode control strategy (OMCS) (HEOS) are also designed to compare with SECMS. An experimental test bench is built to validate the comparative study of three strategies. The results show that compared with RBCS and HEOS, hydrogen consumption of SECMS decreases of 2.16% and 1,47% respectively and it also has the most smooth fuel cell current, which means a lowest fuel cell degradation.

1. Introduction

Traditional gasoline and diesel vehicles have lead to many problems such as global warming, environment pollution and exhaustion of petroleum energy. Electric vehicles including pure electric vehicles, hybrid electric vehicles, and plug in hybrid electric vehicle are thought to be the best way to solve these problems [1]. Compared to traditional internal combustion engine, fuel cell has high efficiency and zero pollution emission, which is ideal energy source for electric vehicles [2].

Gas supply of fuel cell stack lags behind the load variation, which leads to difficulties to track the dynamic response of current specially related to transportation application. Consequently, at least one kinds of energy storage sources (ESS) should be added as the power sources to FCHEV. Batteries have high energy density, which are the most widely used ESS in transportation systems. But batteries also have some shortcomings like low power density, long charging time, high cost, short lifetime and seriously affected by temperature. In contrast, supercapacitor has high power density, very high lifetime and are not affected by temperature, which makes it suitable as device for power pulse. However low energy density, voltage balancing needed and high self-discharge are the main barrier for supercapacitor to be widely used in the hybrid electric vehicles. One of the most promised solution proposed for FCHEV supplying is the topology with fuel cell, battery and supercpacitor. This topology of power train allows the main components to give play to their advantages: fuel cell as main steady power source, battery as energy buffer and supercapacitor as device for power pulse. In order to achieve this hybridization and reach the above goal, an energy management strategy (EMS) is necessary.

In the literature, the EMSs can be classified into rule based control strategies (RBCS) [3] and optimization based control strategies [4].

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Nomenclature

ba_{SOC}	Battery SOC value
F	Faraday constant
I_{FC}	Fuel cell current
m_{BA}	Battery equivalent hydrogen consumption
m_{FC}	Fuel cell hydrogen consumption
m_{SC}	Supercapacitor equivalent hydrogen consumption
N_{cell}	The number of fuel cell stack current
P_{BA}	Battery output power
P_{FC}	Fuel cell power
P_{SC}	Supercapacitor output power
R	Ideal gas constant
S_{fc}	Fuel cell on/off state
SOC_{bamax}	Maximum battery SOC value
SOC_{bamin}	Minimum battery SOC value
T	The temperature of fuel cell stack
V_{FC}	Fuel cell voltage

RBCS uses direct rules or fuzzy rules to split power demand among different power sources, making it simple to design and allowing real time control. State machine control strategy [5], stiffness coefficient model control strategy [6], operation mode control strategy (OMCS) [7] and fuzzy logic control strategy [8] are kinds of RBCS which are widely used. In these strategies, the rules are designed in accordance with engineering experiences, consequently, optimal power split is difficult to reach [9,10]. To consume less hydrogen, increase driving distance or extend the lifetime of fuel cell and ESSs, optimization based control strategies are used to find the optimal result. It can be divided into global optimization strategies and local optimization strategies [11]. Dynamic programming and genetic algorithm are the most effective strategies to solve global optimization problem. Prior knowledge about drive condition and long calculation time limit their application on the real time vehicle control. Pontryagins minimum principle [12] and ECMS transform global optimization problem into instantaneous ones which instantaneously calculate the optimization objective function to split power among power sources [13].

Up to now, few papers focus on building EMS which takes into account three power sources. State machine control strategy of [5] and fuzzy logic strategy of [14–16] are used to control the power split among three power sources. But they belong to RBCS which lead to suboptimal results. There are lesser researches evaluating the fuel economy potential of supercapacitor and battery combination for optimization strategy [17]. Solves this problem with dynamical programming but the proposed method cannot be used in real time. Two-level control structure, where first level calculates the optimal results between fuel cell and battery and the second one lets supercapacitor improve the battery performance, are widely used for three power sources like [18]. ECMSs in Refs. [19–21] are designed as two level architecture and take equivalent hydrogen consumption of supercapacitor as zero which not only counter to the aim of minimizing whole hydrogen consumption but also increase the complication of EMS due to the need of an additional EMS to calculate supercapacitor power demand. Thus, SECMS strategy is proposed to consider energy cost of all three power sources into the objective function to solve this problem. At the same time, a RBCS and HEOS strategies are also compared to demonstrate the superiority of SECMS in minimizing the hydrogen consumption and prolonging fuel cell lifetime.

This paper is organized as following: the first section is introduction, section two gives the vehicle architecture and the model of the power train including fuel cell, battery, supercapacitor and DC/DC converters. In the third section, SECMS, RBCS and HEOS are explained. In the fourth part, the used validating test bench is described and experiment results are compared for different control strategies. Finally, conclusions are drawn.

2. Vehicle models

2.1. Power train architecture

The series architecture is chosen for FCHEV, as shown in Fig. 1. Proton Exchange Membrane Fuel Cell (PEMFC) is the main energy source to supply steady state power and is connected to the DC bus via a unidirectional DC/DC power converter. Lead acid battery as main energy storage source is directly connected to DC bus to hold the bus voltage. Supercapacitor as peak power supply is connect to the DC bus through a bidirectional DC/DC power converter.

The longitudinal dynamics of a road vehicle can be described in the following equation (1), through which the required power P_{cycle} at wheel to drive the vehicle can be calculated [22]:

$$P_{cycle}(t) = v\left(m_v(t)\frac{\mathrm{d}}{\mathrm{d}t}v(t) + F_a(t) + F_r(t) + F_g(t)\right) \tag{1}$$

where P_{cycle} is the power demand from drive cycle, F_a is the aerodynamic friction, F_r the rolling friction, and F_g the force caused by gravity when

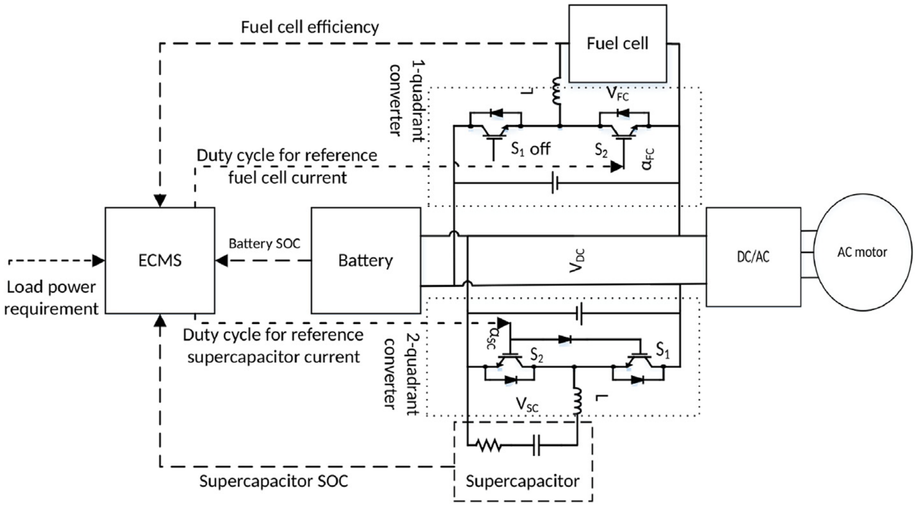

Fig. 1. Powertrain architecture.