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Fuel cell control strategy development based on rapid control prototype

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Abstract: Hydrogen fuel cell system is an emerging power generation system with great potential for application in the automotive industry. In this paper, we design a high-power fuel cell system and take the fuel cell system shutdown purge process as a case, firstly, we complete the control strategy development in Simulink environment. Then the I/O resource configuration and model integration were performed based on the rapid control prototype system of dSPACE. Finally, the code was automatically generated and the simulation verification of the control strategy on this rapid control prototype system was implemented. The results show that the fuel cell system can operate stably according to the demanded power and can execute the shutdown purge procedure according to the established control strategy. This development method, which shortens the development cycle, effectively improves the reliability and flexibility of the control strategy development, and has a high value of use.

Keywords: hydrogen fuel cell system; control strategy; rapid control prototype; purge

1. Introduction

As a major automobile country, China has a huge automobile market. While bringing economic benefits, it is also accompanied by huge energy consumption and environmental pollution. With the introduction of the "carbon neutrality" goal, hydrogen fuel cell vehicles are considered to play a vital role in achieving this goal [1]. Major automobile companies have begun to engage in the research and development of hydrogen fuel cell vehicles, and have initially made breakthroughs. Fuel cell control unit (FCCU) is the core of the entire fuel cell system, and its development quality directly determines whether the system can operate stably and efficiently [1]. Therefore, high-quality fuel cell control unit play an important role in the development of fuel cell systems.

The ECUs of traditional automobile companies need to repeatedly perform upper-level algorithm simulation and lower-level code writing, which has a long development cycle, low flexibility and high cost [2]. This development model is in contradiction with the industry demand in the fuel cell field. The fuel cell market is still in a stage of rapid development and constant change. The market's requirements for products are basically reflected in rapid verification and delivery. Different use environments and application scenarios not only affect the selection and matching of fuel cell system components, but also put forward different requirements for control strategies. At the same time, the technology of fuel cell component suppliers is breaking through constantly. The I/O types of components with the same function are showing a diversified development trend. The I/O resources of ECUs used in traditional automobile industry are also difficult to adapt to the technological development of components of fuel cell systems. All these have brought great challenges to the development of fuel cell control unit.

Rapid control prototype (RCP) refers to the process of quickly establishing a model of the controlled plant and strategy in early stage of product development, and conducting multiple experiments on the control algorithm to verify the feasibility of the control system [3,4]. This technology is widely used in the aerospace and automotive fields, and is also very suitable for use in the development of fuel cell control units. This paper develops the fuel cell control unit based on the rapid control prototype system. Its structure is as follows: Section 2 introduces the rapid control prototype system used. Section 3 focuses on the strategic design of anode purging during the shutdown process of the fuel cell system. Section 4 performs configuration and integration in rapid control prototype system. Section 5 analyzes the test results and finally section 6 concludes the paper.

2. Rapid control prototype system

This article uses the RCP system produced by dSPACE. It is divided into two parts: hardware and software, which is used to complete configuration of hardware resources, integration of control strategy models, automatic generation of codes, and observation of data. A typical development process of RCP development is shown in the Figure 1 below.

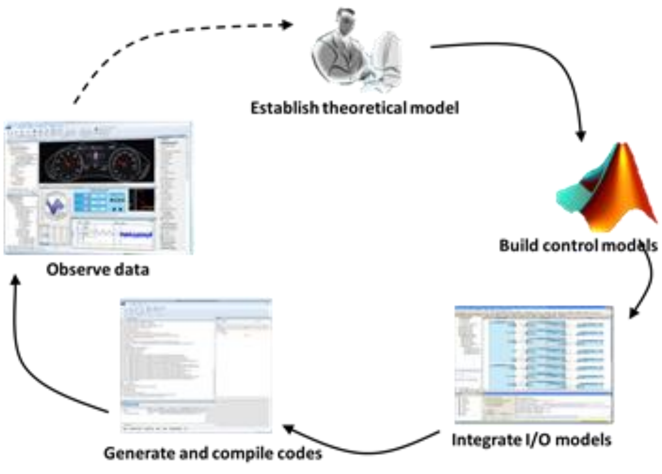

Figure 1. A typical development process of RCP.

2.1. Hardware system of RCP

The hardware system of RCP includes four parts: processor board, component boards, signal conditioning unit and power unit. The composition of the hardware system is as follows (Figure 2).

