Test Platform Development for Fuel Cell Vehicle’s Hydrogen Management System

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Abstract

This paper has proposed a Hardware-in-Loop test platform for Hydrogen Management System (HMS) based on hardware of PXI and software of LabVIEW of National Instrument company (NI) and Matlab/Simulink for plug-in fuel cell vehicle, replacing the real car experiment platform with the feature of complicated test environment, variable parameter, and limited condition in debugging stage. According to HMS working behavior, it has designed the HMS model by simulink for the test platform. And according to HMS’s control strategy, I/O signal map, CAN communication and sensor characteristics, it has designed the platform hardware configuration, software program, test interface, and rapidly made validation to control logic and fault diagnosis of Hydrogen Management Unit (HMU). The experiment result shows that this test platform is effective for HMU control logic validation, system status monitor, fault injection, fault tracing, and it can shorten the vehicle research and development cycle, reduce the development cost, optimize test environment and promise safety for test engineer.

Keywords: fuel cell vehicle, hydrogen management system, simulink model, test platform, hardware-in-loop, Fault injection

1. Introduction

Globally, it has vigorously proposed the development of energy saving vehicles and new energy vehicles according to worldwide vehicle development strategy, especially developing electric vehicle and fuel cell vehicle. Many automotive companies, universities, and research centers, home or abroad, have got significant achievement on technology research and development in small type electric vehicle and plug-in hybrid vehicle [1-9]. Electric control technology is one of key technologies on new energy vehicle. Due to the features of complicated testing environment, variable parameters, limited conditions in real car testing phase, it often causes problems like long development cycle, high development cost, one-sided test, and so on. Now, testing technology has developed rapidly with the development of testing tools and functions, especially the hardware in loop technology which is used widely in automotive ECU control logic validation [10-12].

This paper has proposed a hardware-in-loop test platform for hydrogen management system of plug-in fuel cell vehicle based on hardware NI PXI and Graphic software NI Labview from National Instruments company and Matlab/Simulink. The platform can separate the HMS from the complicated vehicle network. By simulating car conditions like refueling mode, drive mode, hydrogen exchange mode, and simulating HMS status like extreme hydrogen pressure in tank, extreme hydrogen temperature in tank, great hydrogen leakage in vehicle, and some other error, it can rapidly validate the HMS logic algorithm, and trace fault origination, to reduce vehicle development cycle and cut development cost. It will optimize the test environment for test engineer and promise test safety.

2. Hydrogen Management System

Hydrogen Management System is responsible for progress of hydrogen refueling, hydrogen supplying to fuel cell, and hydrogen exchanging of tank. In additional, it has to detect HMS components status and do fault diagnosis, send out warning if components are abnormal.
or hydrogen status is abnormal. HMS is mainly composed of two hydrogen storage tanks, pressure reducing valve, refueling switch, HMU, two hydrogen tank temperature sensors, two hydrogen tank pressure sensors, six hydrogen leakage sensors, pipes, tank valves, and some accessories. HMU is a core control unit and a signal process center. It communicates with vehicle management system (short for VMS) to exchange signal information. The components connection relationship and electrical communication relationship is showed in Figure 1.

In the power up mode, vehicle battery (DC 12 volts) is on, and HMU is powered on. It detects hydrogen temperature in tank, hydrogen pressure in tank, hydrogen pressure in pipe to fuel cell stack, and judge the tank and hydrogen status. In addition, HMU detects hydrogen leakage by six sensors distributed in some important point of vehicle, to judge the leakage status. If hydrogen leakage is more than the preset limits, HMU will send out warning message to LED and buzzer, so to protect vehicle safety.

In the drive mode, the vehicle is started and driven. HMU sends control signals to open hydrogen tank valves, and supplies hydrogen to fuel cell stack according to vehicle power requirement. During the driving process, HMU continually detects components status like hydrogen pressure in tank, hydrogen temperature in tank, hydrogen pressure in pipe, hydrogen leakage, and feeds it back to VMS. If hydrogen pressure in tank is not in safety scale, it will cause urgent error to HMU. As the same with above-mentioned, if hydrogen pressure in pipe or hydrogen leakage, is not in safety scale, any one of above-mentioned situation will cause HMU to go into Error mode. At this time, HMU sends message to hydrogen valve to close itself, and sends error code to Instrument Pack (short for IPK), to protect system safety.

