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Electric power system for a Chinese fuel cell city bus

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Abstract

A state-of-the-art Chinese fuel cell city bus, using a hybrid power system is proposed. This comprises a proton exchange membrane fuel cell and Ni/MH batteries to combine the high energy density of fuel cells with the high power density of batteries. A dc/dc converter is placed between the fuel cell and the battery to control the electric power flow. This paper presents a novel control strategy for efficiency of the fuel cell operation and optimization of the hybrid power system for the bus. The control strategy is able to regulate the output current of the fuel cell and the charging current or voltage for the battery while limiting the discharge current of the battery. It can achieve a higher efficiency, longer fuel cell lifetime, and higher drive performance. The hybrid fuel cell power system and the proposed control strategy were verified by using dynamometer and road test experiments. The experimental results demonstrated that the control strategy has great flexibility and generality, and also validated that the peak power capacity of the active hybrid power source and the vehicle drive performance can be significantly enhanced.

Keywords: Electric vehicle; Fuel cell; Hybrid power system

1. Introduction

There are two types of power system configuration in a fuel cell vehicle, a direct one and a hybrid one. The direct fuel cell drivetrain system is used in the Citaro fuel cell bus made by DaimlerChrysler, and more than 30 of these fuel cell buses have been demonstrated in the CUTE project and the CaFC project [1,2]. Due to the higher price and lower durability of a fuel cell system, there is a trend to use the hybrid power system. The hybrid mode is similar to that used in the ICE/battery hybrid electric vehicle, but using the fuel cell system to replace the internal combustion engine (ICE). This kind fuel cell vehicle includes a fuel cell unit and a secondary battery unit. The other reasons for applying a hybrid configuration includes the ease of using the same platform for regeneration of the brake energy.

For the hybrid electric vehicle, including the fuel cell hybrid vehicle, there are different power system configurations and thus different control strategies. The proper power control strategy will result in extending the fuel cell lifetime, increasing of energy efficiency, and an improvement in the vehicle performance.

Some control strategies has been published by other researchers for different kinds of power system components and the corresponding power system configurations. Ohkawa used a voltage and current control unit to control the power from the fuel cell system in a fuel cell hybrid vehicle while employing the electric double-layer capacitor as the back up power source [3]. Jeanneret and Markel developed an adaptive control strategy to adjust the power ratio between the fuel cell and battery in fuel cell/battery hybrid vehicle [4]. But both of these control strategies do not include the optimization of fuel cell operation. Jiang et al. proposed a multi-objective control method to regulate the current output of the fuel cell and the charging/discharging current or voltage of the battery. They used a bi-directional dc/dc converter to complete this control strategy [5]. Yokoyama et al. increased the efficiency through the power distribution algorithm according to the efficiency characteristics of the fuel cell and battery. The improvement in power efficiency was about 66% better than that of the base diesel engine power bus [6].

For a hybrid fuel cell vehicle power system, besides power system configuration, three other important aspects must been considered, they are the power system efficiency, the vehicle drive performance and the fuel cell lifetime. With the present technology, the fuel cell lifetime is about 4000 h with stable operating conditions, but under the variable operating conditions,

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such as in the vehicle operating environment, fuel cell lifetime is reduced to about 2000 h. The shortened fuel cell lifetime is partly due to the unstable fuel cell operation mode. Besides increasing the power system efficiency, peak output power, acceleration response, the perfect control system or algorithm should include some strategy to decrease the in-stability for the fuel cell to increase the fuel cell lifetime.

This paper proposes a new control strategy for the fuel cell hybrid city bus with an enhancement in the reliability.

The organization of the rest of the paper is described as follows. In Section 2, the components, the configuration of hybrid fuel cell power system and parameter of fuel cell city bus are described according to state-of-the-art in China. In Section 3, the proposed power system and control algorithm are analyzed and its corresponding control algorithm is presented. In Section 4, the dynamometer and road test results are obtained and the performance of first Chinese fuel cell city bus is also presented.

2. Configuration of hybrid fuel cell power system

2.1. Chinese fuel cell city bus

The first Chinese fuel cell city bus was developed in 2004 by Tsinghua University and partners. It is a hybrid vehicle combined the fuel cell as main power and a battery as the auxiliary power unit. The major parameters are shown in Table 1.

2.2. The main components of power system

The main components of the power system include a fuel cell unit, a battery unit and the motor drive unit.

