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Development of master-slave energy management strategy based on fuzzy logic hysteresis state machine and differential power processing compensation for a PEMFC-LIB-SC hybrid tramway

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HIGHLIGHTS

- A power system model for the PEMFC based commercial hybrid tramway was established.
- An energy management strategy based on master FuHSM and slave DPPC was proposed.
- The optimal OER operation of PEMFC subsystem was achieved.
- The real-time EMS based HCM optimization was achieved.
- The influence on system fuel economy and PEMFC performance degradation was verified.

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ABSTRACT

A hybrid power system configuration based on proton exchange membrane fuel cell (PEMFC), lion-lithium battery (LIB) and supercapacitor (SC) was designed without grid connection for the hybrid tramway. To adapt to the rapid load power change and achieve higher fuel efficiency and optimal oxygen excess ratio (OER) operation of the PEMFC power subsystem, a master-slave energy management strategy based on fuzzy logic hysteresis state machine (FuHSM) and differential power processing compensation (DPPC) was proposed for the hybrid tramway, effectively taking into consideration of the dynamic response and optimum OER tracing of the integrated PEMFC subsystem. The master FuHSM controller was utilized to grantee the optimal power coordination of the multiple power sources and the slave DPPC controller was responsible for further compensating the load power demand to enhance the dynamic performance and bus voltage stability. Furthermore, the equivalent H_2 consumption minimization optimization considering characteristics of the proposed energy management strategy was realized by means of EIA-PSO algorithm to further improve the fuel economy of the overall hybrid power system. The results demonstrate that the proposed energy management strategy can guarantee the stability of the hybrid power system throughout the driving cycle. In addition, more efficient power coordination dynamics among the PEMFC, LIB and SC subsystems could be achieved without additional performance degradation of the integrated PEMFC subsystem, and the results of the comparisons with other control strategies verify that the proposed energy management strategy could achieve an increase in fuel efficiency of nearly 7% for the overall hybrid tramway. Finally, the influence of the proposed energy management strategy on the service life of the PEMFC subsystem was detailed discussed, and the performance degradation of the PEMFC subsystem was quantified so as to be integrated into the proposed energy management strategy.

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1. Introduction

Proton exchange membrane fuel cell (PEMFC) is an electrochemical reaction device in which the chemical energy of the fuel can be converted to electrical energy under normal temperature. It has the advantages of high efficiency and environment-friendly because of its independence on combustion process [1,2]. In recent years, the great improvement in the development of integrated high power PEMFC technologies has made it possible for the PEMFC-based power system to be more widely utilized in the rail transportation applications such as hybrid tramway and so on. The commercial high power integrated PEMFC systems has yielded an average electrical efficiency of 45–55% [2,3], which is more than 10% higher than that of the commercial internal combustion motor. The idling of the latter for generating the carbon power achieves has approached 20% [4,5]. Thus, PEMFC-based hybrid power system has become an attractive proposition in high-performance hybrid tramway applications [6–9].

Nowadays, the demonstration and application of low/middle power PEMFC-based hybrid system have already been available in vehicle propulsion, truck auxiliary power unit and renewable energy system. Many literatures have focused on the hybrid architectures of these PEM fuel cell based system applications [4,6–9]. Synthetically considering the system indices of the nominal power demand, the power fluctuation, and the constrained space dimensions for the integrated low/middle power hybrid applications, the supercapacitor (SC) with higher specific power and the Lithium-ion battery (LIB) with higher specific energy are usually chosen for the energy storage subsystem (ESS). These PEMFC-based hybrid systems can be mainly divided into two classes which are namely direct (passive) and indirect (active) hybrids.

