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Object-oriented Physical Modeling and Simulation of Fuel Cell Vehicle Powertrain

Xiong Yun^{1,2}, Zai-min Zhong^{1,2}, Sun Ze-chang¹ and Zhang Tong^{1,2}¹College of Automotive, Tongji University, Shanghai 201805, China²Shanghai Fuel Cell Vehicle Powertrain Co., Ltd, Shanghai 201805, China

Email:xiongyun@fcv-sh.com

Abstract

Fuel cell vehicle (FCV) is the focus of new energy vehicles research, in which the study of the powertrain is one of the crucial. This paper introduces the structure and working principle of the FCV powertrain, and analyses the critical powertrain components. According to complex and multi-domain characteristics of the powertrain, this paper presents an object-oriented modeling language to unify the physical modeling method and establish the physical model of FCV powertrain and the critical components base upon Maplesim platform. Using combined simulation based on Maplesim and Simulink and the results show the effectiveness of the model .

Keywords: FCV, powertrain, object-oriented, physical model

1. Introduction

Fuel cell vehicle is one of the new energy vehicles research topics, and has attracted world attention in recent years. Currently, it is necessary to have one or more energy storage devices in FCV powertrain system. The energy storage devices provides power to the wheels when the fuel cell stack is warming up, they heats up the fuel cells stack, supplies peak powers to the load so that fuel cell stack power

rating can be reduced, and captures the braking energy to increase the efficiency. The powertrain of FCV is complex multi-domain mechatronic systems, which composed by a fuel cell that have the characteristic of electrochemical, a power battery (or ultra capacitors), a DC-DC converter that have the electromagnetic properties, a motor with electric-magnetic-mechanical properties and other critical components.

Using the traditional modeling methods can not fully describe the powertrain, especially

required the model of powertrain components includes parts' information. The above negative factors led to difficult to understand and optimize the fuel cell powertrain of FCHEV. However, Object-oriented modeling can better solve this problem. In addition, components of the system using the object-oriented model is not only beneficial to the whole understanding of powertrain's electrical characteristics, but also for optimization of powertrain design and laid the foundation for fault diagnosis.

2. The Powertrain of FCV

An overview of the FCV is shown in Fig. 2. The block diagram illustrates the components of the FCV and the power flow between them. It is seen that power flows to or from the electric machines (EM) to a common bus through two inverters (Inv). The energy which from the methanol storage goes through a reformer and the fuel cell stack (FC) and then feed to the bus. Power is also can flow into or out from the battery (Bat).

Besides the shaft power $p_{s,R}$ and $p_{s,L}$, the powertrain must also provide power for the light, balance-of-plant of the fuel cell system and the auxiliary devices, i.e. vehicle computer, drivers, control panel, etc.

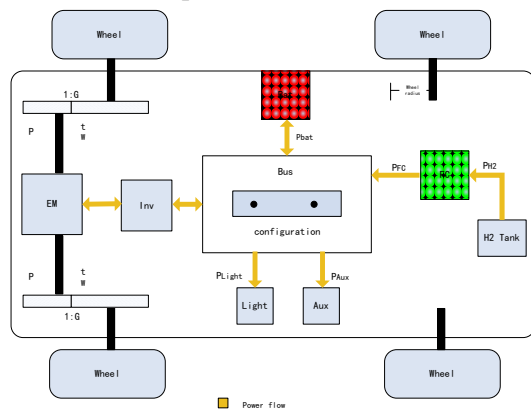


Figure 1: System overview and power flow of powertrain.

3. The Key Components of the Powertrain

3.1. Electric Machines

The motors of the FCV adopt permanent magnet synchronous machines type, which operated by field oriented $I_d = 0$ control. The electric machines model which utilize steady state equations are

$$\tau_e = B_v \cdot \omega_s + \text{sign}(\omega_s) \cdot \tau_c + \tau_s [\text{Nm}] \quad (1)$$

$$i_q = \frac{2}{3} \frac{2}{P} \frac{\tau_e}{\lambda_{pm}} [\text{A}] \quad (2)$$

$$v_q = R_s \cdot i_q + \lambda_{pm} \frac{P}{2} \omega_s [\text{V}] \quad (3)$$

$$P_{EM} = \frac{3}{2} v_q \cdot i_q [\text{W}] \quad (4)$$

τ_e is the electromechanical torque, B_v is the viscous friction coefficient, τ_c is the coulomb friction, v_q and i_q are the q-axis voltage and current respectively, R_s is the stator resistance, P is the number of poles, λ_{pm} is the magnet flux linkage, and P_{EM} is the power between the motor and inverter.