2.2.1. Fuel cell unit

The fuel cell unit uses a PEM stack which is mostly used to drive the vehicle, and a high pressure system is employed [7]. Fig. 1 is its *V–I* curve, which shows that the output voltage lower limit is 262 V and the open circuit voltage is 350 V. The maximum stack current is 405 A. The maximum output power is 100 kW. As shown in Fig. 2, the fuel cell stack has a relatively normal response to the load variation. The power response time from about 10% load (11.3 kW) to near 70% load (67 kW) is about 3 s.

The fuel cell stack has a higher efficiency compared with a conventional internal combustion engine. As Fig. 3 shows,

Table 1
Specifications of the Chinese fuel cell city bus

Parameters	Value
Empty loaded mass (kg)	11600
Fully loaded mass (kg)	15000
Main reducing gear ratio	1:6.83
First shift ratio	1:3.002
Second shift ratio	1:1.862
Wheel radius (m)	0.502
Wind faced area (m^2)	7.5
Windage coefficient	0.7
Rolling resistance coefficient	0.018

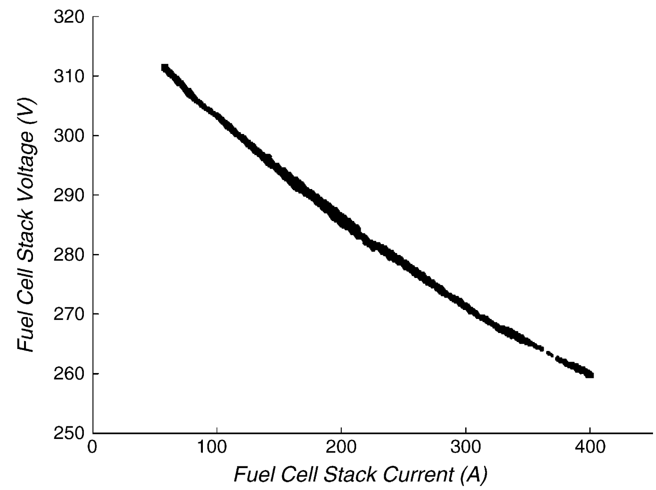

Fig. 1. The fuel cell *V–I* curve.

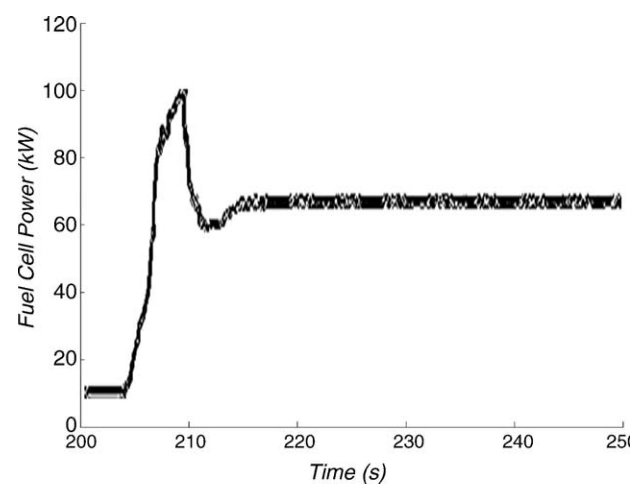

Fig. 2. Fuel cell power response.

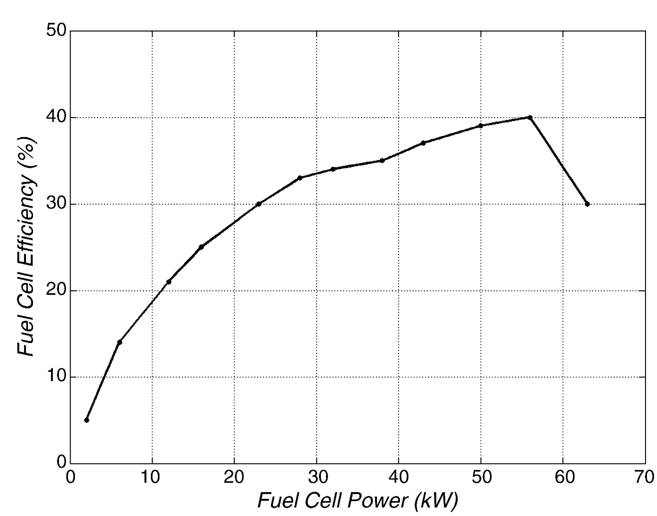

Fig. 3. Fuel cell efficiency curve.