When the hydrogen pressure in tank is too low, the vehicle can’t work normally. And VMS needs to send refueling order to HMU. Then, HMU will go to refueling mode. When the hydrogen in tank has to be exchanged, VMS need to send exchange order to HMU. Then, HMU will go to hydrogen exchange mode and open tank valves.

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Figure 1. Hydrogen Management System in Fuel Cell Vehicle

3. Research Method
3.1 HMS Simulink Model

The hydrogen management system model mainly simulates components action and characteristic, including refueling switch and hydrogen supply valves. The model input is the output of HMU, and the model output is the input of HMU. When the refueling switch, and the hydrogen supply valve is input into the model, the model calculates the cylinder pressure and temperature like real vehicle phenomenon. Simultaneously, the model outputs the cylinder pressure and temperature to the test platform.

Cylinder pressure and temperature characteristic is complicated during the hydrogen refueling and supplying process. Generally, this process can be dealt as an adiabatic process or isothermal change, or some one between them. There is a polytropic exponent to describe the process, which is called $k$.

For some given hydrogen in the cylinder, there is a thermodynamics equation for it, as equation (1).

$$p_1V^k = const$$ (1)
Where \( p \) is hydrogen pressure, \( V \) is hydrogen volume, const is short for constant. In addition, \( k \) equaling to 1.0 represents isothermal change process, and \( k \) equaling to 1.4 represents adiabatic change process.

Equation (1) can be changed into the equation (2) according to the relationship between \( P \), \( V \), \( T \) from ideal gas equation [13].

\[
p_1^{1-k}T^k = \text{const}
\]  

(2)

Where, \( T \) is hydrogen temperature.

As the refueling process is fast in fact and the hydrogen has little heat exchange with ambient environment. Therefore, this process can be treated as an adiabatic process. And the relationship between hydrogen mass and its pressure can be described as equation (3).

\[
kR_H T dm = Vdp_1
\]  

(3)

Where, \( R_H \) is hydrogen property constant, \( m \) is hydrogen mass in cylinder.

As the hydrogen supplying process is slow in fact and the hydrogen has some heat exchange with ambient environment. Therefore, this process can be treated as an isothermal process. And the relationship between hydrogen mass and its pressure can be described as equation (4).

\[
kR_H T dm = -Vdp_1
\]  

(4)

According to pneumatic theory, when hydrogen flows across an orifice by inferior sonic speed, \((0.5283 \leq \frac{p_2}{p_1} \leq 1.0)\), the hydrogen mass flow rate can be described as equation (5) [14][15].

\[
Q_p = \frac{C_d p_1 A}{\sqrt{R_H T}} \left[ \frac{2k}{k-1} \left( \frac{p_2}{p_1} \right)^{\frac{k+1}{k}} - \left( \frac{p_2}{p_1} \right)^{1+k} \right]
\]  

(5)

Where, \( Q_p \) is hydrogen mass flow rate, \( C_d \) is flow index, \( A \) is orifice area, \( P_2 \) is the pressure of another side of orifice. Here, \( P_1 \) is cylinder pressure, \( P_2 \) is pipe pressure.

When hydrogen flows across an orifice by sonic speed, \((0 \leq \frac{p_2}{p_1} < 0.5283)\), the hydrogen mass flow rate can be described as equation (6) [14,15].

\[
Q_p = \frac{C_d p_1 A}{\sqrt{R_H T}} \left[ \frac{2k}{k+1} \left( \frac{2}{k+1} \right)^{1+k} \right]
\]  

(6)

At the same time, the relationship between mass and mass flow rate can be described as equation (7).

\[
dm = Q_p dt
\]  

(7)

According to equation (1) to (7), the hydrogen management model can be built by Matlab/Simulink as Figure 2.

In the Simulink model of HMS, the input is refueling switch, two hydrogen supply valves, and the output is cylinder pressure and cylinder temperature. The main three blocks in the model are strategy, refueling process, hydrogen supply process. The strategy block is used to decide the HMS process. The refueling process block is used to calculated cylinder pressure and temperature in refueling mode. And the hydrogen supply process is used to calculate the cylinder pressure and temperature in hydrogen supply mode. Both refueling process and hydrogen supply process are built according to equation (1) to (7).

The strategy block is showed as Figure 3. When the refueling switch is on, and both two valves are off, hydrogen management system goes to refueling process. When the refueling switch is off, and both two valves are on, hydrogen management system goes to hydrogen supply process.
3.2 I/O and Communication

HMU’s power supply is DC (12 Volts). It collects signal from sensors and VMS, and processes them in the process unit, and sends out control signals to executive components or send out error code to IPK when there is fault existing in HMS. All signals can be separated into battery signals, digital input and output signals, analog input signals, PWM output signals, CAN network signals.

