An EASY5 based research on simulation of fuel cell city bus

LI Zonghua, TIAN Guangyu, ZHOU Weibo, CHEN Quanshi, ZHU Yuan

Abstract

The powertrain of a hybrid fuel cell city bus consists of a 60-kW fuel cell engine, battery packs, a boost DC/DC converter connecting the fuel cell engine with the DC power bus and an induction motor. Using the advanced modeling tools EASY5®, this paper gives the vehicle longitudinal model of the fuel cell city bus firstly. Then, the vehicle system control strategy is obtained based on this vehicle longitudinal model. Finally, the simulation results are also compared with that of the prototype vehicle road test to validate the EASY5® model and the control strategies.

Keywords: fuel cell, modeling, simulation.

1 Introduction

Fuel Cell Hybrid Vehicle as a type of future vehicles has brought itself to wide recognition and undeniable high social status. It is considered as one of the most important research and development directions in a lot of countries, including China. Fuel cell city bus project, supported by the national high-tech research and development (863) program of China, will provide the clean transportation technology for the 2008 Beijing Olympic Games and three prototype buses have been developed.

Fuel cell vehicles can be powered either by pure fuel cell(PFC), or by fuel cell hybrid system, coupled with battery(FC+B), ultra capacitor (FC+C), or battery plus ultra capacitor(FC+B+C). The fuel cell city bus in this paper belongs to FC+B type and its powertrain configuration consists of a fuel cell engine, a battery pack, a boost DC/DC converter connecting the fuel cell engine with the DC power bus, and an induction motor. Table 1 illustrates the major technical parameters of the fuel cell city bus.

Table 1: Parameters of the fuel cell city bus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length × Width × Height (mm)</td>
<td>11,070×2,500×3,420</td>
</tr>
<tr>
<td>Gross Vehicle Mass (kg)</td>
<td>14,200</td>
</tr>
<tr>
<td>Fuel Cell Type</td>
<td>PEMFC</td>
</tr>
<tr>
<td>Maximum Power(kW)</td>
<td>60</td>
</tr>
<tr>
<td>Auxiliary Battery Pack Type</td>
<td>Ni-MH</td>
</tr>
<tr>
<td>Module Weight(kg)</td>
<td>13.4</td>
</tr>
<tr>
<td>Capacity(Ah)</td>
<td>60</td>
</tr>
<tr>
<td>Number</td>
<td>30</td>
</tr>
<tr>
<td>Traction motor and its controller Type</td>
<td>Induction motor</td>
</tr>
<tr>
<td>Rated/Max Power(kW)</td>
<td>100/160</td>
</tr>
<tr>
<td>Rated/Max Torque(N.m)</td>
<td>530/840</td>
</tr>
<tr>
<td>Rated/Max Speed(rpm)</td>
<td>1780/5200</td>
</tr>
<tr>
<td>Transmission Line 1st/2nd gear ratio</td>
<td>3.002/1.862</td>
</tr>
<tr>
<td>Final drive ratio</td>
<td>6.83</td>
</tr>
</tbody>
</table>
This paper will give the vehicle longitudinal model of the fuel cell city bus by means of EASY5® which can easily help us to build dynamic model. Then, the vehicle system control strategy is obtained based on this vehicle longitudinal model. Comparative analysis between the EASY5® simulation results and the prototype vehicle road test has been conducted to validate the EASY5® model and the control strategies.

2 Simulation Tool

EASY5® (Engineering Analysis SYstem) is a graphics-based software tool used to model, simulate, and design dynamic systems characterized by differential, difference, and algebraic equations.[1]

- Models are assembled graphically from primitive functional blocks, such as dividers, lead-lag filters, and integrators, and special system-level components such as gears, clutches, engines and many more.
- EASY5® offers a comprehensive set of Application Libraries that are targeted to a specific application with pre-built, ready-to-use models of physical devices such as hydraulic valves and actuators, internal combustion engines, electric motors, gears, clutches, heat exchangers, fans, and evaporators - hundreds of physical subsystems that can be used to construct a complete dynamic system model.
- These libraries are developed by experts in their engineering discipline, so high-fidelity models of great complexity can be quickly and easily built.

As the primary parameters of components are provided and it is hard to get the other detailed data of components, it is not adequate for building model in some simulation tools. But it is sufficient for EASY5® as the default parameters and the classical engineering models are available. It is only necessary to validate the final model system instead of the uncertain component model. So the tool of EASY5® as a proper choice is selected for simulation.

