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Optimized power management based on adaptive-PMP algorithm for a stationary PEM fuel cell/battery hybrid system

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ABSTRACT

This research develops an efficient and robust polymer electrolyte membrane (PEM) fuel cell/battery hybrid operating system. The entire system possesses its own rapid dynamic response benefited from hybrid connection and power split characteristics due to DC/DC buck-boost converter. An indispensable energy management system (EMS) plays a significant role in achieving optimal fuel economy and in a promising running stability. EMS as an indispensable part plays a significant role in achieving optimal fuel economy and promising operation stability. This study aims to develop an adaptive supervisory EMS that comprises computer-aided engineering tools to monitor, control, and optimize the performance of the hybrid power system. A stationary fuel cell/battery hybrid operating system is optimized using adaptive-Pontryagin's minimum principle (A-PMP). The proposed algorithm depends on the adaptation of the control parameter (i.e., fuel cell output power) from the state of charge (SOC) and load power feedback. The integrated model simulated in a Matlab/Simulink environment includes the fuel cell, battery, DC/DC converter, and power requirements models by analyzing the three different load profiles. Real-time experiments are performed to verify the effectiveness of EMS after analyzing the simulated operating principle and control scheme.

Introduction

At present, the continuously worsening air pollution has resulted in emission regulations becoming increasingly stringent. The current demands for innovative and environment-friendly energy systems are increasing globally [1]. Accordingly, polymer electrolyte membrane (PEM) fuel cell can be utilized as a clean and portable power supply, given this fuel cell's advantages of zero emission, rapid start up, high fuel efficiency, low operation temperature and superior performance [2]. PEM fuel cell is considered as a potential power source in vehicle application and highly recommended for residential power generation because of the aforementioned advantages. However, the use of independent fuel cell system have a few disadvantages including its inability to immediately deliver power because of the slow response

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caused by the capacitance effect, flow delays, mechanical characteristics of the pumps, and thermodynamic characteristics [3]. For example, when the load varies rapidly, the fuel cell encounters several problems related to fuel starvation, which has a considerable effect on the power utilization efficiency, reliability and life time of the fuel cell. By contrast, a hybrid power systems composed of fuel cell and battery entails that the PEM fuel cell generation systems uses hydrogen energy and the battery uses chemical energy as an additional immediate power generator. Therefore, a hybrid power supply system can provide an improved utilization of renewable energy. The goal of using a hybrid power supply system is to maximize the advantages of various power generation technologies and to avoid their weaknesses [4]. Compared with a fuel cell power, a lithium-ion battery has a considerably immediate response to a rapid load change. Accordingly, the fuel cell isn't used as a unique power source and hybrid power system based on fuel cell/battery is preferred [5]. The performance of a hybrid power system depends on the different topologies of hybrid connection. Jiang at al [6]. evaluated the different connections of a hybrid power systems. In the proposed system, the PEM fuel cell and battery act as the primary power and auxiliary power supplies, respectively. The fuel cell is connected to the load via a unidirectional DC-DC converter and inverter. The battery is directly attached to the DC bus. However, the performance of the hybrid power system depends on the hybrid connections and energy management system (EMS) strategy. EMS is an essential component of a hybrid power system and plays an irreplaceable role in achieving fuel economy and system stability [7]. Therefore, developing an EMS that provides excellent performance is regarded as a pivotal step in system construction. Hence the development of EMS with a superior performance has attracted the interest of numerous researchers. This study intends to evaluate the performance of the proposed hybrid power system and EMS involved in rational power distribution in fuel cell and battery for a stationary application. The functions of EMS include monitoring of role of each energy source and interaction between the different sources and coordinating the operation of the entire system. Thus, the control scheme of a hybrid power system is more complex than that of a unique power source system [8].

The research on EMS of hybrid power system covers a broad area, particularly the DC-DC converter control and energy management strategies design. The DC-DC converter as an actuator of splitting the power between the fuel cell and battery is irreplaceable in terms of implementing EMS [9]. Hence, a variety of EMS are proposed based on various power management objectives. Zheng et al. [10] proposed a fuel consumption minimization control based on the minimum principle but without a battery state-of-charge (SOC) constraint. Rules-based method of state machine control (SMC) is familiar to researchers because of easy implementation in a real-time system. He et al. [11] utilized the SMC method to guarantee maximum safety in discharging and charging batteries. Fuzzy logical control methodology can be combined with intelligent power management techniques popularly applied on real-time control system, which is extensively used in various power management objectives, such as fuel minimization, lifetime extension, fuel cell/battery protection, and system stability [12–16]. Li et al. [17] presented the simulation results of fuel consumption using fuzzy logic to improve overall efficiency of a system. Model predictive control (MPC)-based methodologies also are extensively used in EMS of a hybrid power system. Borhan et al. validated the use of different cost functions to minimize the fuel consumption [18]. Torreglosa et al. [19] developed an MPC management system for hybrid powertrain to achieve the proper operation of energy sources and simulated the suitability of the proposed powertrain and control strategy. Another typical project that involved the MPC method using a multi-step Markov prediction model was constructed to predict the driving velocities following the model predictive control (MPC) [20]. However, the aforementioned EMS have difficulty in achieving global optimization in fuel consumption. Dynamic programming (DP), which is a global optimization method, is recursive optimization procedure and popularly applied to the optimal power allocation of a hybrid power system [21]. However, DP is hardly used in a real-time control system because of the high cost of calculation and unpredictability of the load cycle [22]. Optimal control methods based on Pontryagin's minimum principle (PMP) is preferred strategy over DP [23]. An adaptive-PMP (A-PMP) is employed to achieve a blended trajectory of SOC to minimize fuel consumption, thereby resulting in a generally better performance than that of the actual charge depleting/charge sustaining (CD/CS) strategy currently used on-board vehicles [24]. Although numerous EMS are proposed and discussed, several studies remain in the simulation stage without validation through experiments.

The current study constructs an efficient and robust PEM fuel cell/battery hybrid operating system for stationary use. A hybrid power system can overcome a low dynamic response and prolong the lifetime of fuel cell. In the proposed system, the PEM fuel cell acts as a primary power supply and the battery serves as an auxiliary power supply. The effectiveness of the hybrid system is substantially dependent on its control strategy. A-PMP is employed in EMS to achieve fuel minimization in a real-time system. The output power of the fuel cell and the battery SOC constraint problems are solved by introducing a cost function based on the A-PMP optimal control. The integrated model studied system of EMS is simulated in Matlab/Sinmulink environment. The operating principle and control scheme are analyzed in detail and verified by the simulation and experiment results.

Modeling a hybrid power system

This research constructs a hybrid power system model consisting of a PEM fuel cell system and a lithium-ion battery will be simulated to analyze the system's performance with different load profiles. The mathematical and electrical models of the hybrid power system and energy management strategy of PMP are modeled in detail and simulated in MATLAB/Simulink. The PEM fuel cell system as a primary power source connects a DC-AC inverter via a unidirectional DC-DC converter. An auxiliary power source (i.e., lithium polymer battery) is attached to the bus between the DC-AC inverter and DC-DC converter and establishes a parallel connection to fuel cell stack. The specifications of the system and hybrid