INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2015) 1–9

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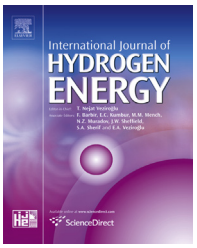

Development and performance analysis of a hybrid fuel cell/battery bus with an axle integrated electric motor drive system

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ARTICLE INFO

Article history:
Received 19 July 2015
Received in revised form
13 October 2015
Accepted 13 October 2015
Available online xxx

Keywords:
PEM fuel cell
Fuel cell/battery city bus
Hybrid powertrain
E-drive axle
Near-wheel motor

ABSTRACT

This paper presents the results of a research project aimed at developing and evaluating the viability of fuel cell vehicles for urban public transit applications and investigating ways to commercialize them. Considering a low-floor bus design and high efficiency of powertrain, one of the salient characteristics of the proposed fuel cell/battery hybrid bus is the E-drive axle, which integrates two near-wheel permanent magnet synchronous motors (PMSMs) in the rear axle. As an important part of the vehicle's powertrain, the E-drive axle was employed to drive the vehicle, capture the breaking energy and match the required speeds of the differential. The configuration and parameters of the powertrain of the hybrid fuel cell/battery bus are given in detail. To extend the life of the fuel cell stacks, the change in the output power of fuel cell stacks is controlled to be gradual via a DC–DC converter depending on the energy management strategy, which was described in this paper. An energy analysis based on a chosen driving cycle has been conducted to study the efficiency of the proposed powertrain, which shows that the hydrogen consumption of the bus is 13.29 km/kg. Also, the road test results indicated the tractive capabilities and maneuverability of the bus can reach the design specifications.

Introduction

Environmental pollution and the limited reserves of fossil fuels have led to an increased interest in alternative vehicle propulsive systems. Fuel cells have garnered many attentions from automakers and researchers as they represent one of the most promising candidates for green power generation. In particular, proton exchange membrane fuel cell (PEMFC) technology is thought to be one of the most likely generation sources for commercialization because of its inherent advantages, e.g., no emissions, high efficiency, high specific power, high specific energy, and low noise [1]. For PEMFCs to be commercially viable, the life and reliability of the systems

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http://dx.doi.org/10.1016/j.ijhydene.2015.10.046

must increase, while the costs must decrease. Hybridization of power sources becomes a viable solution with smaller fuel cell systems and high energy storage devices, such as lithium-ion (Li-ion) batteries [2,3]. City buses are well suited to demonstrating fuel cell applications in transportation, and most of fuel cell buses adopt hybrid powertrain [4].

According to the current status and trends of city buses in China, low-floor bus is becoming popular because of the accessibility and comfort for the public. Low-floor buses generally need a lowered rear axle, which brings more difficulties to the arrangement of the powertrain components, especially, centralized driving motor. Mercedes-Benz Citaro hybrid fuel cell bus provides valuable experiences and references for the issue [5].

During the 2000s, the State Key Laboratory of Automotive Safety and Energy, TsingHua University (ASE, THU), has developed over ten fuel cell bus prototypes that have been used to verify the technical feasibility and commercial viability of fuel cell vehicles for public transportation in urban areas in China. The research group of ASE focuses on the powertrain configurations [6–9] and energy management strategies [10–13], and expects to find some types of fuel cell hybrid powertrain that are most likely to be used in vehicles. All of the prototypes made during the decade were no low-floor bus, which generally adopted one centralized driving motor for propulsion.

The Fuel Cell Bus Powertrain Project, which is funded by central and local governments in China, started in 2011 and encouraged researchers to develop the new generation low-floor hybrid fuel cell/battery bus, PLATFORM, as shown in Fig. 1. This bus has a high efficiency, low cost and long life. The bus also showcases innovative E-drive technologies, such as an E-drive axle that includes two near-wheel permanent magnet synchronous motors (PMSMs) integrated on the rear axle with a fixed reduction gearbox. Compared with the centralized driving in the most of fuel cell buses in service, the E-drive axle has the advantages of improving driving performance through optimized mass distribution and allowing independent torque control for each wheel with a significantly high accuracy [14]. Moreover, it can release space for low-floor bus [15].

This paper focuses on describing the powertrain of PLATFORM, which is based on a PEM fuel cell system, lithium-ion batteries, DC to DC converter and axle integrated PMSMs drive system. The energy management strategy for PLATFORM is also described, and testing results show that this hybrid fuel cell bus performs well.

Fig. 1 – View of PLATFORM.

Vehicle and hybrid powertrain description

Vehicle description

The design specifications of the proposed bus are shown in Table 1. A low floor chassis is employed, which makes it difficult to use one high powered electric motor to drive the bus. As such, the PLATFORM bus uses two near-wheel PMSMs, which are both integrated on the rear axle via a fixed reduction gearbox with a reduction ratio of 13.92. Based on the design specifications and actual driving cycle, the components specifications can be calculated and designed. Also, the components sizing is closely related to the energy management strategy of powertrain when considering fuel economy and cost [16].

General configuration of the hybrid powertrain

Fig. 2 shows the powertrain arrangement on PLATFORM and the layout of the proposed hybrid fuel cell/battery powertrain. The PLATFORM's powertrain is composed of an electric drive system, a fuel cell stack (FCS), a lithium-ion battery pack, a DC to DC converter and a powertrain control system. The FCS and DC/DC converter are placed in the rear of the bus. The battery system is divided into a series of four packs with pairwise arrangements on both sides of the bus body. Fuel cell accessories, air conditioner and hydrogen tanks are installed on top of the vehicle from the rear to the front. The powertrain architecture of PLATFORM is similar to that of a series hybrid electric vehicle. As shown in Fig. 2, each electric motor is connected to the wheel hub through a reduction gearbox. The battery pack includes four units that are connected in series. The FCS is connected to the battery pack via a DC to DC converter, and both power sources provide electrical power to the electric drive system, which consists of one inverter and two PMSMs. Because the fuel cell voltage range varies widely depending on the load or operating conditions, the auxiliary components of the fuel cell, such as the air compressor, cooling subsystem, and so on, are powered by the battery to increase the reliability of the fuel cell system. Sequentially, the other auxiliary components for the powertrain, such as the pumps, 24 V system, and so on, are also directly connected

Table 1 – Design specifications of the proposed bus.

Item	Value
Overall length/width/height (mm)	11,990/2550/3440
Curb mass (kg)	14,400
Gross mass (kg)	18,000
Passengers capacity	55
Maximum speed (km/h)	80
Acceleration time (0–50 km/h) (s)	15
Grade ability (%)	18
Driving range(km)	300

Please cite this article in press as: Gao D, et al., Development and performance analysis of a hybrid fuel cell/battery bus with an axle integrated electric motor drive system, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.10.046