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Development of robust suboptimal real-time power sharing strategy for modern fuel cell based hybrid tramways considering operational uncertainties and performance degradation

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HIGHLIGHTS

- The influence of operational uncertainties on energy management strategies is discussed in detail.
- A suboptimal real-time power sharing strategy considering operational uncertainties and performance degradation is proposed.
- The energy management strategy applied to two preferable indirect hybrid topologies is evaluated.
- The influences on tramway operation robustness, fuel economy and performance degradation balancing are verified.

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ABSTRACT

The powertrain system of modern PEMFC based hybrid tramways typically contains a PEMFC system and a hybrid energy storage subsystem when combing a lithium-ion battery (LIB) modules with a supercapacitor (SC) bank. Based on the detailed analysis of stochastic uncertainties in tramway operation, a suboptimal real-time power sharing strategy considering operation uncertainties as well as fuel economy and system durability is proposed in this paper. The proposed energy management strategy consists of three modules, namely the fundamental real-time penalty power sharing module, the fuzzy-logic based differential power compensation module, and the Rainflow-based predictive SOC balancing module. Firstly, suboptimal real-time power sharing among different energy sources is achieved in the fundamental real-time penalty power sharing module. Secondly, a fuzzy-logic based differential power compensation module is designed to achieve the performance degradation balancing between PEMFCs and LIBs. Furthermore, a Rainflow-based predictive SOC balancing module is developed to realize adaptive updating concerning key parameters of the above two modules based on historical SOC information identification of SC subsystem and enhance the robustness to stochastic uncertainties. Detailed simulation results demonstrate that the proposed energy management strategy can guarantee operation stabilization of PEMFC based hybrid topologies throughout the simulated driving cycle. The influence of the proposed energy management strategy on the service life of the PEMFC subsystem and fuel economy of hybrid tramway is discussed in detail. Finally, the proposed energy management strategy with optimized PEMFC and HESS both decoupled topology is verified to be more suitable for PEMFC-based hybrid tramway applications with minimum equivalent hydrogen consumption and performance degradation balancing among hybrid energy sources, compared with other reductant hybrid configuration-based energy management strategies.

1. Introduction

As an important carrier of hydrogen power generation, PEM fuel cells can provide environment-friendly power for the development of society and economy with the advantages of high efficiency and emission reduction [1–3]. With the development of commercial PEMFC integration technologies, the PEMFC power module is featured with broad application prospects in the fields of co-generation, power stations, electric vehicles and rail transit [2,4]. Especially, the great improvement in service life and power density for integrated high-power

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PEMFC modules has made it an attractive proposition in high-performance hybrid tramway applications [5–7].

Because of the relatively slow dynamic response of the PEMFC system, an energy storage system (ESS) is required for PEMFC-based hybrid tramways to satisfy tramway dynamics. For middle-power hybrid applications such as electric vehicles, a configuration with the individual lithium-ion battery (LIB) module or supercapacitor (SC) bank is sufficient [3]. However, the hybrid ESS that combines both LIBs and SCs is expected to be a more promising solution to hybrid tramway applications with synergistically enhanced overall performance owing to the prospect of mutually compensating deficiencies [8,9]. Chen et al. [10] optimized the hybrid configuration for a hybrid locomotive powered by PEMFCs, LIBs and SCs in typical cases of the maximum speed, acceleration and slopes. In addition, the optimization result showed that space saving and mass reduction benefiting from the optimized hybrid configuration can be achieved. Zhang et al. [11] enhanced the power of fuel cells, LIBs and tractive motors for a hybrid locomotive using the bisection algorithm under the gradeability and acceleration time constraints, and the improvement in dynamic performance and fuel economy was demonstrated. On this basis, many robust energy management strategies (EMS) have been proposed. According to Torreglosa's work [12], Pablo et al. [13] evaluated the designed powertrain based on three energy sources, namely fuel cells, LIBs and SCs, and five energy management strategies were compared from the viewpoint concerning the minimization of equivalent fuel consumption for the hybrid power system and average SOC fluctuations of the ESS, while according to Hanane [14], Li et al. [15] put forward an improved power sharing strategy with the fusion of Haar wavelet transform and fuzzy logic control for the PEMFC-LIB-SC hybrid tramway under development. In this system, the power captured from the backward simulated driving cycle was decomposed into high-frequency and low-frequency counterparts based on the dynamic responses of different energy sources, and the PEMFC subsystem was responsible for covering the low frequency power. Furthermore, the maintenance concerning the average SOC of the ESS was ensured by the inherent symmetrical characteristics of Haar wavelet transform. To achieve equivalent consumption minimization and alleviate the stress on the hybrid power system, a power management strategy based on adaptive droop control is further proposed for PEMFC based large-scale and high-power hybrid tramway [16]. On this basis, Han et al. [17] proposed a multi-source coordination EMS for the sake of improving the SOC consensus for the PEMFC-based hybrid power system which is equipped with multi-ESS. A penalty function based on adaptive self-convergence droop control was proposed in this paper to guarantee the SOC consensus of multi-ESS under different operation conditions. These studies showed that HESS can successfully meet power and energy requirements with reduced dimensioning, while reducing LIBs stress with the load-level aiding of SCs. Therefore, a HESS configuration combining with LIBs and SCs is recommended for high-performance high-power tramway applications. However, the fuel economy enhancement from EMS optimization is not considered in these strategies. A basic consensus is that the optimization of the hybrid configuration and energy management strategy is coupled with each other, that is, the EMS optimization problem can't be avoid when solving a hybrid configuration optimization problem. Although the optimization complexity is increased, the optimum power allocation among different energy sources can be enhanced.

