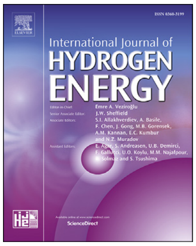
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–8

Available online at www.sciencedirect.com

ScienceDirect

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



Comparison of daily operation strategies for a fuel cell/battery tram

Wenbin Zhang [a,b,*], Liangfei Xu [a,c,d], Jianqiu Li [a,c,**], Minggao Ouyang [a,c], Yuwen Liu [e], Qingjun Han [e], Yankun Li [e]

[a] Department of Automotive Engineering, State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China
[b] Department of Scientific Research, Military Traffic Institute, Tianjin 300161, PR China
[c] Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing 100081, PR China
[d] Institute of Energy and Climate Research, IEK-3: Electrochemical Process Engineering, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[e] CRRC Qingdao Sifang Co., Ltd, Qingdao 266111, PR China

ARTICLE INFO

Article history:
Received 20 January 2017
Received in revised form
9 March 2017
Accepted 18 April 2017
Available online xxx

Keywords:
Fuel cell
Tram
Daily operation
Operation mode
Power allocation method

ABSTRACT

This paper focuses on describing the daily operation strategy of a tram powered by a hybrid system based on fuel cell stack and a battery pack. The daily operation strategy focusses on the hydrogen refueling and battery recharging timing in one-day operation of 18 h, combined with serval driving cycles and three operation modes. The battery state of charge balanced (SOC-) strategy and the dynamic programming (DP-) strategy are two proposed power allocation methods. For one-cycle operation, the latter save 6.6% hydrogen consumption than the former. As for one-day operation, a simplified DP-strategy is deduced to replace the DP-strategy and accelerate the calculation. It shares equivalent hydrogen consumption with the SOC-strategy but guarantees the durability of the fuel cell and prolongs the driving mileage.

Introduction

Trams are popular in large and medium-sized cities for they are comfortable, environmentally friendly and have great passenger capacity, low energy consumption and long service life [1]. Fuel cells serve as promising power supplies for they are much more efficient than the traditional combustion engines and practically null emission of polluting agents [2]. Attention nowadays has been paid on trams powered by fuel cells.

Since 2002, many countries or groups have demonstrated products of fuel cell rail vehicles. The North American consortium present a 1.2 MW large fuel cell hybrid locomotive equipped with a 250 kW fuel cell as prime mover and batteries as auxiliary power, which was developed for potential military

---

* *Corresponding author*. Department of Automotive Engineering, State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China.
** *Corresponding author*. Department of Automotive Engineering, State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China.
E-mail addresses: zhang-wb13@mails.tsinghua.edu.cn, cheerup2006@126.com (W. Zhang), lijianqiu@tsinghua.edu.cn (J. Li), ouymg@tsinghua.edu.cn (M. Ouyang).

http://dx.doi.org/10.1016/j.ijhydene.2017.04.151

Please cite this article in press as: Zhang W, et al., Comparison of daily operation strategies for a fuel cell/battery tram, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.04.151

and commercial applications [3]. Japan's Railway Technical Research Institute released a 120 kW fuel cell-powered railcar [4]. East Japan Railway Company provided a fuel cell hybrid railcar by modifying a prototype railcar based on a hybrid diesel–electric system, fitted with two 65 kW fuel cells and a 19 kWh Li-ion battery directly connected to the dc bus [5]. Italy issued a road-switcher by retrofitting a Trenitalia diesel–-electric D.145 locomotive with a fuel cell power plant integrated with a 120 kW fuel cell, a 600 Ah lead-acid traction battery and on-board pressure vessels containing 160 kg of hydrogen [6]. Hydrogen fuel cell–rail vehicle projects are demonstrated in other European countries such as Spain (24 kW fuel cell), Denmark (105 kW fuel cell) and Germany (80 kW fuel cell). China's first fuel cell locomotive was introduced by Southwest Jiao-tong University in 2013 [7]. However, China's first fuel cell tram, powered by a 150 kW fuel cell, 20 kWh Li-ion batteries and 450 Wh ultra-capacitors, was first tested in 2015 by CRRC Qingdao Si-fang Locomotive Co., Ltd. in collaboration with our group. The tram has maximum passenger capacity of 318 people and maximum speed of 70 km/h [1].

A typical topology of the fuel cell powered vehicle contains at least two power sources, a fuel cell system (FCS) and an energy storage system (ESS), e.g. a Li-ion battery or an ultra-capacitor, called a fuel cell hybrid vehicle (FCHV). Hybridization provides the following benefits: 1) downsizing the FCS; 2) alleviating the downside of a relatively slow dynamic response of the FCS; 3) shortening the warm-up time of the FCS; 4) rising the operational efficiency of the FCS; 5) prolonging the FCS lifetime [8–10].

