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A comparative study of extremum seeking methods applied to online energy management strategy of fuel cell hybrid electric vehicles

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ABSTRACT

As an online adaptive optimization algorithm, the extremum seeking method (ESM) can be effectively employed to find an optimal operating point of a static nonlinear system in real-time. This paper presents a comparative study of different ESM schemes for online energy management strategy of fuel cell hybrid electric vehicles (FCHEVs). By applying the extremum seeking controller, the fuel cell system operating points can be maintained in a high efficiency region and thus saving the hydrogen consumption. In addition, battery state of charge (SOC) is considered as the input of penalty function for extremum seeking controller, in order to prevent over-discharging/over-charging of the lithium-ion battery during the FCHEVs operation. Different schemes of ESM presented in this comparative study consist of first-order ESM, high-pass filter based ESM, and band-pass filter based ESC. The main evaluation criteria in this comparative study include the utilization of lithium-ion battery, the fluctuation of fuel cell system output power, the fuel cell system efficiency and the hydrogen consumption. A Hardware-In-the-Loop (HIL) platform is used to experimentally validate the presented comparative study. Experimental comparison results show that, the performance of all the presented ES controllers is close to that of offline benchmark dynamic programming. The band-pass filter based ES controller is preferred to improve both the performance and durability of energy storage system (ESS) in FCHEVs, since this controller is found to have a good ability to limit the fuel cell power dynamics.

1. Introduction

During the last few decades, hybrid electric vehicles (HEVs) and most recently fuel cell hybrid electric vehicles (FCHEVs) have been widely considered as one of the most promising solutions of environment pollution and energy crisis [1]. As one type of fuel cell technologies, proton-exchange-membrane fuel cell (PEMFC) is more suitable for long-range FCHEVs, due to its advantages of compactness, high power density, fast fueling time, relatively low operating temperature and pressure [2].

As an energy conversion device, the fuel cell directly converts chemical energy into electrical energy, this energy conversion depends on a slow electrochemical process. Thus, using only a standalone fuel cell system will lead to its short lifetime due to the fact that fuel cell system will absorb all the fast dynamic of current [3]. Therefore, for the purpose of a longer lifetime of fuel cell, the lithium-ion battery should also be used as another energy source in the FCHEV powertrain, in order to provide/absorb the fast peak power due to the short-term accelerations and brakes of the FCHEV.

As one of the main challenges for the commercialization of FCHEVs, the development of appropriate energy management control strategies is necessary to improve the performance and durability of Energy Storage System (ESS) in FCHEVs, such as saving the hydrogen consumption of PEMFC for driving range extension of FCHEVs [4], or limiting the power dynamics of fuel cell system for its longer lifetime [5].

Many optimal control strategies were proposed in the state-of-art literature [6–17]. Generally, these strategies can be divided into two categories: offline control strategies [6–11] and online control [12–17] strategies. Offline control strategies aims at optimizing a pre-defined cost function within feasible constraints. As a typical example of offline control strategy, dynamic programming (DP) [6,7] solves a complex problem by transforming it into a collection of simpler problems based on optimal control theory. Ravey et al. [6] uses DP algorithm to minimize the cost-to-go function of fuel cell hydrogen consumption with the constraints condition that the battery final state of charge (SOC) is the same as that at the beginning. In addition to the DP, as another theoretical analysis tool, the Pontryagin's minimum

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Nomenclature

Greek letters

α	amplitude of the perturbation signal
γ	energy conversion ratio
η	efficiency
θ^*	optimal objective point
μ	output of high-pass filter
ξ	output of low-pass filter
ρ	energy density (MJ kg^{-1})
σ	standard deviation
ω	angular frequency of perturbation (rads^{-1})

Roman letters

C	coefficient of the penalty function
E_{BT}	battery energy (kW h)
F	Force (N)
f_{FC}	nonlinear fuel cell system
g	nonlinear function between fuel cell system efficiency and power
I_{FC}	fuel cell current (A)
J_{cons}	penalty function
k	gradient gain
$\mathscr{L}^{-1}$	inverse Laplace transform
m	mass (kg)
P	power (kW)
SOC	state of charge
s	Laplace variable
t	time (s)
v	velocity (ms^{-1})
y^*	optimal objective value of nonlinear system