3 Modeling

Functionally, the structure of simulation system consists of four parts, driving cycle, driver, VCU[2] and vehicle dynamics, as shown in figure 1. The diver model is actually a vehicle velocity controller. It uses the vehicle speed feedback from the vehicle dynamics and the target vehicle speed to generate accelerating and braking pedals. Simultaneously, the pedal signals are sent to the VCU. The VCU not only samples the signals from driver, but also receives other information from components, such as the SOC from battery, the vehicle speed from speed sensor etc. On basis of the present status of vehicle, VCU will decide how to distribute the power between the fuel cell and auxiliary battery and whether to shift. Then the sub-controller will perform the commands to control the components. The inputs and outputs of each of the model are listed in table 2.
Figure 1: the structure of the vehicle simulation system

Table 2: the parameters of inputs and outputs

<table>
<thead>
<tr>
<th>Component</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell</td>
<td>$P_{fc}$ required power</td>
<td>$U_{fc}$ fuel cell voltage</td>
</tr>
<tr>
<td></td>
<td>$I_{fc}$ fuel cell circuit</td>
<td></td>
</tr>
<tr>
<td>Main DC/DC</td>
<td>$I_{dc}$ required circuit</td>
<td>$I_{dc}$ DC/DC output circuit</td>
</tr>
<tr>
<td></td>
<td>$U_{fc}$ fuel cell voltage</td>
<td>$I_{fc}$ fuel cell circuit</td>
</tr>
<tr>
<td></td>
<td>$U_{bus}$ bus voltage</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>$I_{bat}$ battery circuit</td>
<td>$U_{bus}$ bus voltage</td>
</tr>
<tr>
<td>Motor/Motor</td>
<td>$T_e^*$ required torque</td>
<td>$I_m$ motor input circuit</td>
</tr>
<tr>
<td>Controller</td>
<td>$U_{bus}$ bus voltage</td>
<td>$T_e$ motor output torque</td>
</tr>
<tr>
<td></td>
<td>$\omega_e$ motor speed</td>
<td>$\omega_i$ transmission output axle speed</td>
</tr>
<tr>
<td>Transmission</td>
<td>Gear target gear</td>
<td>$\omega_e$ motor speed</td>
</tr>
<tr>
<td></td>
<td>$T_e$ motor output torque</td>
<td>$\omega_i$ transmission output axle speed</td>
</tr>
<tr>
<td></td>
<td>$T_i$ axle torque</td>
<td></td>
</tr>
<tr>
<td>Tire</td>
<td>$T_i$ axle torque</td>
<td>$\omega_v$ wheel speed</td>
</tr>
<tr>
<td></td>
<td>$T_b$ mechanical brake torque</td>
<td>$F_t$ Tire tractive force</td>
</tr>
<tr>
<td></td>
<td>$v$ speed</td>
<td></td>
</tr>
<tr>
<td>Vehicle</td>
<td>$F_t$ traction force</td>
<td>$v$ speed</td>
</tr>
<tr>
<td>Driver</td>
<td>$v^*$ target speed</td>
<td>$Acc$ accelerate pedal displacement</td>
</tr>
<tr>
<td></td>
<td>$v$ actual speed</td>
<td>$Brake$ brake pedal displacement</td>
</tr>
<tr>
<td>Driving cycle</td>
<td>No input</td>
<td>$v^*$ target speed</td>
</tr>
<tr>
<td>VCU</td>
<td>$Acc$ $Brake$ status</td>
<td>$P_{fc}$ $I_{dc}$ $T_e^*$ $T_b$ Gear</td>
</tr>
</tbody>
</table>
3.1 Powertrain Dynamic Model

3.1.1 Fuel Cell Engine Model

The fuel cell engine system is the main power source of the fuel cell vehicle and it is very complicated. Different mathematical models [3] are built according to the different research purposes. Using EASY5® fuel cell library, we can develop the fuel cell engine dynamic model.

As shown in figure 2, the fuel cell engine dynamic model is made up of the fuel cell stack, Hydrogen supply system, air supply system, compressor and cooler, etc. The air compressor is under a kind of multi-level control. Before the load connected to the fuel cell engine, there is a DC/DC converter.

The dynamic fuel cell engine model provides insight of how the fuel cell works and the fuel cell dynamic characteristics. The model has been validated by comparing the simulation results and actual fuel cell engine experiments.

Figure 2: the fuel cell engine dynamic model in EASY5®

3.1.2 Battery Model

Since the fuel cell can only satisfy the average vehicle power requirement, in the case of frequent startup and acceleration, there must be an auxiliary power source to provide the additional peak power. Besides, in order to store the regenerated braking energy, the auxiliary battery is also a suitable selection.

The battery model in EASY5® represents a storage unit with no-load terminal voltage as a function of SOC. It calculates the power delivered to/from the battery and the power dissipated through the generation of heat. The open circuit voltage is a function of SOC and empirical parameters. The dynamic relationship...
between battery voltage and current is modeled, including the polarization capacitive effect, incipient capacitance of the battery, internal battery resistance, and terminal ohmic resistance.

SOC is computed by using ampere hour accumulation method which is one of the most practical ways for valuating the SOC of battery. The primary parameters are obtained by doing a large amount of experiments such as 3 hours rate test and HPPC test.

3.1.3 Motor Model

Analysis of AC machines is complicated because the inductances that couple the stator and rotor vary sinusoidally with rotor position. However, it is possible to define a coordinate transformation to bring stator and rotor quantities into a common, non-rotating reference frame. Equations of motion written in the rotating frame have constant coefficients and may be manipulated into a form that is easily implemented in an EASY5® component. Also, the transformations are not the same for all machines or even for all three-phase machines.

