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Experimental study of drivetrain configurations in fuel cell city bus

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Abstract

The layout of a fuel cell city bus and the structure of the vehicle controller unit are outlined. The bus is field-tested with the drivetrain configuration, both with and without DC-DC converter, and the test data is acquired through controller area network. Since configurations vary in specifications and have both advantages and disadvantages the choice of the drivetrain configuration depends upon the need and suitability.

Keywords: Fuel cell city bus, drivetrain, DC-DC converter, power distribution.

1. Introduction

Environmental problems caused by vehicles and the limitations to the availability of fossil fuel are of current research interest. Some countries have already legislated stricter environmental regulations to control vehicle emissions, prominent among them being US Clean Air Act and LAMTA (Los Angeles County Metropolitan Transportation Authority) [1], CUTE (Clean Urban Transport in Europe) and ECTOS (Ecological City Transport System) [2], and China Clean Vehicle Act. In the context of worldwide demand for cleaner vehicles, fuel cells are extremely attractive as they, unlike internal combustion engines, produce electricity through an electrochemical process combining hydrogen with oxygen.

With the support of the Ministry of Science and Technology we in China have developed a fuel cell city bus. Many types of drivetrain are employed in the bus [3] and each has its own advantages and disadvantages. The bus utilizes hybrid drive system consisting of a fuel cell and battery packs. The fuel cell can fully supply the power or charge the battery pack. It has two important advantages: one is that the battery pack can provide supplemental power for starting and accelerating cases, which helps in reducing the dimension and the power of the fuel cell and also helps the fuel cell system to operate efficiently and steadily. The other is that the battery pack can receive the regenerative energy during braking operation. Though different drivetrain configurations have been studied [4–8], no report of a field

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Table I
Specifications of the fuel cell city bus

Parameters (Unit)	Value
Gross weight (kg)	15500
Length × Width × Height (mm)	11070 × 2490 × 3420
Number of passengers	50
Ratio of gearbox	$i_{g1} = 3.002$, $i_{g2} = 1.862$
Ratio of final drive	$i_0 = 6.83$
Type of storage battery	Li-ion battery
Capacity of the battery (Ah)	100
Voltage of battery pack (V)	384
Maximum speed (km/h)	65
Gradeability (%)	>12
Accelerating time (0–50 km/h)(s)	<40

FIG. 1. Photo of the fuel cell city bus developed.

test of a prototype vehicle is available. This paper presents the experimental results of such a study.

2. The schematic of the fuel cell city bus

The configuration of the drivetrain consists of fuel cell system, DC-DC boost converter, battery pack, AC motor and its controller, and other conventional components. The specifications of the bus are listed in Table I and its photo is shown in Fig. 1. The schematic of the vehicle controller unit (VCU) of the bus is shown in Fig. 2.

The fuel cell and battery pack provide power not only for the AC motor, but also for corresponding equipment. While the fuel cell drives its accessories by itself, the battery pack provides power for the electrical hydraulic power steering system and the electric motor driving air pump in the air-braking system. The power drawn from the fuel cell and the bat-

