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Multi-objective component sizing based on optimal energy management strategy of fuel cell electric vehicles ☆

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HIGHLIGHTS

- A non-linear model regarding fuel economy and system durability of FCEV.
- A two-step algorithm for a quasi-optimal solution to a multi-objective problem.
- Optimal parameters for DP algorithm considering accuracy and calculating time.
- Influences of FC power and battery capacity on system performance.

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ABSTRACT

A typical topology of a proton electrolyte membrane (PEM) fuel cell electric vehicle contains at least two power sources, a fuel cell system (FCS) and a lithium battery package. The FCS provides stationary power, and the battery delivers dynamic power. In this paper, we report on the multi-objective optimization problem of powertrain parameters for a pre-defined driving cycle regarding fuel economy and system durability. We introduce the dynamic model for the FCEV. We take into consideration equations not only for fuel economy but also for system durability. In addition, we define a multi-objective optimization problem, and find a quasi-optimal solution using a two-loop framework. In the inside loop, for each group of powertrain parameters, a global optimal energy management strategy based on dynamic programming (DP) is exploited. We optimize coefficients for the DP algorithm to reduce calculating time as well as to maintain accuracy. For the outside loop, we compare the results of all the groups with each other, and choose the Pareto optimal solution based on a compromise of fuel economy and system durability. Simulation results show that for a "China city bus typical cycle," a battery capacity of 150 Ah and an FCS maximal net output power of 40 kW are optimal for the fuel economy and system durability of a fuel cell city bus.

1. Introduction

Most cars and buses are driven by internal combustion engines (ICEs) running either on gasoline, diesel, or natural gas [1]. The combustion process emits pollutants such as CO_2 or NO_X, causing much damage to the environment and human health [2]. Furthermore, the reserves and resources of crude oil are limited and it is likely that the current supply will not be able to satisfy increased demands within the next decades. A solution must be developed that changes the energy system for vehicles. Currently, there are several candidates: plug-in hybrid, battery electric, and fuel cell electric vehicles (FCEVs). FCEVs have attracted much attention in the past few years because they run on hydrogen and the only output is pure water. They are highly energy-efficient, have zero emission, and are very quiet; FCEVs are a very promising way to provide sustainable transportation [3,4].

A typical topology of an FCEV contains at least two power sources, a fuel cell system (FCS) and an energy storage system (ESS), e.g. a lithium battery system or a super capacitor (SC). The FCS provides stationary power, and the ESS delivers dynamic power. For a pre-defined driving cycle, two factors determine performances in fuel economy and system durability of an FCEV: parameter sizing and energy management strategy (EMS). EMS is widely studied in several fields besides new energy vehicle

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powertrains, e.g. wind power system, microgrid systems or green buildings [5–12]. There is a sole optimized EMS for a pre-defined driving cycle and cost function corresponding to one group of powertrain parameters. These two problems always couple with each other. When we solve a parameter sizing problem, theoretically, we cannot avoid the optimized EMS problem.

There have been many papers on parameter sizing in literature. We can separate these papers into several categories, depending on the consideration of optimal EMS when choosing powertrain parameters.

Some authors tend to ignore the EMS and focus on the optimal sizing problem to reduce the computational load [13]. Wu et al. [14] proposed a methodology for optimal component sizing using a parallel chaos optimization algorithm (PCOA). Using the PCOA, the authors defined a cost minimization problem and regarded the requirements on vehicle performance as constraints. Cai et al. [15] presented a sizing-design methodology based on a flow diagram, and applied it to an unmanned underwater vehicle. Parameters for the ESS, and the fuel cell system were optimized. Eren et al. [16] studied the multi-objective optimum sizing of hybrid electric vehicles. The EMS was simply treated based on power flow analysis. Using this method, the authors defined a multi-objective problem and solved it using the mixed integer linear programming (MILP) method.

Some authors try to include a simple EMS, e.g. rule-based or thermostat strategy. Doucette et al. [17] compared the cost and fuel economy of integrating high-speed flywheels, batteries, or ultracapacitors with an FCS into an FCEV. Rule-based strategies were developed for different powertrain parameters. Ribau et al. [18] proposed the parameter sizing method for fuel cell city buses based on efficiency, cost, and life cycle CO_2. Analysis was conducted in ADVISOR with the default control strategy of thermostat. Ravey et al. [19] gave a new methodology based on energy flow analysis for a statistical description of driving cycles. A fuzzy logic-based EMS was developed to verify the effectiveness of the design. Sorrentino et al. [20] presented an integrated tool for component sizing of FCEVs. A thermostatic EMS was included in the model, and several parameters of the strategy were optimized. Kim et al. [21] set up an FCEV model with fuzzy control EMS and optimized powertrain parameters by comparing simulation results with different parameters. Cipollone et al. [22] presented a model-based design and an optimization method.