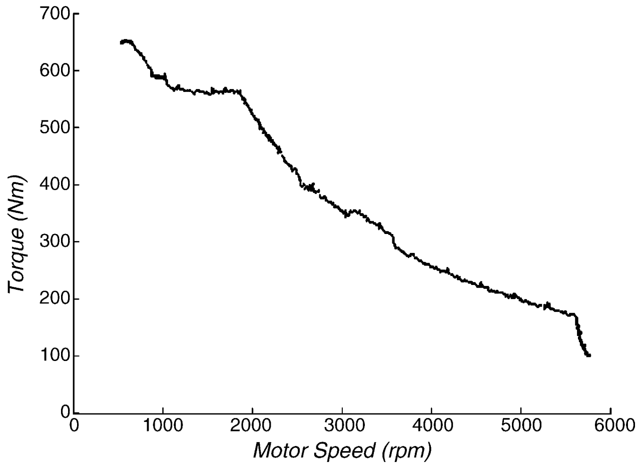

Fig. 4. The output speed–torque characteristic curve of the drive motor.

the maximum efficiency is about 40%, which is higher than the potential maximum 36% efficiency of an internal combustion engine.

2.2.2. Battery unit

The battery unit is a Ni/HM battery with a 80 Ah capacity. Its maximum charging current is 240 A, and maximum discharging current is 280 A.

2.2.3. Drive unit

The drive unit comprises a three-phase bridge inverter and an induction motor. Fig. 4 shows the motor's speed–torque curve characteristics. The maximum output power of the drive motor is 210 kW. The maximum output torque is 670 N m, and the maximum rotating speed is 5750 rpm. The motor is controlled by an inverter using a direct torque control algorithm, and the flux weaken control algorithm is used in a high speed operation.

2.3. Configuration of the power system

The simplest and seemingly most efficient power system configuration is made up of only by two units, the fuel cell and motor drive unit. But many essential functions cannot be implemented by this simple system such as regeneration of brake energy, optimization of fuel cell operation and fast response to load variation. In order to realize the essential power system functions, another energy storage unit is necessary. The candidate for this energy storage unit is a secondary battery such as a lead acid battery, a Ni/HM battery or lithium ion battery.

In this paper, the power system is integrated with four subunits: fuel cell stack, battery, drive motor and power control unit. The power control unit is used to regulate the power flow to achieve the predetermined power distribution. The configuration of this power system is shown in Fig. 5 [8].

In general, the power control unit has two different connecting methods, one is directly connected with the fuel cell unit and the other is with the battery unit. In this research, the former method is selected by considering the following reasons:

(1) In this case, the power control unit is uni-direction, which means that it only regulates the output current of the fuel cell unit and prevents the braking energy feedback to the fuel cell unit, thus protecting the fuel cell from overvoltage or overcurrent.
(2) The response to regeneration braking is fast in this connection. In this case, the battery is directly connected to the generator/motor. The regeneration brake energy would directly charge the battery with high efficiency. Otherwise, if the power control unit is placed on the output side of battery, a bi-directional converter has to be used for charging and discharging the battery, and the response by the bi-directional converter has to be very fast, which is hard to design. Therefore, the control unit will become complex and increase the system cost.

3. Control algorithm of the Chinese fuel cell city bus power system

3.1. Control strategy

The target of the control strategy is to optimize the operational mode of the fuel cell, improve system efficiency and enhance the

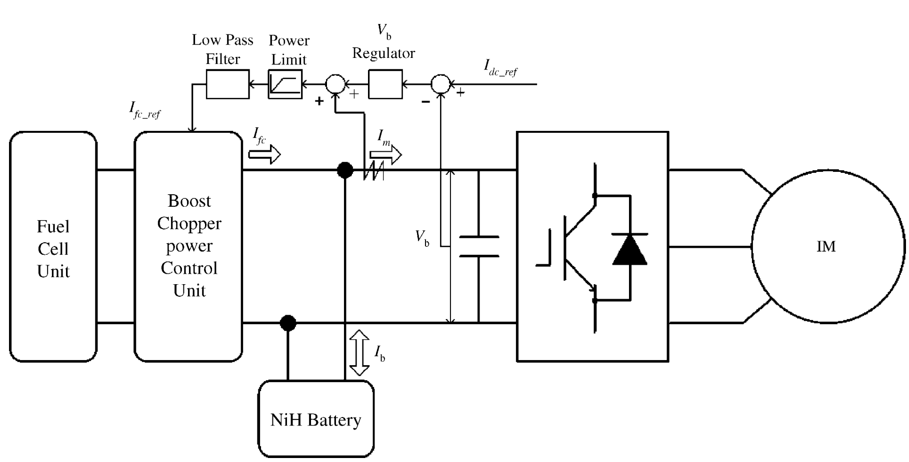

Fig. 5. Configuration and control of the proposed power system.