HMU receives digital signals sent from other components by digital input ports, like vehicle key, safety line in, self protection, this signals are mainly from VMS. And it receives analog signals by analog input ports, such as hydrogen pressure in tank, hydrogen temperature in tank, hydrogen pressure in pipe to fuel cell stack, hydrogen leakage, this signals are mainly from Sensors.

HMU transmits hydrogen tank valve signals, safety line out by digital output ports, this signals are used to control executive components, mainly hydrogen valves. And it transmits hydrogen leakage alarm, leakage buzzer, sensor power by PWM analog output ports.

HMU exchanges signals with test platform by high speed CAN network, with 500k Baud rate. Some signals from VMS is transmitted directly by CAN network, such as hydrogen supply
and hydrogen exchange signals. All signals of test platform are based on HMU. The input of test platform is the output of HMU, and the output of test platform is the input of HMU.

3.3 Hardware Configuration

Hardware components of HMU test platform compose of computer, NI PXI device, electric control unit, BreakOut Box(short for BOB), programmable power device(controlled by GPIB), fault injection module, load box and accessories. The connecting relationship of component is showed in Figure 4. The computer is connected directly to HMU and NI PXI device. HMU is connected to BOB. And BOB is connected to NI PXI device. The 12V DC power is connected NI PXI.

1) Computer is used for down load program file into HMU using flash tool, installing software like NI Labview and Automation & Measurement, setting test environment, programming test model, executing test, monitoring test status, saving and analyzing test results.
2) NI PXI device involves cards like NI PXI-8110, NI PXI-6733, -6229, -8464 and -6624. PXI-6733 is used to output analog signals to HMU. PXI-6229 is used to output digital signals to HMU and receive digital signals from HMU. PXI-8464 is used to exchange CAN message between HMU and test platform. PXI-6624 is used to receive PWM signals which are output from HMU.
3) BOB is connected to NI PXI device and HMU. It can be used to measure the voltage of test device and HMU, and also can make fault injection.
4) Programmable power device is used to supply direct current to HMU. GPIB is used to transmit information to power device from test program.
5) The load box is connected to the HMU output, and is regarded as real load. In the load box, it contains real load or simulation load.
6) The fault injection module is used to test the fault detect and diagnosis of HMU. It can simulate such faults as signals exceed the normal range, pin connection to battery, power ground, other pins, and open circuit.

3.4 Test Program Design

Test platform program is used for signal receiving and transmission of test platform and programmable power. The program design part mainly contain modules as following, choosing data channel module, creating data channel module, writing data module, outputting data module. For example, choose digital output channels in PXI-6229, and create channels by DAQ channel create module, and write data to parameters (AUX and SelfRelay) by DAQ write module, as Figure 5. The program design of all output signals are similar, including digital input and output signals created by PXI-6229, and analog output signals created by PXI-6733.

CAN network signals are processed by PXI-8464. Its program design part contain CAN initializing, CAN read/write, data output. The program design of input signals contains choosing data channel, creating data channel, reading data, outputting data. The program diagram of PWM signal created by PXI-6624 and digital input signals created by PXI-6229 is showed in Figure 5.

Except the program design above-mentioned, it has designed a model of HMS by Simulink. This model simulates executive component action and hydrogen tank characteristic,
including hydrogen temperature and pressure characteristic during vehicle driving and refueling process.

Figure 5. Program design of test platform

3.5 Testing Panel

The test panel is showed as Figure 6. It contains VMS signals simulation, HMS status monitor, CAN signals monitor, fault simulation, error warning display.

Figure 6. Test panel

In the part of VMS signals simulation, it can realize the simulation of VMS sending message to HMU according to vehicle requirement, signals as vehicle key on, ignition switch, hydrogen supply switch in vehicle driving process, and refueling switch in vehicle refueling process, and key off switch in vehicle pause process.

In the part of HMS status monitor part, it can realize the function of monitoring components status of HMS, including refueling switch status, hydrogen pressure and
temperature status in tank, hydrogen pressure status in pipe to fuel cell stack, hydrogen leakage status in vehicle, hydrogen valve status, and HMS logic status.

In the part of CAN communication, it can realize the monitor of all CAN messages, including messages transmitted from VMS, and messages transmitted from HMU, and fault messages. In addition, it can monitor the transmission cycle and load.

