



Optimization for a fuel cell/battery/capacity tram with equivalent consumption minimization strategy



Wenbin Zhang^{a,b}, Jianqiu Li^{a,c}, Liangfei Xu^{a,c,d}, Minggao Ouyang^{a,*}

^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 Transport University, 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

ARTICLE INFO

Article history:

Received 10 August 2016

Received in revised form 26 October 2016

Accepted 4 November 2016

Keywords:

Fuel cell

Hybrid tram

Operation mode

Equivalent consumption minimization strategy

ABSTRACT

This paper describes a hybrid tram powered by a Proton Exchange Membrane (PEM) fuel cell (FC) stack supported by an energy storage system (ESS) composed of a Li-ion battery (LB) pack and an ultra-capacitor (UC) pack. This configuration allows the tram to operate without grid connection. The hybrid tram with its full load is tested in the CRRC Qingdao Sifang Co.; Ltd. It firstly works on the operation mode switching method (OPMS) without energy regenerative and proper power management. Therefore, an equivalent consumption minimization strategy (ECMS) aimed at minimizing the hydrogen consumption is proposed to improve the characteristics of the tram. The results show that the proposed control system enhances drivability and economy, and is effective for application to this hybrid system.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Trams, for their merits of comfortable, environmentally friendly, great passenger capacity, low energy consumption and long service life, are popular public transport in large and medium-sized cities [1]. Proton Exchange Membrane (PEM) fuel cell (FC), due to higher efficiency than the traditional combustion engine and practically null emission of polluting agents [2], is ideal promising power supply for electric vehicles (EVs) [3]. Therefore, PEM FCs have been tried in the propulsion system for rail vehicles. A 1 200 kW large fuel cell hybrid locomotive equipped with a 250 kW fuel cell as prime mover and lead-acid batteries as auxiliary power was developed for potential military and commercial applications by the North American consortium [4]. Japan's Railway Technical Research Institute released a 120 kW fuel cell-powered railcar [5]. East Japan Railway Company provided a fuel cell hybrid railcar fitted with two 65 kW fuel cell and a 19 kWh Li-ion battery [6]. Italy issued a road-switcher integrated with a 120 kW fuel cell and a 360 kWh lead-acid traction battery [7]. 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 [8]. However, China's first fuel cell tram, powered by a 150 kW fuel cell, 21 kWh Li-ion batteries and 0.5 kWh ultra-capacitors, was first tested in 2015 by CRRC Qingdao Si-fang Locomotive Co., Ltd in collaboration with our group, which is also focused in this paper.

From the examples above, to use the FC in dynamic applications for transport, the system must incorporate at least one energy storage system (ESS) [9], a Li-ion battery (LB) pack and/or an ultra-capacitor (UC) pack, which improves the system performance when the electrical load requires high powers in short periods of time, such as accelerations and decelerations. In comparison to pure FC powertrains, adding an ESS to form a hybrid powertrain is advantageous for the following main reasons: (1) FC exhibits slow dynamics and long start-up times; an ESS is needed to improve the responsiveness of the power source to abrupt load changes during accelerations; (2) in the hybrid system, the ESS helps meet the peak power demands, so that the FC needs to be sized according to the cruising demand only, not to the peak demand as in pure FC powertrains; (3) the ESS significantly improves the hydrogen economy by restricting the operation of the FC to high-efficiency operating points and by adding the possibility of regenerative braking [2]. In comparison with UC, LB used in hybrid vehicles powered by FC present a higher specific energy, which can generate an extra power for a longer period of time [10]. Today, at equal weight, the commercially available UC are capable

* Corresponding author.

E-mail addresses: zhang-wb13@mails.tsinghua.edu.cn, cheerup2006@126.com (W. Zhang), ouymg@tsinghua.edu.cn (M. Ouyang).

of generating a smaller amount of energy than the batteries can provide. In contrast, the UC are capable of delivering energy faster than batteries. However, the cost of hybrid vehicles that integrate FC and UC is higher than those that use FC and LB [11].

There are several combinations of FC, LB and UC, which are related to the application of DC/DC converters. The DC/DC converter gives the ability to achieve an active control of each power source and match its voltage to the DC bus voltage in the boost or buck mode. Commonly, the FC must use a unidirectional DC/DC converter while the LB or UC may use a bidirectional DC/DC converter or not. Researches are concerned on the following configurations: (1) “FC + LB” while the LB is directly connected to the DC bus [12]; (2) “FC + LB” while the connection of the LB to the DC bus through a bidirectional DC/DC converter [13]; (3) “FC + LB + UC” while the LB is directly connected to the DC bus and the connection of the UC to the DC bus is through a bidirectional DC/DC converter [14]; (4) “FC + LB + UC” while the connection of the LB and the UC to the DC bus are respectively through a bidirectional DC/DC converter [15].