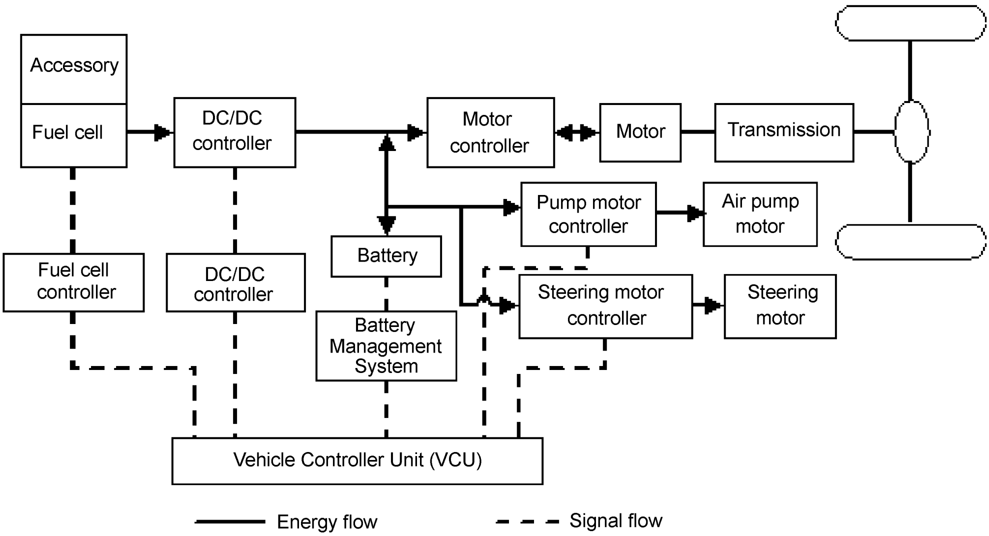


FIG. 2. The schematic of the vehicle control unit of the bus with DC-DC converter.

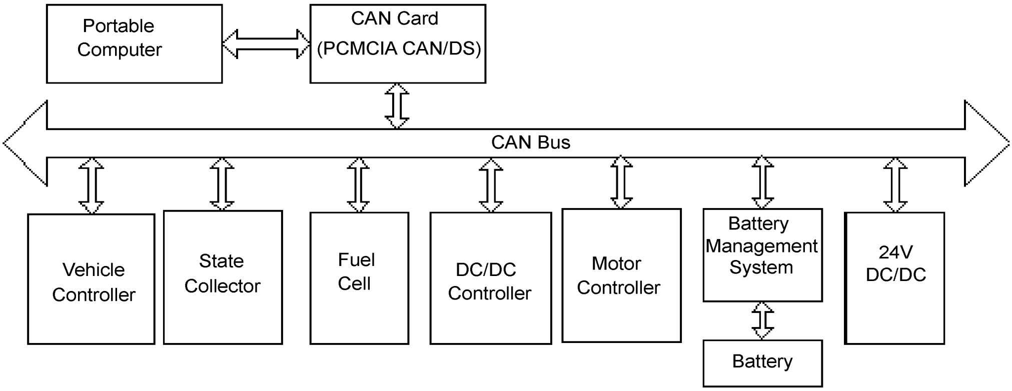


Fig. 3. The communication network in fuel cell city bus.

tery pack is controlled by the VCU, which is dependent on the running condition of the vehicle. Two kinds of configurations of drivetrain are considered. One consists of a fuel cell system with DC-DC boost converter and auxiliary lithium-ion battery pack, and the other is a fuel cell system in parallel with auxiliary lithium-ion battery pack directly, in which there is no DC-DC converter. In hybrid drivetrain, the two configurations are relatively simple, and can be employed if they satisfy the requirements of the vehicle.

During field tests, data is acquired by controller area network (CAN). For each of the subsystems described above, we have developed a sub-ECU, which takes charge of data acquisition and data transformation according to CAN protocol. Each ECU includes a CAN bus driver, 82C250, which sends or receives data by means of voltage differential and realizes the CAN bus communication functions, such as bus-access arbitration, and sequence control. Based on this network, we use a CAN card, purchased from the American National Instrument Corporation, as the interface device, and a portable PC as the monitoring/diagnosing node, to form the FCEV signal monitoring and diagnosing system (Fig. 3) [9]. The efficiency of the fuel cell DC-DC converter, the AC motor, and the battery pack are tested in the laboratory [10]. The test was performed on the highway, which is comparatively flat and has intersecting crossways.

3. Experimental results of drivetrain with DC-DC converter

The low voltage of a fuel cell stack appears to be more attractive because the efficiency of a fuel cell stack for higher voltages is relatively low and more cells are also needed for the stack. In this system, the voltage of the fuel cell system is lower than the battery pack voltage, and hence a DC-DC boost converter is used (Fig. 4). At this time, the output power of the fuel cell stack and battery pack can be regulated using different control strategies as the voltage difference between the DC-DC converter and the battery packs affects their output power.