Other authors tried to optimize the powertrain parameters and EMS simultaneously. Murgovski et al. [23] solved the component sizing and energy management problem via convex optimization. Compared to dynamic programming (DP), convex optimization has similar results, and no curse of dimensionality. Similar results were also achieved by Hu et al. [24], who proposed the optimal sizing and EMS for an FCEV. These authors proposed a convex optimization framework and used a CVX tool for parameter optimization. Jain et al. [25] studied an optimal component sizing of an FCEV using a multi-objective generic algorithm regarding fuel economy and vehicle performance. Several Pareto optimal solutions were found for the vehicle. However, this study did not incorporate system durability. Vasallo et al. [26] studied the problem of optimal sizing for UPS systems based on battery and FCS. An optimal EMS was involved in the whole framework, but not explained in detail. Masoud et al. [27] proposed the problem for optimum sizing and EMS for battery life improvement. A DP algorithm was adopted as the optimal EMS. Hung et al. [28] studied a combined optimal sizing and EMS for in-wheel motors of EVs. They used a global search method (GSM) to solve the problem. Kim et al. [29] suggested a comprehensive and systematic framework to optimize EMS and component sizing simultaneously for FCEVs. A near-optimal EMS based on statistic dynamic programming (SDP) was chosen in simulation.

For EMS research, recent papers mostly focused on an optimized algorithm with single- or multi-objectives. Hemi et al. [30] presented an EMS for an FCEV based on Pontryagin's Minimal Principle (PMP) and the Markov chain. The Markov chain was adopted for power prediction in the algorithm. Chen et al. [31] gave a rule-based multi-mode algorithm for a range-extended electric vehicle. The rules-based strategy was developed according to a two-point boundary DP algorithm. Driving pattern recognition technology was also developed based on this strategy. Zheng et al. [32] studied an optimal control EMS based on PMP for an FCEV. Results show that a constant co-state can be used instead of a PMP algorithm because the open circuit voltage and resistance of the battery is kept almost constant during the operation. Segura et al. [33] proposed an EMS based on sliding control theory for the DC converter, which joins constant and variable frequency control technologies. Trovao et al. [34] presented a multi-level EMS for a multi-source electric vehicle. The strategy is separated into energy level and power level, and is mainly developed by using a rule-based algorithm.

From previous analyses, we derive the following viewpoints.

(1) EMS is always coupled with component sizing for a hybrid electric vehicle. It can be simplified using some rule-based strategies or near-optimal strategies, or treated as a low-level optimization problem in the whole component sizing optimization loop.
(2) Some algorithms, such as convex optimization, can solve the combined optimized problem for component sizing and EMS simultaneously.

This paper proposes a multi-objective optimization method for parameter sizing of an FCEV. An optimized EMS based on DP is included in the component sizing problem. Section 2 describes the powertrain topology of a fuel cell city bus, and presents the dynamic model regarding fuel economy and system durability. Section 3 defines the problem of parameter sizing, and introduces a two-loop framework based on Pareto optimization. The inside loop is built on a DP-based optimal EMS, and the outside loop is set up on comparison of different powertrain parameters for fuel economy and system durability. Section 4 gives the simulation results, and Section 5 is the conclusion.

2. Powertrain description and dynamic model

2.1. Powertrain structure

There are several different powertrain topologies in FCEV development history. At the beginning, a PEM FCS was the sole power source. However, it could not meet the quick dynamic requirement of an electric vehicle. Later, an ESS, e.g. a battery system or a super capacitor, was installed to compensate for the dynamic load. The FCS and an ESS can be connected with each other through different modes. They can be connected directly (upper part of Fig. 1(a)), or via a DC converter (middle and bottom parts of Fig. 1(a)). The directly connected system is simple, but the two power sources are uncontrollable. Since the FCS prefers to provide stationary power and the battery can provide dynamic power, a DC converter on the FCS side is favored (middle part of Fig. 1(a)).

This paper focuses on the powertrain system illustrated as in the middle part of Fig. 1(a). The PEM FCS provides stationary power, which equals to the average or part of the average power of the electric vehicle. A lithium battery system is installed as the ESS of the whole vehicle. A boost or bulk DC converter regulates the output power of the FCS. An EMS is designed (1) to fulfill the power requirement of the powertrain, (2) to minimize hydrogen consumption,