drive performance. The functions of the power system control strategy are described as follows:

(1) The battery voltage (V_b) is detected and regulated within an appropriate range by the battery voltage regulator. The output of the battery voltage regulator is the charging current.
(2) The load current (I_m) is detected and adds to the above battery charging current to give an overall output current reference for the fuel cell unit. This overall current reference is limited by the maximum power of the fuel cell unit.
(3) A low pass filter (LPF) is used to prevent the fuel cell from fatigue damage caused by the fast fluctuations in load current. According to the fuel cell output power response time (Fig. 2), a smooth load current is produced by the fuel cell unit. The remaining high frequency load currents are supplied automatically by the battery. With this strategy, the operation mode of the fuel cell is relatively stable and this results in a longer lifetime for the fuel cell unit, meanwhile, the peak output power is provided by the battery unit and results in a good vehicle drive performance.
(4) The maximum load current (I_m) is limited by the inverter. If the battery voltage is out of range, the inverter controller will limit the load current to regulate the battery voltage.
(5) The fuel cell unit is prior to respond with the load current. If the load current is less than the fuel cell maximum output current, all load current is provided by the fuel cell unit. Otherwise, the rest of the load current exceeding the maximum output current of fuel cell is provided by the battery unit. The efficiency of the power system is increased by simplification of power flow.

3.2. Stability analyses of control algorithm

Fig. 6 shows the simplified connection between the fuel cell and battery. The fuel cell unit includes the fuel cell stack and boost converter. The boost converter is operated in the current mode, so the fuel cell unit can be regarded as a current source. The battery unit is regarded as a voltage source connected in series with its internal resistance. The motor driver unit is also regarded as a current source, which is a current load to the hybrid fuel cell power system. In brief, there are two current sources and one voltage source connected together at point ‘a’.

As shown in Fig. 6, the relation between I_{FC}, I_B, and I_M is given by

$$I_B = I_M - I_{FC} \tag{1}$$

From power system control strategy, the relation between I_{FC} and I_M is as follow

$$\frac{I_{FC}(s)}{I_M(s)} = G_{LPF}(s) \tag{2}$$

where $G_{LPF}(s)$ is the transfer function of the low pass filter.

From (1) and (2), it follows that

$$I_B = (1 - G_{LPF})I_M, \qquad I_{FC} = G_{LPF}I_M \tag{3}$$

Eq. (3) shows that if the low pass filter is stable, for any given load current I_M, the I_B and I_{FC} are also stable. So the hybrid fuel cell power system and control strategy is a stable system.

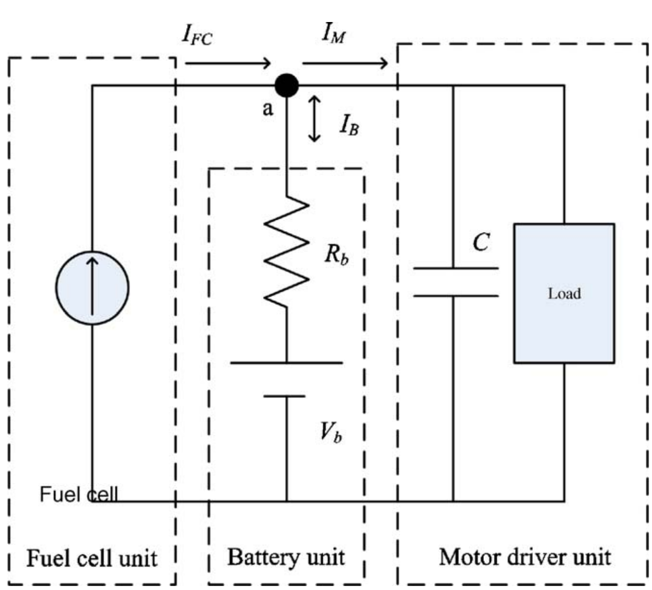

Fig. 6. Schematic of the fuel cell and battery connection.