Subscripts

aero	aerodynamic
BT	lithium-ion battery
DC/AC	direct current to alternating current
demand	demand
drive	drive
FC	fuel cell
gra	gravity
h	high
l	low
motor	motor
net	net
prop	propulsion
roll	rolling friction
theoretical	theoretical
v	vehicle

principle (PMP), developed by Russian mathematician Lev Pontryagin in 1956, has been demonstrated to provide global optimal solutions for powertrain control problem of HEVs [8,9]. Other offline optimization strategies, such as particle swarm optimization (PSO) [10] and genetic algorithm (GA) for HEVs energy management have been investigated in [11]. These optimization methods can be effectively applied to design global optimal controller for energy management system. However, a common drawback of these offline strategies is that the future driving cycles must be known *a priori*. Therefore, these offline strategies are unsuitable for implementation in real-time controllers, and they are mostly used as a benchmark for performance comparison.

Online control strategies are employed based on real-time controllers. As a commonly used strategy, fuzzy logic controller can be easily performed to provide a satisfactory solution for energy distribution of HEVs based on decision-making logic. Ferreira et al. [12] present a fuzzy logic based control method for energy management of HEV. By using this control strategy, not only individual power device has a high efficiency, but also the energy distribution can be effectively regulated at peak and average power demand. Simulation and experimental results show that the presented control strategy is a satisfactory solution to control the overall power system. However, as a crucial step of fuzzy logic controller development, the design of "IF-THEN" rules requires expert experience and knowledge [13].

The artificial neural network is a machine learning technique that can be used for solving classification, regression and forecasting problem. The neural network based controller has been applied for online energy management strategy. Tian et al. [14] propose a neural network based controller to achieve optimization of energy distribution for plug-in hybrid electric city bus. In this neural network controller, the demanded power, ESS energy, driving information, and engine power are considered as the training data. Experimental results show that the online optimization results are close to the benchmark DP. However, the neural network requires a large amount of training dataset and is very prone to over-fitting.

Other online management strategies for HEV powertrain control problem have been investigated in literature, such as adaptive optimal control [15], sliding mode control [16], and model predictive control [17]. These complex strategies usually require heavy computations, which leads to difficulty of implementation in real-time applications.

As an online adaptive optimization algorithm, the extremum seeking method (ESM) can be effectively employed to search an optimal state of a static nonlinear system in real-time. This adaptive optimization method has been successfully implemented in various applications, such as mode matching in vibrating gyroscopes [18], maximum torque-per-ampere control in permanent magnet motors [19] and maximum power point tracking in photovoltaic array [20]. In the terms of online energy management strategy of FCHEVs, the fuel cell system can be considered as a static nonlinear system, by applying the ESM, the fuel cell high efficiency operating point can be easily identified and tracked in real-time. In addition, the expert experience and knowledge are not necessary for ESM, and the parameters tuning of ESM controller can be easily performed to achieve its fast convergence speed and robustness. Nevertheless, such a simple and efficient controller for the energy management of FCHEVs has not been reported so far in the literature.

In this paper, the extremum seeking (ES) controller is developed and implemented to improve the performance and durability of ESS in FCHEVs. For the primary energy source PEMFC system, ES controller allows maintaining its high efficiency operating region and thus saving hydrogen consumption. For the second energy source lithium-ion battery, the battery SOC limitation is considered as constraints condition for ES controller, in order to prevent its over-discharging/over-charging during the FCHEVs operation. It should be noted that, the ESM has different schemes [21]. The objectives of this paper are to present and

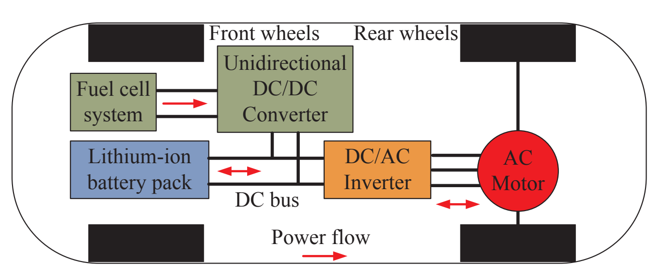

Fig. 1. Architecture of the proposed FCHEV powertrain.

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