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Multi-objective energy management optimization and parameter sizing for proton exchange membrane hybrid fuel cell vehicles

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ABSTRACT

The powertrain system of a typical proton electrolyte membrane hybrid fuel cell vehicle contains a lithium battery package and a fuel cell stack. A multi-objective optimization for this powertrain system of a passenger car, taking account of fuel economy and system durability, is discussed in this paper. Based on an analysis of the optimum results obtained by dynamic programming, a soft-run strategy was proposed for real-time and multi-objective control algorithm design. The soft-run strategy was optimized by taking lithium battery size into consideration, and implemented using two real-time algorithms. When compared with the optimized dynamic programming results, the power demand-based control method proved more suitable for powertrain systems equipped with larger capacity batteries, while the state of charge based control method proved superior in other cases. On this basis, the life cycle cost was optimized by considering both lithium battery size and equivalent hydrogen consumption. The battery capacity selection proved more flexible, when powertrain systems are equipped with larger capacity batteries. Finally, the algorithm has been validated in a fuel cell city bus. It gets a good balance of fuel economy and system durability in a three months demonstration operation.

1. Introduction

Increasing awareness of environment pollution and the growing energy crisis have spurred interest in developing new energy technologies for automobiles. The fuel cell hybrid vehicle (FCHV), with its low environment impact, long range and zero pollution, has attracted the attention of enterprise and government. Although fuel cell hybrid system has been very popular in some areas, such as photovoltaic solar panels, wind turbine and fuel cell hybrid generation systems [1], and a battery-fuel cell hybrid powertrain system [2]. It suffers from great efforts from high manufacturing costs and a short service life.

The powertrain system of the FCHV is more complex than that of conventional vehicles, and usually contains at least two energy sources: a fuel cell system (FCS) and an energy storage system (ESS), for example, a lithium battery (Li-battery) system or a super capacitor (CS) [3]. Both parameter sizing of the components and energy management strategy (EMS) must be optimized. The system that links the two parts is called intercoupling.

The EMS is designed to achieve an optimal power allocation between the two energy sources. Applying optimization theory, two approaches can be defined: rule-based strategies and optimization-theory-based strategies.

Usually a rule-based strategy can be used for real-time control. Hemi et al. [4] used a fuzzy logic algorithm to control the powertrain system. It was effective in real-time control, but the optimization results were dependent on the design of the fuzzy rule. Optimization-theory-based strategies are more effective in optimization. Dynamic programming [5] is the most commonly used algorithm for global optimization. And Pontryagin's minimum principle (PMP) combined with markov chain [6] or traffic preview information [7] are effective for the forward optimization process. However, global optimization algorithms can't be used in real-time control directly, which require too much computation, it usually works as the theoretical guidance of real-time control strategy design.

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In addition to reducing fuel consumption, how to improve the durability of FCS and ESS is also important. Torreglosa et al. [8] present a hierarchical control algorithm to satisfy the load power demand, to maintain the hydrogen tank level and the *SoC* of the battery, and to take also economic aspects into account. Guo et al. [9] proposed a complex rule-based strategy to keep the state of charge of the batteries within an optimal range and meet power demand of the locomotive at a high efficiency. Xu et al. proposed a three mode (start up, normal working and shut down) real-time control strategy [10], combined with an adaptive supervisory controller (ASC) [11], to minimize the fuel consumption, extend the battery charge, and improve the fuel cell durability of a fuel cell/ Li-battery hybrid city bus. However, the optimization strategies of system durability in prior researches are usually based on the engineering experience, and the adaptability of EMS in different configurations is not taken into consideration.

The optimization of components parameter sizing is another focus of the study, because it decides the potential of powertrain system and affects the efficiency of EMS. Muhsen et al. [12] proposed a differential evolution based multi-objective (Loss of load probability, life cycle cost and the volume of excess water) optimization algorithm to optimally size a photovoltaic water pumping system (PVPS). Gan et al. [13] developed a model-based sizing tool for Hybrid wind–photovoltaic–diesel–battery system by empirical approach, life-cycle cost and performance analysis. Ravey et al. [14] proposed a novel methodology based on the statistical description of driving cycles to size the energy source of FCEV, and applied it to a collection truck working in fixed cycles. However, prior researches of parameter sizing mainly focus on the dynamic performance or system cost. The influence of parameter sizing on EMS design is ignored.