In this configuration, the power distribution is

$$P_F h_{DC} + P_B = \frac{P_V}{h_D h_M h_C} \tag{1}$$

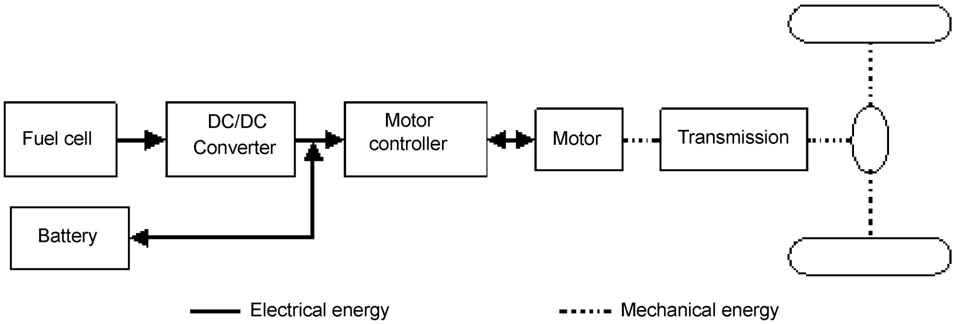


Fig. 4. Drivetrain configuration with DC/DC converter.

where P_F and P_B are the output power originating from fuel cell and battery pack, ς_{DC} is the efficiency of DC-DC converter, P_V, the power consumption of the bus, which results from rolling resistance, hill resistance, wind resistance and accelerating resistances; ς_D, ς_M and ς_C are respectively the efficiencies of the driveline including transmission and final drive, the motor and the motor controller.

The output voltage V_{DC} of the DC-DC converter is equal to the terminal voltage V_B of the battery pack, and the output voltage V_{FC} of the fuel cell is the input voltage of the DC-DC converter. Assuming that the battery pack is an energy source with internal resistance R_{Bin} and open-circuit voltage V_{B0}, we get the following formula,

$$I_B = \frac{V_{B0} - V_B}{R_{Bin}} = \frac{V_{B0} - V_{DC}}{R_{Bin}}. \tag{2}$$

We can adjust on real-time, while driving the bus, the output voltage of the DC-DC converter to change the output current of the battery pack. Additionally, the battery pack can also vary its own output current, but it has to be put in place at the design stage itself.

Figure 5 shows the speed of the bus during the field test, in which the average speed is 23.3 km/h and the maximum 57.1 km/h. Output power of the fuel cell, the battery pack and

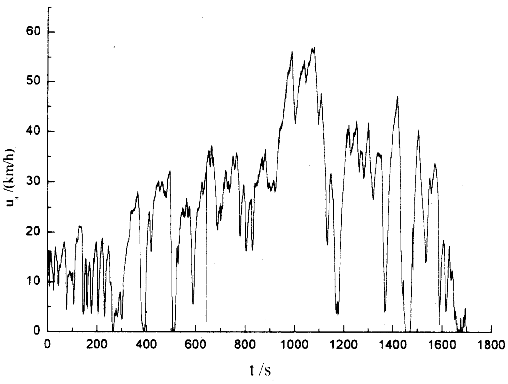


Fig. 5. Vairation of the speed of the bus.

