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Stochastic self-optimizing power management for fuel cell hybrid scooters of different sized components

*Chao-Ming Lee**, *Wei-Song Lin*

Department of Electrical Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei, Taiwan

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ABSTRACT

Electric-powered scooters supplied by hybridizing a fuel-cell system (FCS) with lithium-ion batteries (LIB) need a good power management strategy (PMS) for attaining long driving distance and preventing from damage to the FCS or LIB while supplying adequate power to the vehicle. This paper proposes a stochastic self-optimizing power management strategy (SSOPMS) for the scooters to achieve this aim in various driving cycles. The power train of the scooter contains a lithium-ion battery and a boost converter interfacing an FCS to the DC-bus. The boost converter is under control of a power controller executing the trajectory of the SSOPMS. Various driving cycles are modeled as the discrete Markov process which extracts the statistical features from standard driving cycles. The SSOPMS determines the fuel-cell power trajectory depending on minimum fuel consumption and the constraints of FCS power, FCS power slope, LIB power, and LIB state of charge (SoC). To demonstrate the performance of the SSOPMS, two fuel-cell hybrid scooters of distinct FCS and LIB sizes are designed. Simulation results show the effectiveness of the SSOPMS under different components sizing and driving conditions.

Introduction

In recent years, there has been a rapid development of the electric scooter industry due to the CO_2 emissions of the internal-combustion engine based scooters. This development can improve the air quality and reduce the noise problem significantly, especially in east Asia cities, where the residents rely heavily on scooters [1]. Nowadays, the scooters powered by lithium-ion batteries (LIB) dominate the markets. However, limited driving range, long recharge time, and deep discharge problem of batteries [2] are still shortcomings to battery-powered scooters.

The fuel-cell system (FCS) and battery hybrid power source could be an alternative solution for electric scooters. Some literatures investigated the potentiality of the FCS for zero-emission electric scooters [3–5]. FCS features a high-energy density, which can charge the LIB to prevent them from the deep discharge problem, enhance the sustainability of the scooter. Moreover, the LIB features higher power density than FCS, which can enlarge the load power range. Benefits of fuel cell and battery hybrid power systems are considerable but to determine an efficient power management strategy (PMS) between the FCS and the batteries is challenging and crucial. In the past decades, numerous studies surveyed power

* *Corresponding author*. Tel.: +886 911269104.
E-mail addresses: d97921033@ntu.edu.tw (C.-M. Lee), linweisong@ntu.edu.tw (W.-S. Lin).
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Nomenclature

$\dot{m}_{H_2}$	hydrogen-consumption rate of the FCS, in units of gs^{-1}
P_{LIB}	power at the terminal nodes of the LIB
P_{FC}	net output power of the FCS, in units of 1 kW
P_L	power at the input nodes of the traction motor system
P_{ST}; P_{AUX}	stack power of fuel cell; power consumption of auxiliary devices
SoC	state of charge (SoC) of the LIB; $SoC = Q/Q_{max}$ where Q is the electric charge stored; Q_{max} is the rated capacity of the LIB
$\mathbf{u}_k$	$\mathbf{u}_k \triangleq [P^{desired}_{FC,k}]$; desired output power of the FCS
$\mathbf{r}_{k+1}$	$\mathbf{r}_{k+1} \triangleq [P_{L,k}]$; load power of the fuel-cell/LIB power system
Γ	$\Gamma = \{P_{L,k}\}^K_{k=0}$; sequence of load powers associated with a driving cycle
η	efficiency of the dc/dc boost converter
η_{FC}	efficiency of the fuel cell stack
t; τ; k	time index; sampling period; index for discrete time
$\mathbf{U}(\cdot, \alpha)$	the strategy network; α is the adjustable weights
LHV	the lower heating value of hydrogen; $LHV = 120\ kJg^{-1}$
θ_i	penalty constant
$\triangleq$	defined by equality
$\boldsymbol{\delta}_k$	strategy residue
$\boldsymbol{\varepsilon}_k$	judgment residue

