A Control Strategy for Fuel Cell Hybrid City Bus

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Abstract

Fuel Cell Hybrid Electric Vehicle has recently become one of the focuses in the development of electric vehicles. China has launched a large project-Fuel Cell City Bus. The City Bus is a series Fuel Cell hybrid electric vehicle. All the components of the power-train have their own Electronic Control Unit (ECU). They communicate with the Vehicle Control Unit (VCU) through the Controller Area Network (CAN). VCU is the core of the power-train, it makes decisions according to the information from the driver and other ECUs. The control strategy of the VCU is one of the key technologies. In this paper, the design of the control strategy is divided into two main modules and many blocks. Some of the blocks are presented in detail. The control strategy is tested and calibrated on the hybrid power-train test bench. The test results show that the control strategy can meet the request of the City Bus.

Keywords

control strategy, design, fuel cell, hybrid bus, energy distribution

1. INTRODUCTION

The Fuel Cell Electric Vehicle has recently become one of the targets in the development of electric vehicles. Among the fuel cell vehicles, Fuel Cell Bus is more practical in use. Many countries and companies have made researches on it [Gilchrist et al., 1997], [Krauss et al., 1997], such as Daimler-Benz (Nebus 1997, Citaro 2002); Ballard (P1, 1993, P2, 1995, Nebus, 1997, P3_CTA, 1997 , P3_BCT, 1998, P4_Zebus, 1999, Citaro, 2002), Toyota_Hino Motors (FCHV-BUS1, 2001, FCHV-BUS2, 2002); Georgtown_University (Generation I buses TBB, 1994, 1995, Generation II, IFC, 1998, XCELLSiS X1, 2001, Generation III); ThunderPower (Thor ThunderPower Bus, 2001); Irisbus (City Class FC, 2001); Elenco EUREKA (City Bus, 1995); Neoplan (Bus, 1999); MAN (NL 263 "Bavaria I", 2000, NL 223, 2001); Proton Motors (Bayern-Bus II, 2000), Scania (FC Midi City Bus, 2001); Ansaldo Ricerche Srl. (Citybus, 1997). Hydrogen-air proton exchange membrane fuel cell (PEMFC) has high efficiency and true zero emissions advantages. Hybrid fuel cell buses with the PEMFC supplying the constant power and the storage devices such as battery or ultra capacitor supplying the peak power, are cheaper than the vehicles using fuel cell only. In the mean time, hybrid vehicles can recover the braking energy by storing it into the storage device. Most of these buses mentioned above are hybrid. China has also launched a large project-Fuel Cell City Bus. The City Bus is a series Fuel Cell hybrid electric vehicle. The power-train configuration of the city bus is showed in Figure1. The technique parameters of the bus are shown in Table 1. All the components of the power-train have their own Electronic Control Unit (ECU).

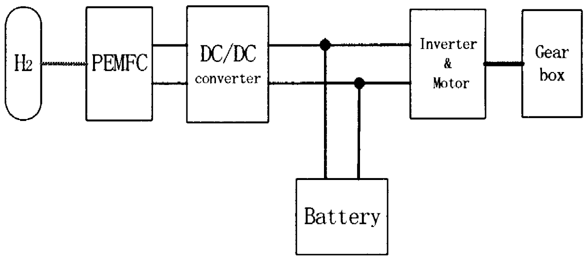

Fig. 1 Power-train configuration of the PEMFC city bus

Table 1 Technique parameters of the PEMFC city bus

Physical parameters		Vehicle L×B×H (mm): 10890×2490×3360. Vehicle mass: 10800kg. Cargo/passenger weight: 3400kg. Rolling radius of the bus: 0.502 m. Front area: 7.5m^2. Coefficient of drag: 0.7. Coefficient of rolling resistance: 0.018.
Power-train	PEMFC	Stack rating Power: 75 kW; Net output power: 50 kW
	DC/DC converter	Rating power: 75 kW; Input voltage: 220~400 V; Output voltage: 320~460 V
	Battery	Total voltage: 384 V; Capacity: 100Ah
	Motor	Rating power: 100 kW @1780rpm; maximum power: 160 kW (5 min) @ 5200 rpm; Operating voltage: 320~460 V;
	Transmission	Planetary gearbox with two shifts: 3.002 and 1.862; Final ratio: 6.83