4. Experimental study and results

The above hybrid fuel cell power system and its control strategy were firstly validated through a dynamometer test bench and then were assessed in the fuel cell city bus.

4.1. Dynamometer validation

Fig. 7 shows the test bench used for the dynamometer validation. Considering the safety issue, the fuel cell unit is in another room, so it is not shown in this photograph. But it is connected with the hybrid power system by wire. One electric dynamometer is connected with the drive motor to simulate the actual city bus load variation.

In this experiment, a driving cycle called the Summer Palace mode is used to simulate the Beijing city traffic condition. As

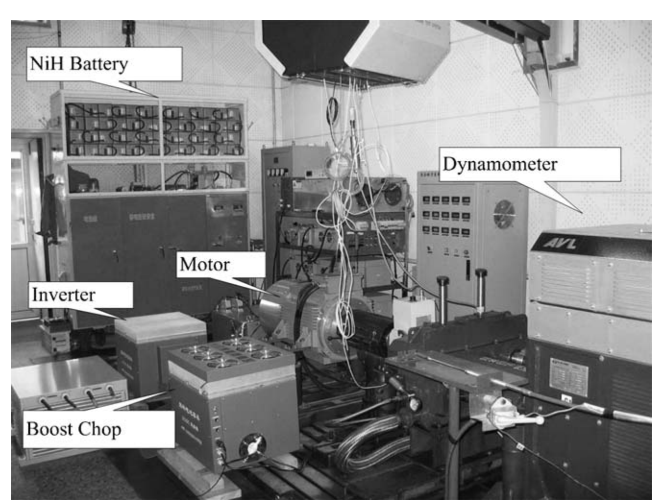

Fig. 7. Photograph of the experimental environment.

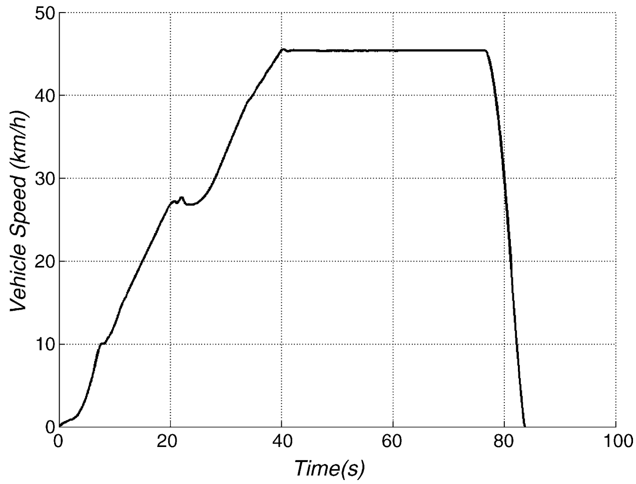

Fig. 8. The Summer Palace mode.

shown in Fig. 8, this driving cycle includes three operating processes: acceleration, constant speed driving and deceleration. Two simulations are carried out to model the bus loads, the empty load running mode refers to no passengers in the bus, the power requirement is only the need to drive the bus with its mass of 11 600 kg. For the full load mode, the bus is full of and the total mass is about 15 000 kg.

Fig. 9 is the experimental result of an empty load running mode test. The cutoff frequency of the low pass filter is 0.1 Hz. Which means that the frequency band of the fuel cell's response is from 0 to 0.1 Hz. The maximum output current of the fuel cell is 150 A. When the load current fluctuates rapidly, the charging and discharging current of battery synchronously fluctuates, which slows down the fluctuation of fuel cell's output current. Because of the fast fluctuation of the battery charging and discharging current and the large battery internal resistance, the battery voltage also fluctuates rapidly from 360 to 500 V.

Fig. 10 is the experimental result of a full load running mode test. The maximum load current increases from 250 A in the empty load running mode to 300 A, and the power distribution between fuel cell and battery unit is the same as that of the empty load running mode.

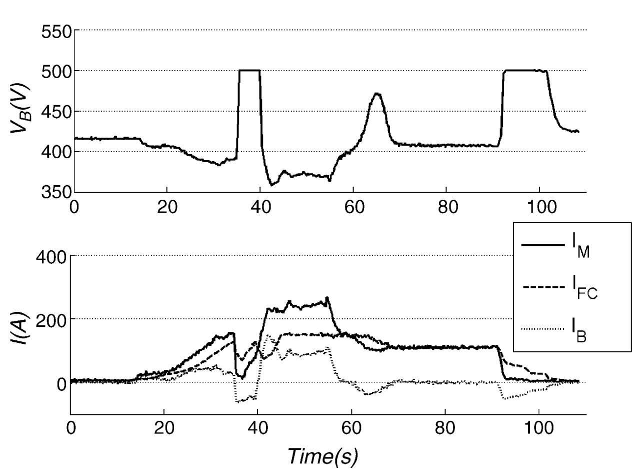

Fig. 9. Experimental result in the empty load running mode.