In the case of direct hybrids, the PEMFC and ESS are connected directly or with switch/diode devices to simply protect fuel cell from reverse power flow, as it cannot withstand reverse current. Then the integrated hybrid power system is directly connected to the DC bus [4,9,10]. However, the active power regulation between the energy sources and the cascaded power load cannot be achieved with the resulted simple hybrid topology. Additionally, the power split between the PEMFC and ESS is passively dependent on the share of their internal resistances. For the PEMFC portion with a soft V-I output characteristic, a small change in output voltage will result in slight variation in output power, and a large alteration in the ESS power for a given sharing of the power demand. Under this condition, the transient power fluctuation will more easily exceed the limit of ESS with a minimal power scheduling effect for PEMFC, which will lead to system breakdown. Therefore, the voltage deviations of both energy sources must be the same at each operation point, which is generally difficult for energy sources with different output characteristics. To force a high voltage deviation of fuel cell stack, Bernard et al. [11] presented an active control topology by adjusting the operating pressure of the fuel cell to regulate the output voltage and further the output power of fuel cell. The results show that this method is feasible for pure H_2/O_2 fuel cell stacks to achieve an acceptable energy efficiency. Nevertheless, improper pressure adjusting will result in the oxygen starvation which will worsen the internal electrochemical reaction environment and eventually reduce the service life of the high power integrated PEMFC modules. Hence, this method is not recommended for high power fuel cell applications. Besides, this type of configuration is only suitable for the application with low average energy demand. The ESS can meet the most energy demand, while the fuel cell in turn charges the ESS under a nearly constant operation condition to achieve a high efficiency [4,12]. Obviously, this configuration cannot make full use of the endurance capability of on-board hydrogen energy. To make the sharing of power demand between fuel cell and ESS more reasonable, Morin et al. [13] proposed a novel direct hybridization topology with PEMFC - supercapacitor (SC) pairs with higher specific power, which can realize a passive transient power sharing between a single PEM fuel cell and SC. The maximum buffering effect of the hybrid system can be achieved with the match between the number of SCs and the open circuit voltage of the PEMFC stack [14]. Nevertheless, this modified topology requires the nominal power output of the PEMFC stack to cover the rated power demand. This condition restrains its extension to high power applications, as it is only necessary for the on-board PEMFC power system to take charge of the average power demand. Besides, the voltage deviation predominated by direct hybrid energy sources will make the efficiency optimization of cascaded traction or auxiliary subsystems more difficult, because it needs additional voltage conversion components and the efficiency advantage benefited from the direct hybrid would be weakened. All the problems mentioned above are critical for the realization of an optimum energy scheduling for high power hybrid tramway.

In contrast to direct hybrids, at least one energy source is connected to a voltage converter in indirect hybrids. This energy source can be used for decoupled design, and its operation can be more independent and intelligent. The disadvantages of indirect hybrids lie in a more complex system topology and a reduced efficiency due to the losses at the voltage converter. Nonetheless, direct hybrids must face problems, including the impedance matching among different energy sources, DC bus voltage variation, and oxygen starvation of fuel cell subsystem. The optimum energy management can be realized with indirect hybrid topologies using appropriate dimensioning methods and advanced control strategies. In the case of indirect hybrids, the development of energy management strategies for PEMFC-based hybrid propulsion system has become a topic of interest. Das et al. [15] reviewed different indirect hybrid topologies for fuel cell hybrid propulsion systems in transportation applications. Their differences could be identified by the electrical connection of the FC and ESS with DC bus. The related energy management strategies were categorized into classic control, filtering [7,16,17], heuristic strategies [18–20], fuzzy control [21,22], and optimizing strategies [23,24] to achieve efficiency maximization or minimum hydrogen consumption. On this basis, many strategies were proposed in the real-time power sharing procedure of multiple energy sources with fuel economy, taking system durability into consideration, to coordinate the multiple energy sources accordingly. Erdinc et al. [11] put forward an energy management strategy integrated with the fusion of wavelet transform and fuzzy logic control for a fuel cell/battery/supercapacitor hybrid vehicular power system. In this system, fuel cell can be downsized to meet the average power demand without facing peak loads, and braking energy can be recovered by the ESS. However, the filter length in the time domain makes wavelet transform unsuitable for real-time control, which has been improved by the power sharing strategy (proposed in [10]) that combines the Haar-wavelet with fuzzy logic control. Based on Torreglosa's work [25], Pablo García et al. [26] evaluated the options of using a new powertrain based on fuel cell, battery, and SC for the tramway. Five energy management strategies used for controlling the components of the new hybrid system were compared for the optimization of the fuel consumption by applying an equivalent consumption minimization strategy. Taking fuel economy and system durability into consideration, Liangfei Xu et al. [27–29] developed a multi-mode real-time control strategy based on three typical processes of the fuel cell system for a fuel cell electric vehicle. Qi Li et al. [3] presented a state machine strategy based on droop control for an energy management system of PEMFC-battery-supercapacitor hybrid tramway. For this system, the circulating currents are limited through drop control and voltage adjusting can benefit from the modification of power injections and absorptions with the state machine-based control strategy. Besides, there are also other approaches based on time delay control [30,31] and non-linear sliding mode control [32,33] to enhance the dynamic performance of the controllers for low-level power converters. The application of these control strategies becomes possible through the decoupling of at least one energy source from the voltage bus. By means of this decoupling, the voltage of one component can be set independently, and then the others must meet the rest power demand.