In the part of fault simulation, it can realize simulation of sensor data to HMU, including hydrogen temperature in tank, hydrogen pressure in tank, hydrogen pressure in pipe, hydrogen leakage in vehicle. The data scale is corresponding to sensors’ limits, including normal working scale and fault scale. By fault simulation, it can simulate the extreme value of sensor scale and validate the HMU control strategy. In addition, we can realize fault injection to each signal, such as circuit open, circuit short to battery, circuit short to ground, circuit short to other signal, and so on.

In the part of error display, all errors will be listed in the table. As to an error, its details will be listed out either. The details include time, counter, code, grade. Time refers to the point error happens. Counter refers to how many times a same error happens. Code refers to an error identification. Grade refers to how urgent the error is. In this platform, there are 4 grades to describe the error code, 1-4. Number 1 represents urgent error. And, number 4 represents light error.

4. Experiment Results and Discussions

The hardware devices of test platform are connected as Figure 4, and the test program is designed as Figure 5. The test panel is designed as Figure 6. After the rapid prototype program of HMU is developed and built, the program is flashed into HMU by tools. According to HMU functions, execute test and record experiment data in NI Labview environment. The test steps are similar to normal car driving steps. First, set the Key to on. VMS checks all components status. Then, set the safety Line validly. Then, simulate some error during vehicle driving progress. In the test process, monitor the CAN communication status, data values, HMU alarm message, and record HMU status.

According to test result, when the Key is on, CAN communication is online. If all components are normal, VMS sets safety line validly. Then, HMU goes into PowerUp status. When ignition is on, HMU goes into Ready status. And if VMS sends hydrogen supply order, the tank valves open and HMU goes into Enabled status. During the vehicle driving process, hydrogen in tank is consumed.

The hydrogen characteristic is showed as Figure 7. Figure 7.(a) shows tank pressure characteristic during hydrogen supply process. Figure 7.(b) shows tank temperature characteristic during hydrogen supply process. During this process, hydrogen pressure gets lower and lower, so does hydrogen temperature.

![Tank Pressure Characteristic](image1)

![Tank Temperature Characteristic](image2)

(a) Tank Pressure Characteristic  (b) Tank Temperature Characteristic

Figure 7. Hydrogen Supply Process

All characteristics in Figure 7 and Figure 8 are obtained in the condition that the pressure tank has no thermal exchange with ambient environment. When the hydrogen is not enough for driving, VMS will set refueling order to HMU. And in the refueling process, the
hydrogen characteristic is showed as Figure 8. Figure 8.(a) shows tank pressure characteristic during hydrogen refueling process. Figure 8.(b) shows tank temperature characteristic during hydrogen refueling process. During this process, hydrogen pressure gets higher and higher, so does hydrogen temperature. The experiment result is coincided with HMU control strategy.

If fault injection (signals exceed the normal range or circuit fault, such as circuit open/circuit short to battery/circuit short to ground/circuit short to other signal/open circuit) is made to sensors, HMU will detect it and go to error mode, sending out error information to test panel in the same time. When HMU does not detect urgent error, system will be normal (PowerUp/Ready/Enable). If HMU detects urgent error, system will go into Error status, sending information to IPK, closing hydrogen valves, setting safety line invalid in the same time, to protect vehicle safety. If all urgent errors are excluded, HMU still stay in Error Status. Only power restarting will make the HMU return back to PowerUp status. If HMU detects errors which are not urgent, all HMU status and executive components’ status will be kept, only send out error code to test panel. If the power is off, HMU has no communication with test platform and its mode goes to sleep status.

5. Conclusion

By simulating HMS behavior in simulink model and executing test in platform, the platform can fully validate signals of Hydrogen Management Unit, with features of clear test panel, convenient result display, convenient fault injection, and convenient fault tracing, providing a good test bench for validation of Hydrogen Management Unit’s control algorithm of Plug-In fuel cell vehicle. Especially, this platform can realize extreme fault simulation which is impossible or hard in real car test, including simulating high hydrogen pressure, high hydrogen temperature, vehicle hydrogen leakage, hydrogen pressure abnormal in pipe to fuel cell stack, signal circuit open, signal circuit short to battery, signal circuit short to ground, signal circuit short to other signals. This test platform can shorten development cycle, reduce development cost, optimize testing environment for test engineers, making good effect and reference to vehicle electric system development and test.

References