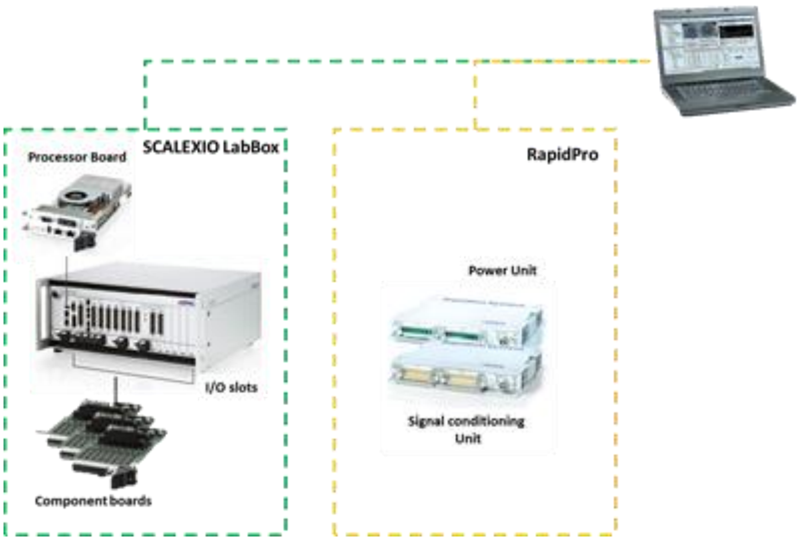

Figure 2. The composition of the hardware system of RCP.

The DS6001 processor board equipped with an Intel i7 quad-core processor features high computation power and good real-time performance with minimum jitter and latency. The component boards contain DS6101, DS6202 and DS6221. The DS6101 I/O board offers 69 I/O channels for voltage-related functions, including analog, digital, resistance, and special input/output groups, for example for lambda probe simulation, which is tailored to automotive project requirements, such as voltages of 12 V, 24 V and 48 V. The DS6202 digital I/O board provides 32 high-speed digital channels that support 3.3V and 5V TTL voltage levels. Each channel is configurable as an input or output. The DS6221 is an A/D board. Each of the DS6221's 16 differential input channels have an independent A/D converter with a resolution of 16 bits and a minimum conversion time of 250 ns. The above-mentioned boards together constitute the SCALEXIO system [5].

The signal conditioning unit supports RCP system wherever demanding signal conditioning tasks such as signal protection, amplification, attenuation, filtering, and electrical isolation have to be performed. In turn, actuators like drives, valves, injectors, lamps, and relays require high current and/or high voltage output drivers. The power unit provides RCP system with the necessary power stages. Automotive protection and extensive diagnostic capabilities are especially important for power stages [6]. Both of them are organized together into the RapidPro system.

2.2. Software system of RCP

MATLAB/Simulnik is a common-used control system modeling tool in automotive industry. Engineers can build control models in the graphical interface and perform offline simulations to verify control strategies and algorithms.

Real-Time Interface (RTI) is a library of real-time interfaces provided by dSPACE. To connect a model to SCALEXIO, engineers simply drag and drop I/O modules from the RTI library and connect them to the Simulink module. All settings can be done by clicking on the corresponding module. It collaborates with MATLAB's Simulink Coder toolbox, which is used to generate the code of models, while the former provides the corresponding modules (Figure 3). RTI can also check for consistency in the configuration, so potential errors in the model can be detected before or during the compilation process [7].

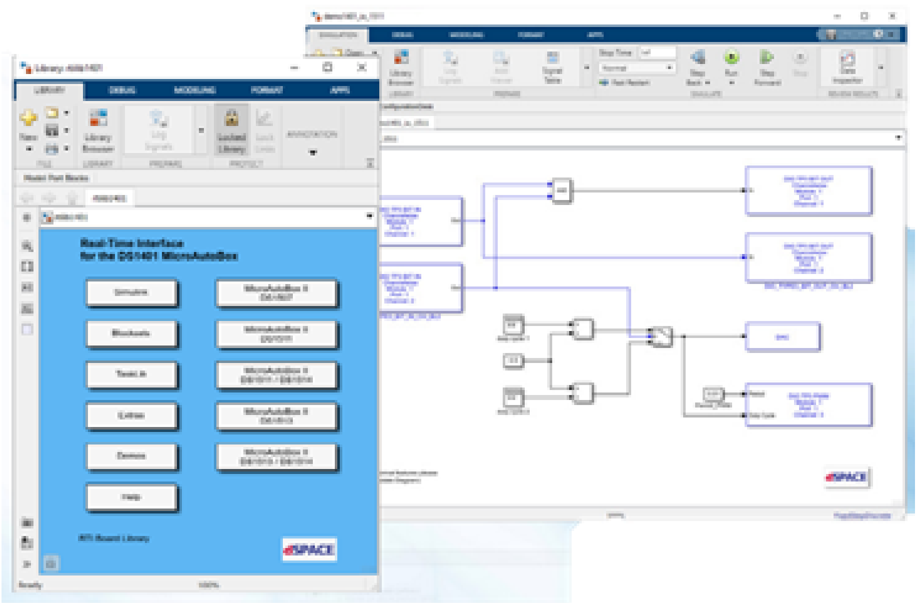

Figure 3. Collaboration of Real-Time Interface with Simulink.

ConfigurationDesk is a graphical configuration and implementation tool developed by dSPACE(Figure 4). It enables the connection of Simulink models to I/O modules and the configuration of SCALEXIO hardware to generate real-time code. Engineers have the option to define and document external devices such as ECUs, electrical devices, and loads, including their signal properties [8].