3.2. Inverters

It is assumed that the losses of the inverters are given by an equivalent switch resistance R_{Inv} . Therefore

$$R_{Inv} = \frac{\eta_{Inv}(1-\eta_{Inv})V_{Bus,min}^2}{P_{Inv,meas,max}} [\Omega] \quad (5)$$

$$i_{Inv} = \frac{v_{Bus} - \sqrt{v_{Bus}^2 - 4R_{Inv}P_{EM}}}{2R_{Inv}} [A] \quad (6)$$

$$P_{Inv} = v_{Bus}i_{Inv} [W] \quad (7)$$

$V_{Bus,min}$ is the bus voltage allows minimum value. P_{Inv} and i_{Inv} are the power and current between the inverter and bus, respectively. η_{Inv} is the efficiency at the maximum measured inverter power $P_{Inv,meas,max}$. R_{Inv} is the equivalent resistance.

3.3. Fuel Cell Stack

A fuel cell stack of high temperature proton exchange membrane (HTPEM) type is the reference to fuel cell stack. The fuel cell stack can be modeled as an internal voltage source $V_{FC,int}$ with an internal series resistance, i.e.

$$v_{FC} = V_{FC,int} - R_{FC} \cdot r_{FC,pu}(i_{FC,pu})i_{FC} [V] \quad (8)$$

v_{FC} and i_{FC} are the fuel cell stack voltage and current respectively. R_{FC} is the internal resistance at maximum current $i_{FC,max}$ and $r_{FC,pu}(i_{FC,pu})$ is a current depending per unit resistance. The input power of the fuel cell

stack, i.e. the output power of the reformer, is given by

$$P_{H_2} = \frac{M_{H_2}N_{FC}LHV_{H_2}}{2F}i_{FC} [W] \quad (9)$$

$$M_{H_2} = 0.00216 \frac{kg}{mol} \text{ is the hydrogen}$$

molar mass, $LHV_{H_2} = 120.1 \cdot 10^6 \frac{J}{kg}$ is the lower heating value of hydrogen,

and $F = 96485 \frac{C}{mol}$ is Faraday's constant.

It assumed that the internal voltage is $V_{FC,int}$ and that the voltage at maximum power is $V_{FC,min}$. The maximum fuel cell stack current $I_{FC,max}$, the internal resistance at maximum power R_{FC} , and the number of cells, are therefore given by

$$I_{FC,max} = \frac{P_{FC,rat}}{V_{FC,min}} [A] \quad (10)$$

$$R_{FC} = \frac{V_{FC,int} - V_{FC,min}}{I_{FC,max}} [\Omega] \quad (11)$$

$$N_{FC} = \frac{V_{FC,min}}{V_{FC,Base}} N_{FC,Base} [-] \quad (12)$$

3.4. Battery

The battery is also modeled as an interval voltage source $V_{Bat,int}$ with an internal resistance. Therefore

$$R_{Bat} = \frac{V_{Bat,int}^2}{4P_{Bat,max}} [\Omega] \quad (13)$$

$$v_{Bat} = V_{Bat,int} - R_{Bat} \cdot r_{Bat,pu} (SoC_{Bat}) i_{Bat} \text{ [V]} \quad (14)$$

$$SoC_{Bat} = 1 + (5 |i_{Bat}|)^{k-1} \frac{\int i_{Bat} dt}{3600} C_5^{-k} \text{ [-]} \quad (15)$$

$$DoD_{Bat} = 1 - SoC_{Bat} \text{ [-]} \quad (16)$$

$P_{Bat,max}$ is the maximum power capability of the battery. v_{Bat} and i_{Bat} are the battery voltage and current respectively. $r_{Bat,pu} (SoC_{Bat})$ is a factor utilized in order to model the low charge acceptance at high battery state-of-charge SoC_{Bat} . k is the Peukert constant. C_5 are the 5h discharge Ah capacity of the battery, and DoD_{Bat} is the battery depth-of-discharge.

The loss-of-lifetime of the battery is defined by [17]:

$$LoL = \sum_{DoD_{Bat}=0.01}^{DoD_{Bat}=1} \frac{N_{cyc} (DoD_{Bat})}{N_{ctf} (DoD_{Bat})} \text{ [-]} \quad (17)$$

N_{cyc} is the number of full cycles with depth-of-discharge amplitude DoD_{Bat} .

3.5. DC/DC Converters

The fuel cell DC/DC converter bucks and boosts the voltage in one direction. However, in order to simplify the same topology is utilized.