The voltage equations may be manipulated into a set of ordinary differential equations of the form:

\[
\frac{di}{dt} = [v] + [C]*[i]
\]

Where \(\frac{di}{dt}\) is a vector of derivatives of the QD0-frame currents, \(v\) is a vector of the QD0-frame applied voltages; \(C\) is a coefficient matrix and \(i\) is a vector of the QD0-frame currents.

3.1.4 Tire Model

The tire model relates the torque generated by the drivetrain to the tractive effort (at the tread-ground interface) which ultimately drives the vehicle. The driving torque applied to the wheel is transmitted to the driveline and the vehicle. The relationship between the wheel-tread slip and the tractive force is specified using either a physical model, or the Pacejka "magic" tire model. The model is shown in figure 5. It is simplified as a spring + damper system.
If the vehicle speed is $V$, slip is defined as

$$s_s = \frac{w_r r - V}{V}$$

As the friction coefficient $\mu$ is a function of $s_s$ marked as $\mu(s_s)$, and $F_z$ is the normal force on tire.

So:

$$F_t = \mu(s_s) \cdot F_z$$

According to the characteristic of spring and damper, there is

$$T_w = K_T (\theta_w - \theta_i) + C_T (w_w - w_i)$$

$$= F_t \cdot r$$

The equation of motion for the wheel is:

$$T_D - T_b - F_t r - T_w = I_w \frac{dw_w}{dt}$$

### 3.1.5 Vehicle Model

The vehicle model calculates the translational motion of the vehicle as well as the weight transfer from front to rear axles due to acceleration. External loads on the vehicle (grade, drawbar, and aerodynamic loads) are specified via this model.

The tractive force from the tires drives the vehicle, while the drawbar and aerodynamic loads act on the vehicle. This model also accounts for the effect of grade angle on the motion and load distribution.
3.2 Control Strategy

The control strategy of fuel cell city bus has been developed and one of its main functions is to determine the power distribution between the fuel cell and auxiliary battery. The principle is shown as follows:

As an advanced function of vehicle control strategy, the optimal operating efficiency depends on the power distribution strategy. The power distribution problem of the fuel cell bus is to distribute power between the fuel cell and the storage battery to meet the demand of the drive motor. Considering the control strategy of maintaining the battery voltage at a constant value, the self-adaptive control strategy of the main DC/DC converter and the output power control strategy of the fuel cell, we can obtain the control strategy for power distribution of the fuel cell bus as shown in figure 7.

The driver’s power demand plus the additional power loss equals the vehicle power demand. According to the vehicle power demand and the fuel cell power control strategy, the output power of the fuel cell is determined. Then, the vehicle power demand minus the fuel cell net output power equals the battery power demand. And according to the set value of the main DC/DC’s output voltage and the constraint
conditions of the storage battery, the battery power is determined. Finally, the net output power of the fuel cell system plus the actual power of the storage battery equals the total power, which can be regarded as the power command for the motor.

4 Simulation and Validation

Analyzing the difference between the actual data and simulation results can find the cause of the problem so as to improve the simulation system. In prototype vehicle, only the input current and speed of the motor can be sampled from CAN network, while other signals of motor can not be achieved. So with this limitation, the battery voltage multiplied by the motor input current is the motor power. According to the results of interpolating, filtering and calculating the road test data, the actual vehicle speed and motor power can be obtained and applied for comparing with the simulation data.

In figure 8, the vehicle speed in simulation tracks the actual speed very well although there are still a few distinctions in some area, especially when the driver begins to release the accelerating pedal. Since the driver model is a PI controller, the process of fast releasing the accelerating pedal can not be simulate completely, even if the PI parameters are adjusted repeatedly. So it is necessary to do research on the driver’s behaviors and habits.

Figure 9 shows the trends of motor power in road test and simulation are almost identical. The simulation motor power delays about 4 seconds and in some area there are shocks, as the motor model is idealized with some characteristic and the motor controller still needs to be improved.

Selecting another road cycle, performing the simulation and comparing the actual test data with simulation data, the same conclusions are achieved.

![Figure 8: the simulation speed and actual speed vs. time](image)
Figure 9: the simulation motor power and actual motor power vs. time

5 Conclusion

Simulation on fuel cell vehicle has been done in recent years, and it is becoming more common. This paper proposes a new method for simulation on fuel cell city bus with EASY5® instead of Matlab/Simulink. The virtual fuel cell city bus simulation system with the dynamic component models is built and the dynamic performance of the fuel cell city bus is analyzed. Simultaneously, these models also provide insight when modeling and identifying potential problems. The comparisons between actual test data and simulation results show that the simulation system is reasonable and available. The future work will be how to carry on more work with this system, to design the optimal control strategy and to optimize some cost variables such as fuel economy and/or emissions.

References


Using EASY5, Master thesis Tsinghua University 2002

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