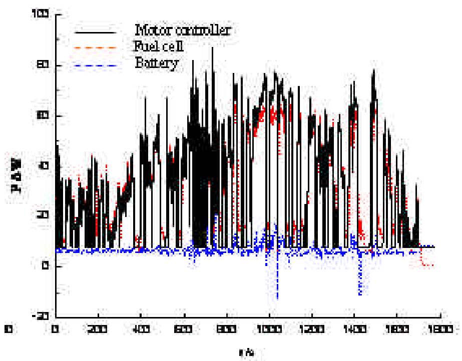
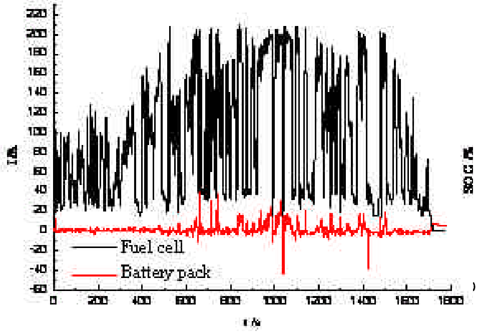


Fig. 6. Power of the input of the motor controller, fuel cell and the battery.



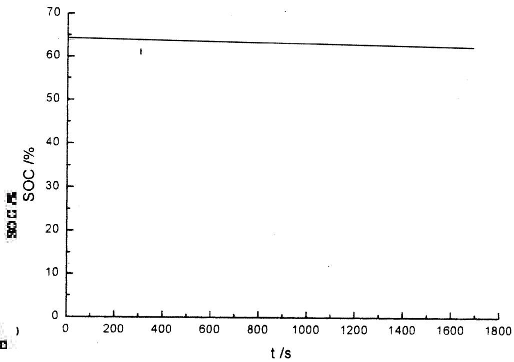


Fig. 7. Current variation of the fuel cell and the battery pack. Fig. 8. SOC variation of the battery pack.

input power of the motor controller are depicted in Fig. 6. Current and state-of-charge (SOC) variation are shown in Figs 7 and 8, respectively.

Power variation rate, *dP*/*dt*, of energy sources is defined as the power difference in sampling interval divided by sampling interval, which can be used to evaluate the state of power variation. Power variation rate of the fuel cell and the battery pack are depicted in Figs 9 and 10, respectively.

Based on the results, the output power and the SOC of the battery pack can be varied to a small extent, as the control strategy makes the fuel cell produce maximum power. Of course, if the control strategy makes battery pack produce more power than the fuel cell, power variation of the fuel cell will decrease and that of the battery pack will increase. Besides, the battery pack can be used to warm up the fuel cell system and bring the output voltage to a nominal level, so that it becomes easy to start the fuel cell system.

4. Experimental study of drivetrain without DC-DC converter

In this configuration, the power required by the vehicle is shared directly by the fuel cell and the battery pack (Fig. 11). It is obvious that the configuration without DC-DC converter

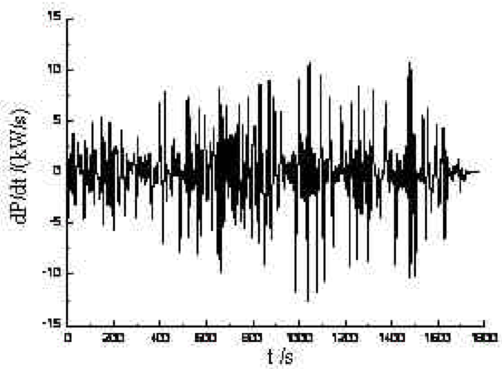


Fig. 9. Power variation rate of the fuel cell.

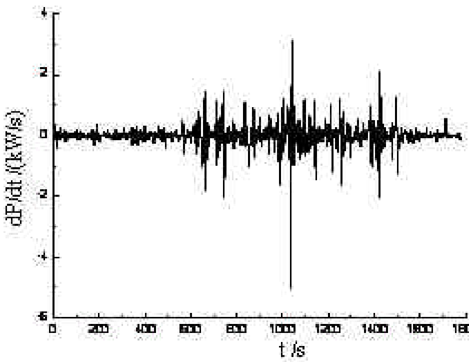


Fig. 10. Power variation rate of the battery.