It is assumed the switch resistances R_T are the only loss component in the converters. If it is assumed the DC/DC converters have efficiency at maximum power $P_{1,max} = V_{1,min} I_{1,max}$, and

efficiency at this time is η_{Con} , the resistance of each switch is

$$R_T = (1 - \eta_{Con}) \frac{V_{1,min}}{2I_{1,max}} \text{ [\Omega]} \quad (18)$$

The current i_1 can be calculated from the duty cycle D . For $v_1 \geq v_2$ and $i_2 \geq 0$:

$$D = \frac{v_2 + 2R_T i_2}{v_1} \text{ [-]} \quad (19)$$

$$i_1 = D i_2 \text{ [A]} \quad (20)$$

For $v_1 < v_2$ and $i_2 \geq 0$:

$$D = \frac{2v_2 - v_1 - \sqrt{v_1^2 - 8R_T i_2}}{2v_2} \text{ [-]} \quad (21)$$

$$i_1 = \frac{i_2}{1 - D} \text{ [A]} \quad (22)$$

For $v_1 \geq v_2$ and $i_2 < 0$:

$$D = \frac{v_1 - v_2 - 2R_T i_2}{v_1} \text{ [-]} \quad (23)$$

$$i_1 = (1 - D) i_2 \text{ [A]} \quad (24)$$

For $v_1 < v_2$ and $i_2 < 0$:

$$D = \frac{v_1 + \sqrt{v_1^2 - 8R_T v_2 i_2}}{2v_2} \text{ [-]} \quad (25)$$

$$i_1 = \frac{i_2}{D} [\text{A}] \quad (26)$$

4. Physical Modeling Based on Object-oriented

Powertrain is a complex multi-domain electromechanical system. It is difficult to describe and simulate in a unified platform. In order to increase the accuracy of the model and improve modeling efficiency, Modelica as a new, object-oriented physical modeling language is paid more and more attention. After the traditional model used language which based on signal is completed, it is difficult to modify for the failure and simulate fault conditions. In some cases, faults cause the changes of system's transfer function, but the new transfer function is unknowing, so it is difficult to modeling based on signal directly and efficiently. However, the object-oriented physical modeling language is evaded this point, that can modify according to fault conditions directly but it is not the whole system's transfer function.

Modelica is a new simulation language formed in the later 1990s which is an object-oriented and non-causal high-level modeling language used in many fields. Modelica simplify modeling of complex physical systems, improve the system modeling capabilities and reduce the modeling and verification time.

Simulation software MapleSim is developed on the Maple platform by Maple soft which has superior ability of symbolic computation that increased computing speed by nearly 6 times and speeded up the development process. Cause the Modelica is non-causal that makes the language very rigor demanding when it works. The MapleSim has obvious advantage in the DAE equation solver speed.

Simulink is very powerful on the control system design based on signal flow. This paper uses combined simulation based on Maplesim and Simulink. The physical model based on MapleSim generates S-Function through the converted interface. Then to design control and fault diagnosis algorithm using Simulink that realize hybrid modeling and simulation.

5. Combined Simulation and Validate Based on MapleSim and Simulink

In the MapleSim, the physical modeling based on object-oriented builds models. Take motor for example, concrete steps are as follows: First, using object-oriented language in Maple write into the source code of motor; Then, use the program of Maple in the MapleSim to generate a graphical motor module, cause this module is object-oriented approach to modeling, but in the Simulink does not have corresponding input and output, so the use of some sensors in the MapleSim to complete the conversion between physical quantity and signal flow; Finally, using Simulink Block Generation module in MapleSim and generating a M file in the specified folder and a C file that will be used by S-Function module later. The M file is the role of generate images of Simulink module and settings interface and so on. Run the M file in the Matlab environment, can not only create a module written by Simulink. Figure 2 - 5 is batteries, fuel cell stack and DC / DC conversion's physical model.

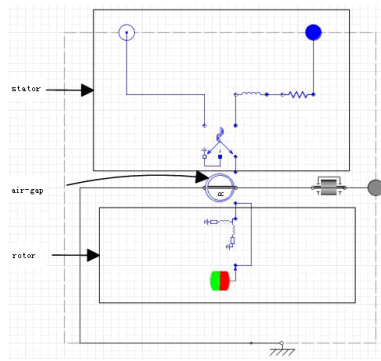


Figure 2: PMSM physical model

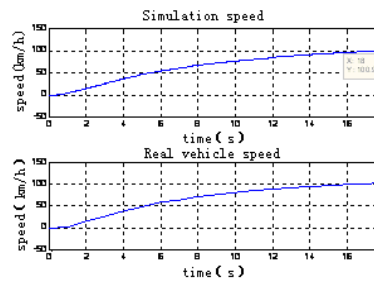


Figure 7: Comparison chart of 0-100km/h Simulation Acceleration and data of actual observation