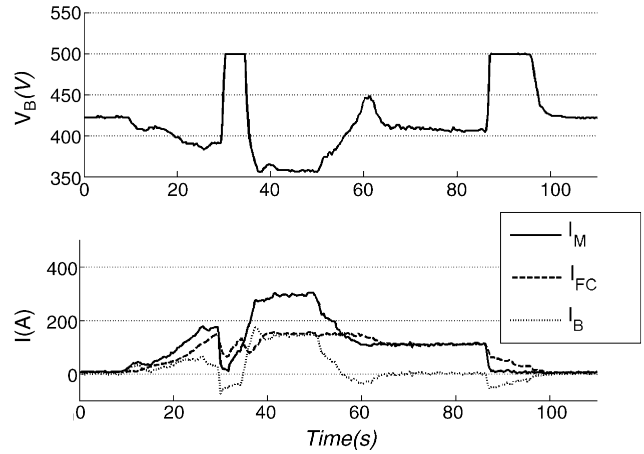

Fig. 10. Experimental result in the full load running mode.

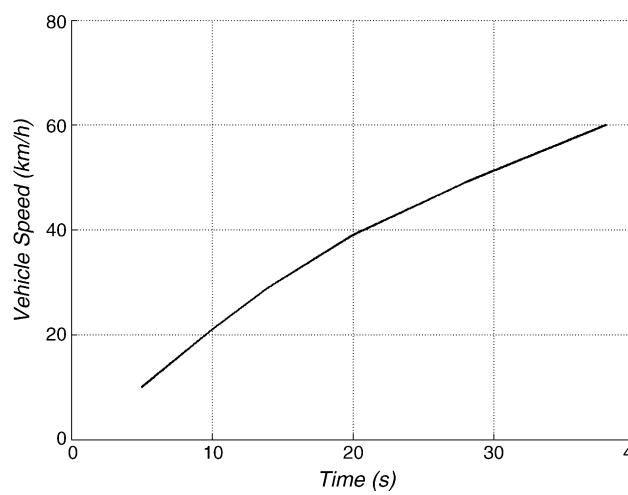

Fig. 11. Acceleration time using high shift.

The acceleration performance and grade-ability are also simulated. As shown in Fig. 11 and Table 2, the acceleration time from 0 to 60 km h^{-1} is 37.9 s and the maximum climbing angle is 15°.

4.2. Road running test

The 3000 km road test has been successfully done in the environs of Beijing in 2004. The road condition includes many incidents such as traffic light, flat fading road, downward and upward sloping road. The city bus was operated in the hybrid fuel cell power mode regulated by the proposed control strategy.

Table 2
Climbing performance

Angle of gradient (°)	Speed (km h^{-1})
10	19
11	14
12	8.5
13	6.5
14	3.7
15	2.1

Table 3
Vehicle performance

Parameter	Performance
Hydrogen consumption (kg/100 km)	9.68
Maximum speed ($km\,h^{-1}$)	69.7
Acceleration time from 0 to 50 $km\,h^{-1}$ (s)	22.97
Continuous running distance (km)	120

The road test results of vehicle performance are shown in Table 3. Except for hydrogen consumption, the vehicle maximum speed, acceleration time and continuous running distance showed good performance. The hydrogen consumption per 100 km was 9.68 kg/100 km, which is equivalent to the gasoline of 35 L/100 km.

5. Conclusions

The power system of a Chinese fuel cell city bus was analyzed and the following conclusions can be drawn:

(1) When a boost converter is used to control the hybrid power system, this kind of power system is appropriate to optimize operation mode of fuel cell.
(2) The proposed control strategy of the power system can satisfactorily distribute the load current between the fuel cell unit and the battery unit.
(3) The hybrid fuel cell power system and the proposed control strategy were validated by tests on a dynamometer in the laboratory and also assessed on the actual fuel cell city bus. The experimental results show that this power system has good performance.

Acknowledgement

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