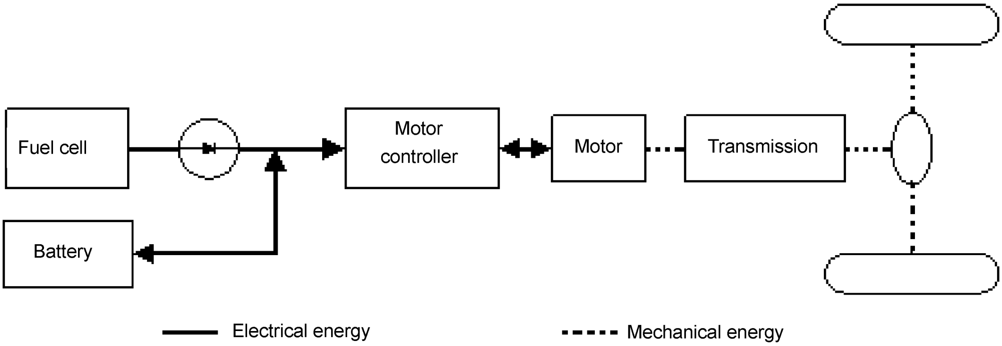


Fig. 11. Drivetrain configuration without DC-DC conveter.

is simpler than that with the DC-DC converter. In this drivetrain configuration, the power distribution is

$$P_F + P_B = \frac{P_V}{h_D h_M h_C}. \tag{2}$$

When eqn (2) is compared with eqn (1), the system efficiency, without DC-DC converter, is higher than that with DC-DC converter.

The values of I_{FC} vs V_{FC} of the fuel cell may be expressed as [11]

$$V_{FC} = V_{FC0} - b\log\left(\frac{I_{FC}}{A_{FC}}\right) - R_{FC} I_{FC} \tag{3}$$

where V_{FC0} is the open-circuit voltage of the fuel cell, b, the Tafel slope, and A_{FC}, the cross-sectional area of the fuel cell. Considering $V_{FC} = V_B$ in this structure, the following formula can be arrived at.

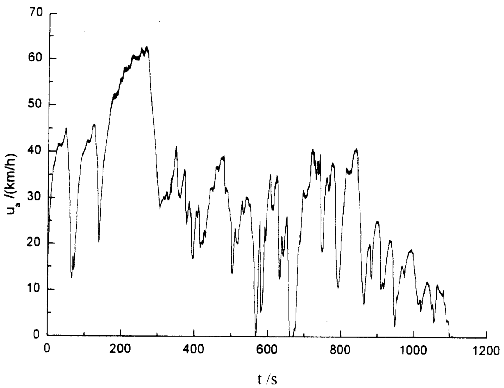


Fig. 12. Varation of the speed of the bus.

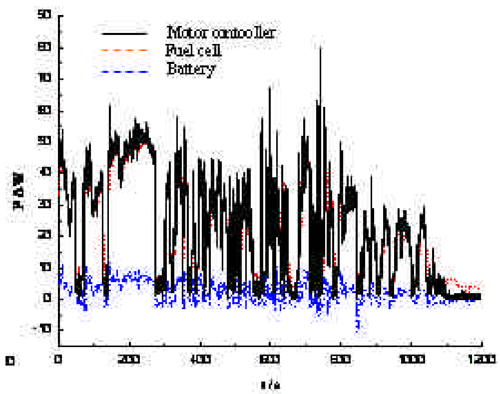


Fig. 13. Power of the input of the motor controller, fuel cell and the battery pack.

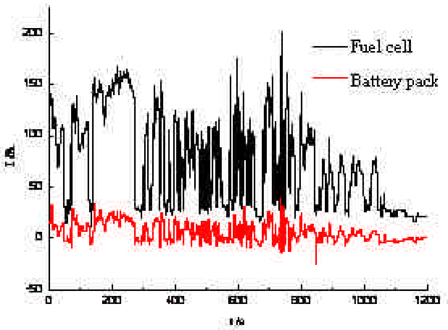


Fig. 14. Current variation of the fuel cell and the battery pack.