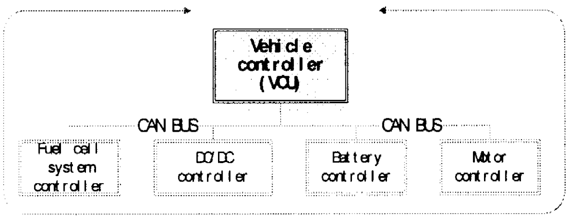

Fig. 2 Vehicle communication network

They communicate with the Vehicle Control Unit (VCU) through the Controller Area Network (CAN) as shown in Figure2. VCU is the core of the power-train, it makes decisions according to the information from the driver and other ECU's. So the control strategy of the VCU is one of the key technologies.

2. DESIGN OF THE CONTROL STRATEGY

The control strategy of the VCU can be divided into two main modules, the Driving Management Module and the Energy Management Module as shown in Figure 3. The Driving Management module consists of many blocks, such as the driver torque demand block and the state control block etc. The Energy management module also consists of many blocks. The main purpose of the energy management module is to distribute the energy between the battery and the Fuel cell system correctly.

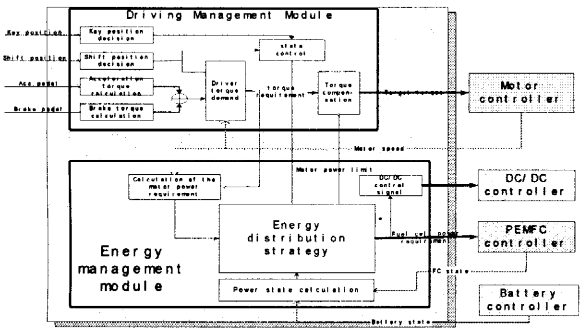

Fig. 3 The control strategy of the VCU

The process of the control is described briefly as follows. When applying acceleration, the amount of traction is determined by the driver torque demand block, and the traction required for driving after it is compensated in the Torque compensation block is sent to the motor control unit by CAN, which is also sent to the Energy Management Module. After the traction power is calculated, it is sent to the Energy distribution strategy block where the required traction power is distributed between the battery and the fuel cell system. The fuel cell required power is sent to the fuel cell system control unit by CAN, then the fuel cell system control unit adjusts its working point base on the power requirement. At the same time, the control signal is sent to the DC/DC converter control unit, which will control the power drawn out from the fuel cell system. When the driver applies the brake, in order to operate the regenerative brake, the traction torque from the driver torque demand becomes negative. In that case, the operating point of the fuel cell is sent to the zero location, the regenerative power produced by the motor is absorbed into the high voltage battery. For one reason or another, when the fuel cell and/or the high voltage battery's output are limited, the energy distribution strategy block indicates to the Torque compensation block to supply the minimum necessary torque. Some of the blocks are presented in more detail following.

2.1 The state control block

The state control block shown in Figure 4 controls the process of the power-train of the vehicle according to the key position, the shift position, and the failures signals from failures detect module (not shown in the Figure 3).

