INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 10094–10103

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Experimental investigation on the online fuzzy energy management of hybrid fuel cell/battery power system for UAVs

Xiaohui Zhang, Li Liu, Yueling Dai, Tianhe Lu*

School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

ARTICLE INFO

Article history:
Received 2 November 2017
Received in revised form
16 January 2018
Accepted 9 April 2018
Available online 2 May 2018

Keywords:
Online energy management
Fuel cell
Battery
Hybrid power system
UAVs

ABSTRACT

The hybrid powerplant combining a fuel cell and a battery has become one of the most promising alternative power systems for electric unmanned aerial vehicles (UAVs). To enhance the fuel efficiency and battery service life, highly effective and robust online energy management strategies are needed in real applications.

In this work, an energy management system is designed to control the hybrid fuel cell and battery power system for electric UAVs. To reduce the weight, only one programmable direct-current to direct-current (dcdc) converter is used as the critical power split component to implement the power management strategy. The output voltage and current of the dcdc is controlled by an independent energy management controller. An executable process of online fuzzy energy management strategy is proposed and established. According to the demand power and battery state of charge, the online fuzzy energy management strategy produces the current command for the dcdc to directly control the output current of the fuel cell and to indirectly control the charge/discharge current of the battery based on the power balance principle.

Another two online strategies, the passive control strategy and the state machine strategy, are also employed to compare with the proposed online fuzzy strategy in terms of the battery management and fuel efficiency. To evaluate and compare the feasibility of the online energy management strategies in application, experiments with three types of missions are carried out using the hybrid power system test-bench, which consists of a commercial fuel cell EOS600, a Lipo battery, a programmable dcdc converter, an energy management controller, and an electric load. The experimental investigation shows that the proposed online fuzzy strategy prefers to use the most power from the battery and consumes the least amount of hydrogen fuel compared with the other two online energy management strategies.

Introduction

Fuel cell based power system for UAVs has become a hot research topic in aviation industry and in academia [1–3]. The use of a hybrid power system, in which a fuel cell is combined with a battery, can reduce the design difficulty in fuel cell powered UAVs by power decoupling. The hybrid power system can support fast responses to demand power fluctuations, especially during the high-power transient. However,

* *Corresponding author.*
E-mail address: liuli@bit.edu.cn (L. Liu).
https://doi.org/10.1016/j.ijhydene.2018.04.075

the difference in dynamics characteristic between the fuel cell and the battery makes the hybrid power system highly coupled and structurally complicated. Therefore, effective and efficient energy management strategies are very important and necessary in design of hybrid fuel cell/battery power systems.

The realization of energy management strategies relies on the hybrid power system architecture. In general, the fuel cell is directly controlled by a unidirectional dcdc converter, and the battery directly connects with a bidirectional dcdc converter or an independent battery management system (BMS) in electric vehicles [4,5]. The energy management is done through the control of the dcdc converters and the BMS. However, the design of UAVs usually prefers the takeoff weight as low as possible. The dcdc and BMS together are simply too heavy to be used in UAVs. Thus, a light yet functional hybrid power system architecture is crucial in the design of UAVs.

Bradley *et al* [6,7] used a power management system for the charging and discharging control of battery, without considering the voltage matching of the fuel cell and the battery. But their energy management system is limited to the stage of concept without being further developed. Karunarathne *et al* [8,9] developed a model-based power and energy management strategy for the fuel cell/battery propulsion system. A unidirectional dcdc converter and a bidirectional dcdc converter were employed to control the fuel cell and the battery, respectively. The hardware electric circuits of converters were designed and fabricated. A simple finite state machine strategy was adopted for energy management. However, the whole power system design is very sophisticated and its weight should be too heavy for small UAVs. Verstraete *et al* [10–13] experimentally investigated the characteristic of the hybrid power system and the role played by the battery in such system by using a commercial AeroStack hybrid fuel cell/battery system, which was developed by HES Energy Systems Pte. Ltd [14]. The AeroStack hybrid system, which features the control of battery through a bidirectional dcdc converter, is basically developed from a concept similar to what proposed by Bradley et al. [6,7]. The fuel cell works with load-following mode, and the operation of the battery is in charge-sustaining mode. The hybrid power system is a highly integrated system and is quite convenient to be applied to UAVs [15,16]. But such system is not very flexible for other energy-management-strategy researches and the power allocation of fuel cell and battery cannot be accurately controlled, especially in the high-power demand situations.

Rule-based energy management strategies, including state machine, fuzzy logic, and artificial intelligence, are usually used online for hybrid fuel cell systems due to the low computational complexity [17]. The online fuzzy energy management strategies with higher level of robustness and flexibility have been simulated for real application in fuel cell vehicles [18]. A number of researchers also tried to use the fuzzy logic strategy in hybrid fuel cell/battery UAVs [8,19–21]. But all the studies still stay at the modeling and simulation stage. Very few studies addressed the performance of the hybrid fuel cell/battery power system for UAVs through experimental investigation.

In this study, an energy management system mainly including a programmable dcdc converter and an energy management controller is designed to manage the hybrid fuel cell and battery power system for UAVs. A test-bench of the hybrid power system is established and the characteristics of the fuel cell and battery are experimentally investigated. Based on the test-bench, an executable process of online fuzzy energy management strategy is proposed to control the power flow between the fuel cell and the battery. A pulsed-power profile is adopted in the experiment to evaluate the online fuzzy energy management strategy. The passive control strategy and the state machine strategy are also carried out to compare with the online fuzzy energy management strategy in terms of the battery management and the fuel efficiency.

Hybrid power system

A hybrid power system test-bench is designed and the schematic of it is presented in Fig. 1. In addition to the fuel cell controller, there is an independent energy management system including an energy management controller (EMC) and only one dcdc converter to achieve the direct control of the fuel cell and the indirect control of the battery.

Fuel cell system

A customized EOS600 proton exchange membrane fuel cell (PEMFC) made by Pearl Hydrogen Technology Co., Ltd [22], is used here as the main power source for small UAVs. The stack of the fuel cell has 42 cells and its static performance curves are shown in Fig. 2.

As a feature of the fuel cell, its controller is self-powered and it controls the cooling fan and the purge valve based on the internal temperature and the output power of the fuel cell. The carbon fiber hydrogen tank with a constant outlet pressure about 0.5 bar provides 99.999% high purity hydrogen to the fuel cell through a mass-flow meter (MF4000 by Siargo Ltd [23]) and the flow rate of hydrogen is sampled at 50 Hz to guarantee at least two samples are captured during the purging water process.

Battery

An ACE 6s-cell lithium-polymer (LiPo) battery with nominal capacity 5300 mAh [24] is selected as the auxiliary power, which connects in parallel with the dcdc converter through a current-voltage (CV) sensor to power the programmable electric load. The maximum discharge rate and the maximum charge rate of the battery are 30C and 5C, respectively. To protect the battery, the maximum charge voltage is set to 25.2 V and the lowest discharge voltage is limited to 22.5 V. The current and voltage (CV) sensor consists of two voltage dividing resistors for voltage measurement and one hall current sensor ACS756xCB [25] for current measure-ment. The CV sensor is calibrated each time before used in the hybrid power system.

Programmable dcdc converter

The fuel cell outputs power through a programmable buck-boost converter dcdc converter, which is the crucial execution component of the energy management process. The output voltage and current of the converter can be regulated by the energy management controller (EMC). A brief schematic of the