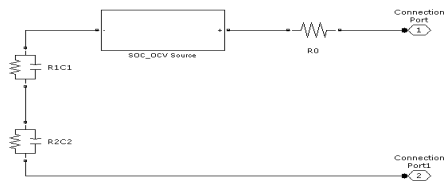


Figure 3: Battery's physical model

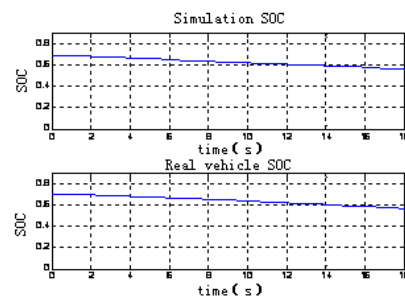


Figure 8: Comparison chart of SOC

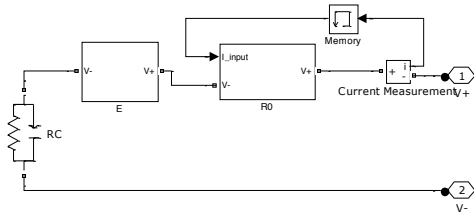


Figure 4: FCE's physical model

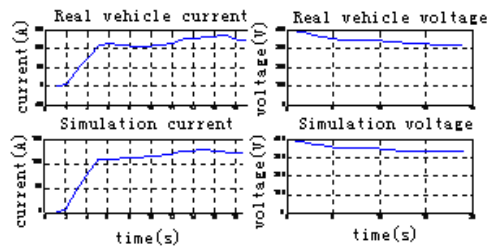


Figure 9: Comparison chart of battery current and voltage

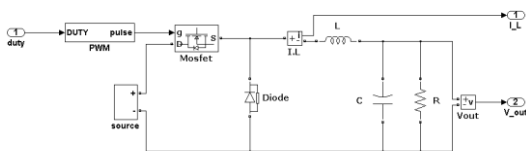


Figure 5: DC-DC converter's physical model

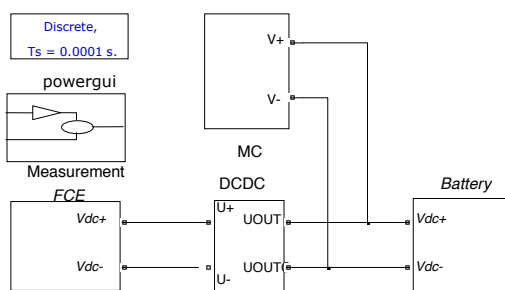


Figure 6: Hybrid simulation model of FCV powertrain

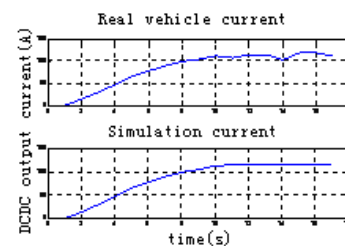


Figure 10: Comparison chart of DCDC output current

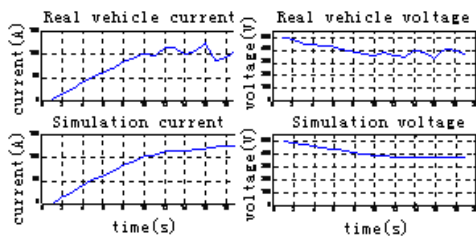


Figure 11: Comparison chart of FCE current and voltage

Simulation results as figure 7 -11: date of actual observation about the vehicle powertrain proved that this model can reflect the actual situation of the powertrain.

6. Conclusions

This paper detailed introduce FCV powertrain and critical components' basic structure, principle of work and relevant performance parameter, emphasis the characteristics of multi-domain and complex. For this situation, this paper presents an object-oriented physical modeling language and formed the physical model of critical components and powertrain. Through the combined modeling and simulation based on Simulink and MapleSim, proves the available and reliable of the multi-domain modeling. For the further optimize and fault diagnosis of FCV laid the foundation.

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Author



Xiong Yun

Shanghai Fuel Cell Vehicle Powertrain Co., Ltd., NO.6988, Jiasong Road, N.Jiading District Shanghai 201805, P.R.C
Tel: 13816571396

Fax: (021) 51650002

Email: xiongyun@fcv-sh.com



Zai-min Zhong

Clean Energy Automotive
Engineering Center of Tongji
University, No.4800, Cao An
Road, Jiading District Shanghai
201805, P.R.C

Tel: 13040631486

Fax: (021) 51650002

Email: zm_zhong@tongji.edu.cn