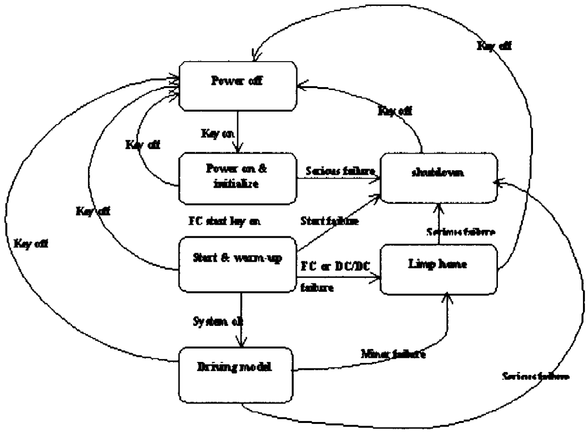

Fig. 4 State control

2.2 Driver torque demand block

The request traction torque is calculated in the driver torque demand block based on the accelerator pedal and the brake pedal. The torque of the motor demand is shown in Figure 5. The torque is proportional to the rate of operation of the accelerator pedal, but at higher speeds and lower pedal operation rates negative torque, or deceleration like an engine brake, is applied. In addition, if the vehicle is going in the opposite direction of the driver's operation, the torque direction should be kept forward. In the case of backward, reverse the Figure 5. When the brake is applied, the braking torque shown in

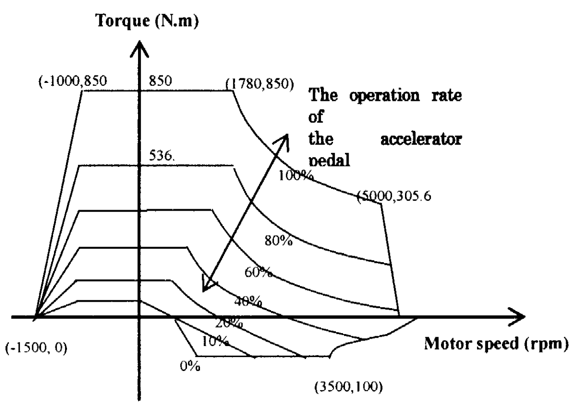

Fig. 5 Traction torque characteristic (driving forward)

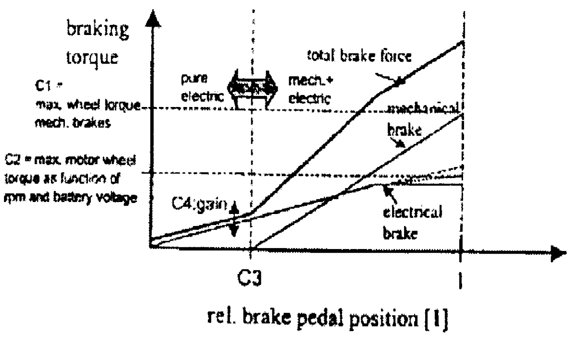

Fig. 6 Braking torque characteristic

Figure 6 [Hauer et al., 2001] is used (because the limit of capacity for the motor, inverter and high voltage battery, a hydraulic brake is also used).

The fuel cell system step response from idle to full power is about 3 seconds. As the fuel cell manufacturer requirement, in order to protect the fuel cell system, the torque sent to the motor control unit and to the energy management module are asynchronous in this strategy. When acceleration is applied, the torque sent to the energy management module is preceding to the torque sent to the motor control unit. Nevertheless, when decelerating the reverse occurs as shown in Figure 7.

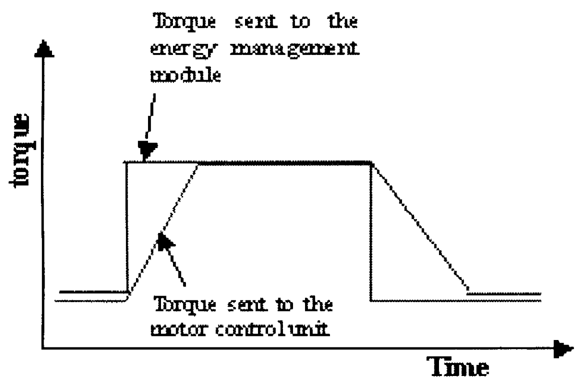

Fig. 7 Torque management

2.3 Energy distribution strategy block

The energy distribution strategy block is the heart of the Energy management module. There are many distribution strategies [Tarnow et al., 2001], [Matsumoto et al., 2001]. In this paper, a simple strategy called Constant charging voltage strategy is used. The strategy is described as following:

The strategy is based on the idea of a conventional battery charging method, which attempts to keep the bus voltage constant. During steady state and low load process, the motor's power is supplied by PEMFC only, while in transient and high load process, the bus voltage drops because of the characteristic of the DC/DC converter, then the power of the motor is supplied by both the PEMFC and the battery.