Consequently, an optimized EMS with hybrid configuration dimensioning and well-defined driving cycles is expected for optimal hybrid tramway operation. In most cases, driving cycles are predefined (or from real tests) in the development of configuration optimization-based EMSs. In recent years, some researchers have focused on the joint optimization of hybrid configuration and EMSs for PEMFC based hybrid tramways with predefined or real-test driving cycles [18–20]. Hu et al. [18] solved the HESS dimensioning and EMS optimization of a fuel cell hybrid electric bus by combining both LIBs and SCs with efficient convex programming based on real-time driving cycles from a city bus-line test. Xu et al. [19] proposed a multi-objective joint optimization method based on dynamic programing (DP) for hybrid configuration and EMSs of an FCEV, and the fuel economy and system durability were both considered. Based on predefined driving cycles, the above studies optimize the power sharing strategies among multiple energy sources. However, these offline optimization processes are not suitable for real-time applications due to increased algorithm complexity and the requirement for a priori knowledge of the driving cycle. Therefore, the design of a real-time energy management strategy is inevitable, and many real-time power management strategies have been also proposed which can be categorized as proportional-integral control [21,22], fuzzy logic control [14,23], rule-based control [24], sliding mode control [25], and model predictive control [26,27] to achieve efficiency maximizing or minimum hydrogen consumption. Among them, it should be mentioned that Hu et al. [28] designed a multi-objective optimization based soft-run strategy framework for an FCEV based on the NEDC driving cycle. Some critical criterions are derived from the optimization results to form a simplified soft-run strategy. It shows that the performance of the derived soft-run strategy is equivalent to that of the DP optimization-based EMS with optimal hybrid configuration.

Moreover, whether the predefined driving cycle is optimized or not has a significant impact on system performance and fuel economy, although many standard driving cycles have been provided [29], especially for PEMFC based hybrid power system in which performance degradation and fuel economy need to be fully considered. On the one hand, the energy-efficient problem in tramway driving cycle optimization has been in-depth researched. Based on the Pontryagin maximum principle (PMP), Howlett et al. [30] found the necessary conditions for an optimal journey on some certain gradients for a hypothetical hold strategy at constant speed and identified the energy saving driving trajectory on a flat track, which is currently well known in the railway operation. On this basis, PMP based optimization algorithms can be obtained by minimizing a Hamiltonian function [31,32]. However, as the co-states in the utilized Hamiltonian function are determined by a trial-and-error method, the PMP-based method cannot ensure the global optimization [33,34]. Therefore, many multi-variables global optimization methods based on swarm intelligence algorithm are proposed [35–37]. Gu et al. [37] put forward a new model for energy-efficient tramway operation and derived energy-efficient operation strategies when combining the analytical method with the numerical method. Furthermore, Fernández-Rodríguez et al. [36] proposed a method of designing robust and efficient speed profiles when considering the uncertainties in the traffic operation including the train load and delays. In these studies, the optimal control problem can be solved under varying gradient and speed restrictions, but the model complexity and optimization accuracy have to be compromised. On the other hand, the evaluation of driving cycle mismatch has also attracted the attention of some researchers. Based on the tractive driving system model, some researchers have attempted online mass estimation with event-based and averaging methods. Event-based methods seek for driving conditions that provide sufficient excitation for mass estimation with GPS (Global Positioning System) to derive mass estimation [38] and supervisory control approaches [39]. Instead of seeking for events, averaging methods continuously monitor the vehicle dynamics to directly estimate the mass online, using recursive least squares (RLS) [40,41] and adaptive observer [42,43]. Besides, velocity prediction and driving pattern recognition can also utilized to evaluate the driving cycle mismatch with artificial neural network algorithm [44], torque requirement exponentially decreasing model [45] or Markov Chain based velocity predictor [46]. However, as the current driving condition is usually identified according to historical driving information and assumes that the driving condition will not change, misidentification cannot be avoided [47].

From the literature review, the following limitations of prior studies can be found.