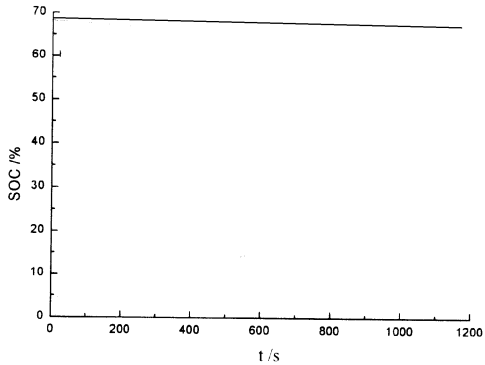


Fig. 15. SOC variation of the battery pack.

$$I_B = \frac{V_{B0} - V_B}{R_{Bin}} = \frac{b\log\left(\dfrac{I_{FC}}{A_{FC}}\right) + R_{FC}I_{FC} - (V_{FC0} - V_{B0})}{R_{Bin}}. \tag{4}$$

It can be seen that the bigger open-circuit voltage difference between the fuel cell and the battery pack is the smaller current of the battery pack which can change the output current of the battery pack. At the same time, if the characteristic of the battery pack is constant, which means R_{Bin} is small, the output current of the battery pack can be increased. However, these adjustments can only be realized during the design stage, and no controls can be employed in this configuration.

Figure 12 shows the variation of speed of the bus during the field test. The average speed is 24.2 km/h and the maximum 62.9 km/h. The power distribution, current and SOC variations are shown in Figs 13, 14 and 15, respectively. Figures 16 and 17 show respectively the power variation rate of the fuel cell and the battery pack.

A comparison of the experimental results among drivetrain configurations shows that the SOC of the battery pack without DC-DC converter decreases faster than that with the DC-

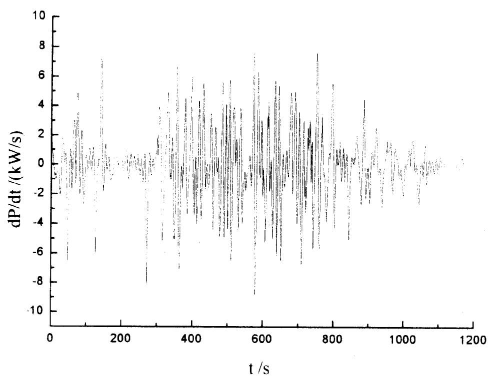


Fig. 16. Power variation rate of the fuel cell.

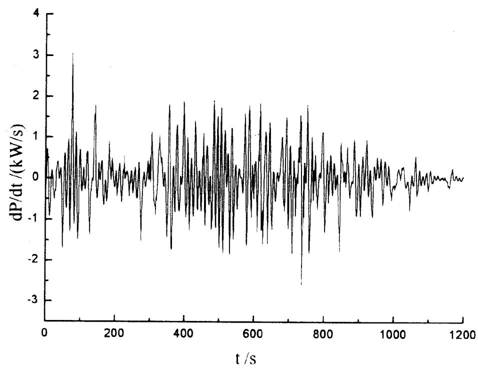


Fig. 17. Power variation rate of the battery pack.

DC converter. Where there is no DC-DC converter, the battery pack voltage affects the variation of the fuel cell voltage. To avoid frequent voltage variation in the fuel cell, it is necessary to keep the battery pack voltage constant. In addition, the output power of the battery pack without DC-DC converter varies more frequently than that with the DC-DC converter.

5. Conclusions

Hybrid drive system consisting of fuel cell and battery pack makes efficient use of the high-energy density of the fuel cell and the high-power density of the battery. The DC-DC boost converter in the drivetrain uses the output current of the battery pack and does not depend on the high voltage of the fuel cell. The drivetrain without DC-DC boost converter is a simple construction, and the output current of the battery pack can be determined after the design is completed. Additionally, if the battery pack voltage has inflexible characteristics its output current will increase.

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