In normal operations, power flows automatically among DC/DC, battery and motor. But in some cases, in order to protect the battery some measures must be taken. When the bus voltage is lower than the voltage of the battery allowance, the motor's power must be reduced. The charging current must be limited when it is very large. When the vehicle is braking, the bus voltage must be well controlled to protect the battery from over current by reducing the energy regenerative braking torque. In the constant charging voltage control, it is very important to select the voltage value. To avoid over discharge (or low SOC), the voltage cannot be too low. In the mean time, the voltage cannot be too high because the battery may become overcharge, and it will also reduce the vehicle efficiency for the battery's low recovery of regenerative braking energy. In general, the voltage must not be higher than the maximum charging voltage the battery allowed. Figure 8 and Figure 9 are the simulation results based on a forward model developed on ADVISOR. The driving cycle used in this simulation is the UBDBUS. The results show that battery SOC can maintain unchanged by selecting the constant charging voltage carefully.

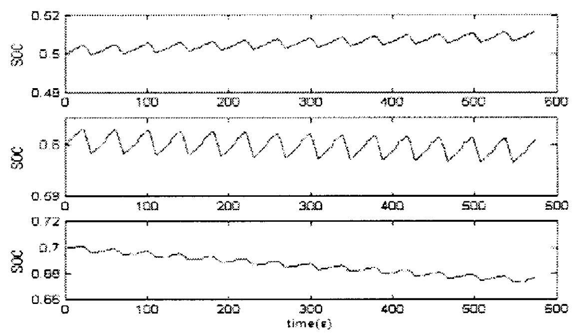

Fig. 8 SOC vs operating time with different initial SOC value

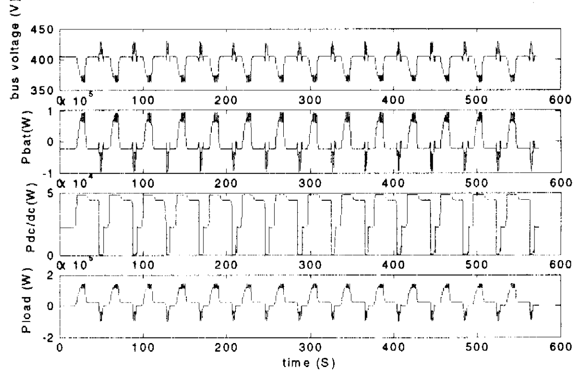

Fig. 9 Bus voltage, battery power (Pbat), DC/DC output power (Pdc/dc) and motor input power (Pload) vs time respectively

DC/DC converter characteristic plays a very important role in this strategy. Its characteristics must match the fuel cell system very well. Otherwise the fuel cell system will overload in the case of high load and transient.

The DC/DC converter used in this city bus has the characteristics of low input voltage limit and over current limit shown in Figure 10. As the power of the motor increases, the power drawn from the DC/DC converter increases too. The output current of the fuel cell increases, while the output voltage decreases. When the input voltage of the DC/DC converter (namely the output voltage of fuel cell system) reaches the low limit voltage or when the output current reaches the limit current, the power draw from the DC/DC converter is holding unchanged and the shortage power of the motor is supplied by the high voltage battery.