management strategies could be categorized into two major types. The first type is the analytic approach that is an application of the control technique such as model predictive control and rule-based control. Greenwell and Vahidi [6] designed the rule-based power management strategy with low-pass filter to determine the desired current of the model predictive controller for the fuel-cell hybrid system. Arce et al. [7] utilized the multi mode model predictive control with the mode switch selector under different power conditions. Thounthong et al. [8] proposed the SoC rule based control with slope limiter and saturator to manage the fuel-cell/battery hybrid power system. Feroldi et al. [9] presented heuristic energy management strategies based on the knowledge of the fuel-cell efficiency map. Literatures [10–13] employed fuzzy logic rule to achieve the power split. And literatures [14,15] introduced the rule-based energy management strategies for the fuel-cell hybrid systems. However, those kinds of methodologies are depended on designers' experience. As a result, the analytic approaches of PMS are challenging to achieve optimality under various real-world driving conditions. The second type is the optimization approach that tries to draw out the optimal power management strategy. Equivalent consumption minimization strategy (ECMS), which is a kind of static optimization method, has been introduced as a near-optimal power split strategy [16]. However, the global optimality over the horizon of ECMS is not guaranteed. Deterministic dynamic programming (DDP) is one of the representative dynamic optimization methods. However, it is not implementable due to the requirement of full knowledge of the future power request. Besides, the DDP optimal solution for one driving cycle might not be optimal for other driving cycles [17]. Stochastic dynamic programming (SDP), which is another dynamic optimization method, enables the power management in real driving. Lin et al. [18] utilized SDP to the fuel cell/battery hybrid vehicle that control laws optimized through random driving cycles modeled as the discrete Markov process. Nevertheless, the SDP suffers from the curse of dimension and heavy computation load.

In this paper, we discuss the power management problem of the fuel-cell/LIB hybrid scooters with distinct components sizing. Two models of 1.5 kW and 1 kW fuel-cell system are designed respectively. The maximum power consumption of the scooters reaches to 4.5 kW, which is much greater than the maximum power generation of the fuel-cell systems. The power management problem is formulated as an optimal control problem subjected to the equality and inequality constraints. Then, this research proposes a stochastic self-optimizing power management strategy (SSOPMS) to solve the power management problem. Since the SSOPMS is implemented by radial basis function (RBF) neural network, it is suitable to be applied in discrete-time conditions. By the reinforcement learning mechanism, the SSOPMS is trained and optimized over stochastic driving cycles generated from the discrete Markov process. As a result, the proposed SSOPMS is not dependent on a particular driving cycle but more driving conditions.

This paper is organized as follows. Section Problem formulation of the optimal power management describes the models of fuel-cell/LIB hybrid scooters and formulates the problem of the optimal power management. Section The Stochastic self-optimizing power management strategy introduces the stochastic self-optimizing power management scheme optimized over a series of stochastic driving cycles. Section Simulation results shows the simulation results and Section Conclusion draws the conclusions.

Problem formulation of the optimal power management

Consider hybridizing a proton-exchange-membrane (PEM) fuel-cell system (FCS) with a pack of lithium-ion batteries to supply an electric scooter, as shown in Fig. 1. The dc/dc boost converter interfaces the FCS to the load bus, and protects the fuel cell stack from damaged by the reverse electric current. The power controller manipulates the turn-on durations of the power electronic devices of the boost converter to convey a desirable amount of electric power out of the FCS. The lithium-ion battery (LIB) connects directly to the load bus to supply urgent electric power and to store regenerative electric power. The SSOPMS determines desirable fuel-cell net power to minimize hydrogen consumption and power fluctuations in the FCS while supplying adequate electric power to the scooter, and the state of charge (SoC) of the LIB maintained at the permissible levels. Optimization on the PMS must cope with every permissible driving conditions while satisfying the