For the hybrid structure of FCHVs, the power allocation methods among power sources are widely talked and mainly categorized into rule-based and optimization approaches [11]. Rule-based strategy can be implemented in real-time operations but the results are not the optimal. The optimization approaches can obtain optimal results but not for real-time applications. If the frequently released optimization approaches are divided by time domain, dynamic programming (DP) [12] and convex optimization strategies [13] are served as global optimization methods while Equivalent Consumption Minimization Strategies (ECMS) [14] and Pontryagin's Minimum Principle (PMP) strategies [15] are treated as instantaneous optimization methods.

For the hybrid trams, Bae et al. [16,17] simulated and tested a serial hybrid rubber-tired tram powered by a set of compressed natural gas engine and a Li-ion battery pack. Qi Li et al. have adopt a state machine controller [18] and a fuzzy logic controller [19,20] on the fuel cell/battery/ultra-capacitor tram to improve the fuel economy and powertrain efficiency. Garcia et al. have studied both the fuel cell/battery tram and the fuel cell/battery/ultra-capacitor tram. Four methods for power allocation are proposed and compared [21]: a state machine controller [22], a cascade controller [22], a fuzzy logic controller and ECMS [23,24].

However, none of the former studies have dealt with the daily operation of a fuel cell hybrid tram whose time scale is one day in which there may be frequent changes of operation modes. In this paper, three daily operation modes for the fuel cell/battery tram are studied and two power allocation methods are given and compared targeting at minimizing the daily hydrogen consumption and simultaneously improving the fuel cell efficiency and durability.

Power-train structure and system model

Power-train structure

Fig. 1 shows the structure of the fuel cell/battery tram and its specifications are given in Table 1. Corresponding to the congestion of the compartment, the tram mass has three levels marked as AW1~AW3. AW1 denotes an unloaded weight of 61.6 tons, AW3 represents a full load of 79.6 tons and AW2 is 75.1 tons. The tram is powered by a 230 kW fuel cell stack and a 120 Ah Li-ion battery pack. A boost DC/DC converter is arranged between the fuel cell stack and the bus to regulate the fuel cell output power. The Li-ion battery pack is connected directly to the bus whose end voltage represents the bus voltage. The traction systems include twelve three-phase electric motors regulated by three Variable Velocity Variable Frequency (VVVF) converters. The air-conditioner is the main accessories of the tram, the output power is about 40 kW in spring or autumn, and 85 kW in summer or winter.

Driving cycle

The driving cycle is related to the railway line, the tram mass and the accessory power. The railway line is determined in advance. The tram runs on a round railway line and a round trip L_{rtrip} is 13.14 km. The maximum speed of the tram V_{max} is limited to 50 km/h based on transport conditions. The tram mass has three levels and the accessory power has two choices. Therefore, six cases should be considered. For case one when the tram mass M is AW1 and the accessory power P_{aux} is 40 kW, the driving cycle are shown in Fig. 2.

The power demand P_{dmd} is deduced in Eq. (1) where P_m is the motor mechanical power, η_m is the motor and VVVF combined average efficiency (~82%). The power demand is supplied by the fuel cell and the battery expressed as Eq. (2). P_{fc}, P_{dc} and P_{bat} are the fuel cell, the DC/DC converter and the battery output power, respectively. η_{dc}(~91%) is the DC/DC converter average efficiency and $\eta_{fc,aux}$(~90%) is the fuel cell efficiency excluding its accessory components such as air compressors and cooling fans.

$$P_{dmd} = P_{aux} + P_m \cdot \eta_m^{-sign(P_m)} \tag{1}$$

$$\begin{aligned} P_{dmd} &= P_{dc} + P_{bat} \\ P_{dc} &= P_{fc}\eta_{fc,aux}\eta_{dc} \end{aligned} \tag{2}$$

Component model

Fuel cell stack is modeled based on experiment data [25] expressed as three curves: power to current (P_{fc}~I_{fc}), current to voltage (I_{fc}~V_{fc}) and power to efficiency (P_{fc}~η_{fc}) shown in Fig. 3(a)–(c). The hydrogen mass flow rate $\dot{m}_{H_2}$(kg/s) can be calculated by Eq. (3) where LHV is the low heart value of hydrogen (120 MJ/kg). The hydrogen mass flow m_{H_2} (kg) is the integer of $\dot{m}_{H_2}$ by time.

$$\dot{m}_{H_2} = \frac{P_{fc}}{LHV\eta_{fc}} \tag{3}$$

Please cite this article in press as: Zhang W, et al., Comparison of daily operation strategies for a fuel cell/battery tram, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.04.151