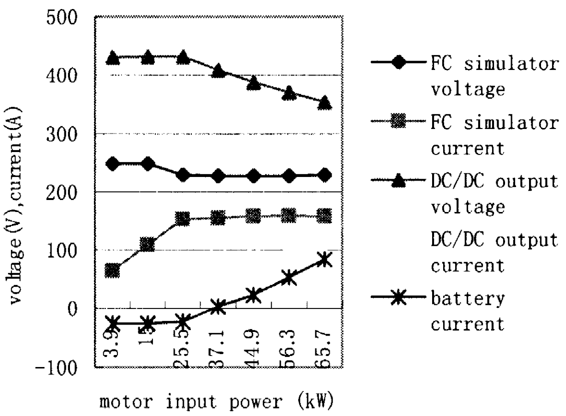

Fig. 10 Characteristic of the DC/DC converter

3. TEST

The control strategy is tested and calibrated on the hybrid power-train test bench. The hybrid test bench is composed of a fuel cell simulator, a target DC/DC converter, a target driving induced motor, a lead-acid battery system, and an AVL dynamometer system. The dynamometer can simulate the cycle load of the vehicle and it can also fulfill the driver's commands such as accelerating pedal position, braking pedal position and start/stop key etc. A photo of the hybrid power-train test bench is shown in Figure 11. The fuel cell V-I curve can be put to the fuel cell simulator. The tests include failure processes and driving cycle (CBDBUS) test. Some of the test results are shown in Figure 12 and Figure 13. The test confirms that the control strategy can meet the request of the City Bus. Now the control strategy is applied to the fuel cell city bus.

Fig. 11 The hybrid test bench

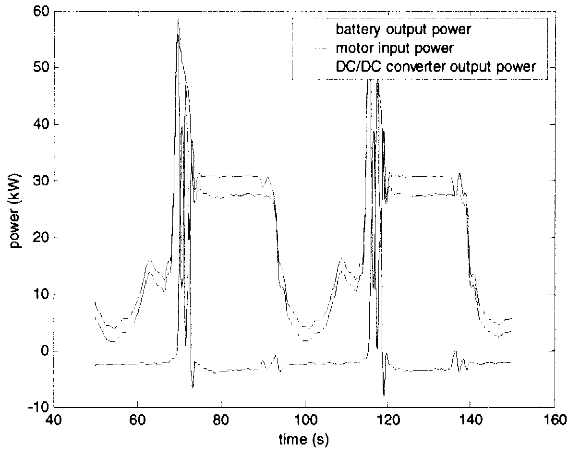

Fig. 12 Power distribution

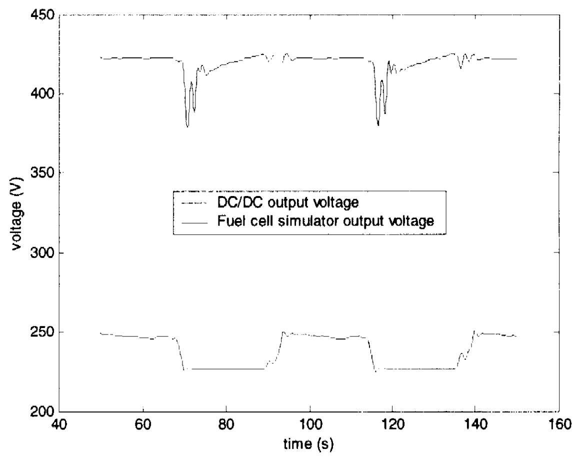

Fig. 13 The output voltage of DC/DC and the fuel cell simulator

4. CONCLUSION

In this paper, the design of a control strategy is presented. The design consists of the state control design, the driver torque demand design, the energy distribution strategy design etc. In the energy distribution strategy design, the constant charging voltage strategy is introduced. The strategy is very simple and easy to be realized. However, the characteristics of the DC/DC converter must be designed carefully to match the fuel cell system, or the fuel cell will overload in the case of high load and transient. Test results show that the strategy can meet the bus requirements.

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