An energy management strategy (EMS) is called to defines the power sources. The EMSs can be classified into two kinds, rule-based strategies and optimization-based strategies [16]. Rule-based strategies are suitable for real-time control applications [17]. Rules can be designed according to power-train characteristics, or extracted from optimized algorithms. Chen et al. [18] proposed a global optimization strategy based on dynamic programming (DP) for range extended EVs. They subsequently developed a rule-based multi-mode strategy, and applied it to real-time operations. Caux et al. [19] designed an online Fuzzy logic (FL) strategy, in which the parameters are optimized using a genetic algorithm. Other examples of rule-based strategies include: wavelet transform combined with FL control [20], sliding mode control [21], model predictive control [22], load-following mode control [23]. Optimization-based strategies have been widely studied. Basing on length of the time horizon, optimal energy management strategies can be categorized into global optimizations (GO), instantaneous optimizations (IO), and real-time optimizations (RO). DP [24,25] and convex optimization strategies [26] are powerful tools for solving GO problems, while the Equivalent Consumption Minimization Strategies (ECMS) [27–30] and Pontryagin’s Minimum Principle (PMP) strategies [31–34] are suitable for IO problems. A critical parameter called the equivalent coefficient, representing the equivalent power ratio between two power sources, needs to be defined in ECMS while the initial value of the co-state in PMP should be determined. Both the equivalent coefficient and the co-state are related to the driving cycles, if

the future driving conditions are properly estimated or several rules are extracted from the optimization results, these optimization strategies can be applied in RO problems.

The paper has the following configuration. After introduction, it presents the power-train structure and the models of the power components. In Section 3, the experiments based on the OPMS method are analyzed. ECMS is proposed in Section 4 and compared with the OPMS method. Section 5 presents the conclusions.

2. Power-train structure and system model

2.1. Power-train structure

Fig. 1 shows the structure of the hybrid tram and the main specifications of the hybrid tram are listed in Table 1. This tram is firstly composed of the following elements: A Li-ion battery pack, an ultra-capacitor pack, two dc/dc bidirectional converters, tram loads, braking chopper, and energy management services. Latterly, to enhance drivability and range, a PEM FC stack and a dc/dc unidirectional converter are added, marked with star symbols in Fig. 1.

The fuel cell system serves as a primary power source, while the Li-ion battery pack and the ultra-capacitor pack are auxiliary power units. Three converters, either unidirectional or bidirectional, are used to regulate the output power of the three power units for one thing; for another thing the converters match the low DC voltage delivered by the power units to the traction standard power bus.

As Table 1 shows, the fuel cell stack is a Ballard HD6 module and its rated power is 150 kW. The output voltage of the fuel cell stack is from 440 V to 710 V and the maximum current is 320 A. The li-ion battery pack is composed by 900 cells with 150 in series and 6 in parallel. Each cell capacity is 10 Ah and rated voltage is 2.3 V. Therefore, the pack capacity is 60 Ah and rated voltage is 345 V. The battery pack electric energy is 21 kWh. When its rated charge/discharge rate is 4C, the rated charging power is –84 kW and rated discharging power is 84 kW. For the ultra-capacitor, its total capacity is 15.75 F, its electric energy is 0.5 kWh and its rated power is 130 kW. Compared with the tram in [13], the power-train structure is similar to ours, but the power component size is a little different. The power plant in [13] are composed of (1) a 150 kW Ballard’s heavy-duty fuel cell stack; (2) three hundred and forty 90 Ah, 4.25 V Thundersky’s li-ion batteries connected in series; and (3) five 63 F, 125 V Maxwell’s BMOD0063-P125 UC modules connected in series, which shows equivalent fuel cell size to ours but bigger battery pack and ultra-capacitor pack size than ours.

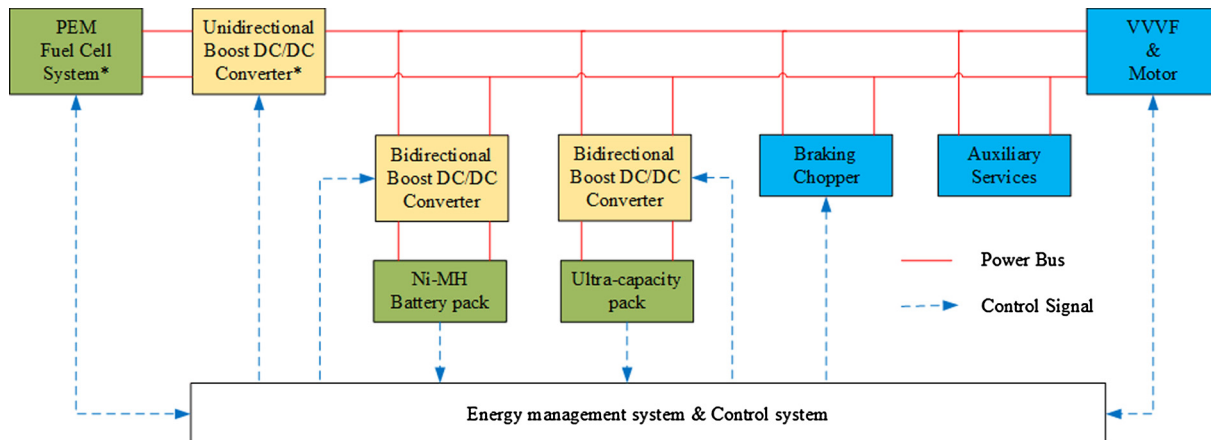


Fig. 1. Structure of the hybrid tram.

Download English Version:

<https://daneshyari.com/en/article/5013053>

Download Persian Version:

<https://daneshyari.com/article/5013053>

[Daneshyari.com](https://daneshyari.com)