Because the optimizations of the EMS and parameter sizing are linked, some authors have tried to optimize them simultaneously. Kavvadias et al. [15] proposed an electrical-equivalent load following strategy for a trigeneration plant with better economical efficiency and performance characteristics, and a parametric analysis design method to define the optimal investment size. Hung et al. [16] developed a combined optimal sizing and control approach by using the global search method to minimize the accumulated energy consumed during predefined cycle. Liu et al. [17] proposed a power source sizing model by applying the Pontryagin's minimum principle (PMP) as an energy management strategy, to optimize the battery life and reduce battery energy loss, fuel consumption, and powertrain cost. While the FCS durability is neglected and the influence of parameter sizing on EMS design is still unclear.

From the literature review, the following conclusions were reached about the boundedness of prior researches:

(1) The adaptation of EMS is imperfect, and can only can be applied to a specific FCEV. In addition, the optimization results are off-line and need much computation, which is unsuitable for real-time control strategy design.
(2) The optimization of parameter sizing and the EMS are usually separate issues, prior researches mainly focus on the optimal results of EMS, and the impact of parameter sizing on the EMS design is uncertain.
(3) Fuel cell durability plays a minor role in the optimization of parameter sizing and the EMS design. While fuel cell stack is a very expensive and damageable component, which can't be neglected.

In consequence, the multi-objective real-time EMS design by taking Li-battery size into consideration for FCHV is a novel issue, which few literatures has discussed. To be specific, fuel economy and system durability, parameter sizing, and EMS design are three intercoupling problems. The fuel economy, including Li-battery durability and FCS durability, is minimized by using the DP approach. In the DP analysis, the characteristic of optimization results for a system with different size Li-batteries and auxiliary power consumption are considered and compared. Generally, the service life of Li-battery is longer than FCS's. When FCS is scrapped, the rest service life of Li-battery is wasted. With advances in fuel cell service life, how to balance the fuel economy and manufacturing cost is also considered. At last, all the factors above need to be considered simultaneously, when designing a real-time EMS. In consequence, it's necessary to propose an adaptive real-time energy management design strategy to solve these problems simultaneously.

This paper proposes a novel multi-objective optimization EMS design using a soft-run strategy for the design of a fuel cell/Li-battery hybrid system energy management algorithm. A soft-run strategy based on DP focuses on fuel economy, system durability and the adaptation of the Li-battery sizing. Section 2 describes the structure of a hybrid powertrain system and introduces a mathematic model for fuel economy, Li-battery durability, and fuel cell durability. Section 3 defines the soft-run strategy based on the optimization results of the DP algorithm. Section 4 discusses the evolution of a soft-run strategy with battery sizing change, and the validation through simulations of two strategies based on the soft-run strategy. Section 5 defines a life cycle cost function and the optimization of Li-battery sizing with different service lives of the fuel cell stack. Section 6 presents the validation of the Soft-run strategy in a fuel cell city bus. Section 7 presents the conclusions.

2. Structure of the powertrain and multi-objective quantitative model

How to model the powertrain system and the optimization objectives is the basis for this problem. Especially for a multi-objective optimization problem, the weight of each part in the quantitative model can significantly affect the optimization results.

2.1. Fuel cell system

The configuration of powertrain system on which this paper is based is shown as Fig. 1. The FCS is connected to the bus via DC/ DC converter and supplies energy to the motor in parallel with the Li battery. This research attempts to improve fuel economy and durability by optimizing the power distribution strategy.

Based on related parameters of the FCHV in Table 1, this paper introduces a multi-objective optimization problem and defined in terms of fuel economy and system durability.

2.2. Equivalent hydrogen consumption model

The energy consumption of a FCHV involves both hydrogen and electricity. When evaluating fuel economy, it is necessary to ensure

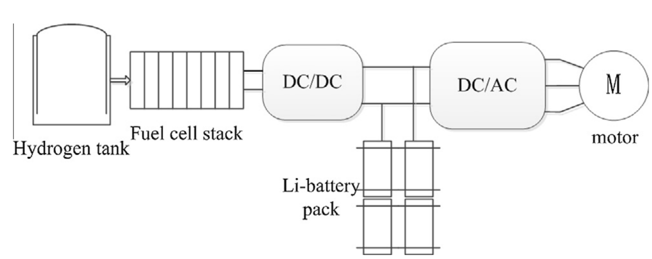

Fig. 1. Structure of FCEV.