ControlDesk is a universal modular experimentation and instrumentation software developed by dSPACE for the development of ECUs. It provides access to both the simulation platform and the connected bus system, as well as data observation and calibration on the ECUs and diagnostics (Figure 5). Its flexible modular structure is highly scalable and can be used for fuel cell control system development in different application scenarios [9].

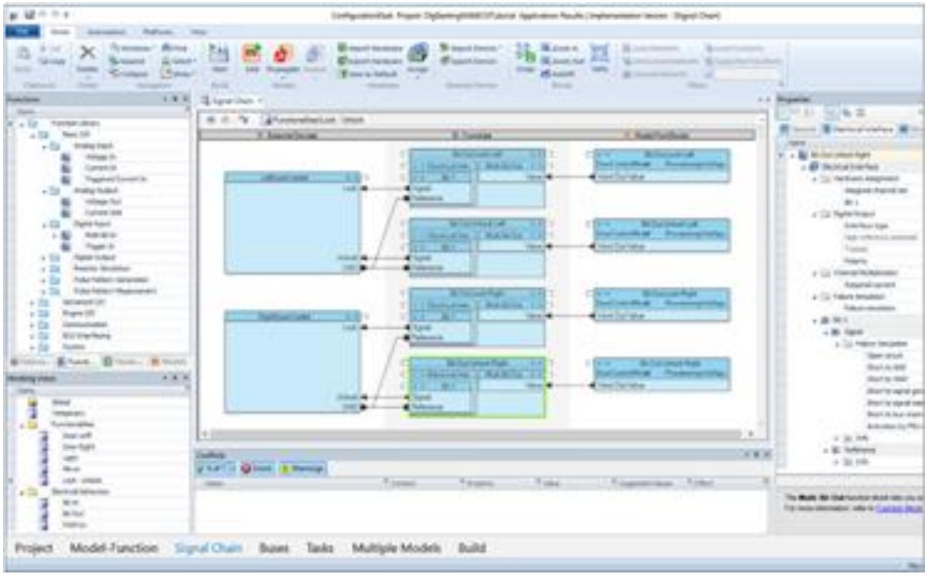

Figure 4. User interface of ConfigurationDesk.

Figure 5. User interface of ControlDesk.

3. Fuel cell system structure and control strategy design

3.1. Fuel cell system structure

The fuel cell system researched in this paper is a high-power fuel cell system applied to a vehicle. The structure is shown in the Figure 6, which mainly consists of fuel cell stack, hydrogen subsystem, air subsystem, thermal management subsystem [10].

The working principle is that the air enters the stack through the air compressor, intercooler and humidifier, while the hydrogen enters the stack through the proportional valve. Electrochemical reaction between them occurs in the stack to produce electric energy, which is delivered to vehicle. The proportional valve is a solenoid valve with adjustable opening, which regulates the pressure at the anode inlet of the stack. The hydrogen circulation pump is used to circulate the unreacted hydrogen from outlet of anode side into the stack, thus improving the hydrogen utilization. When the shutdown purge program is executed, the purge valve opens to discharge the hydrogen and use the pressure difference to take away the excess water. The function of the thermal management subsystem is to keep the stack operating at the proper temperature, where the electronic thermostat enables switching between large and small cycles of cooling water to help the stack dissipate heat quickly.

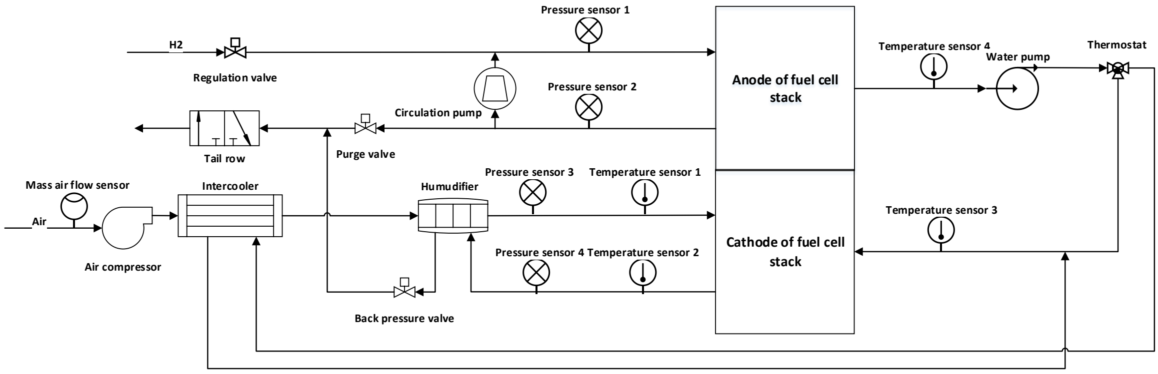

Figure 6. Fuel cell system architecture schematic.

3.2. Fuel cell system control strategy design

The on/off control of the fuel cell system is one of its important functions, the purpose of which is to achieve an orderly turn-on and turn-off of the system to prepare for its normal operation. In the shutdown process, a key task is to purge the anode of the fuel cell stack to drain excess water and prevent icing [10,11].

Fuel cell shutdown purging reduces internal water residue and ensures more reaction paths for the gas during cold start. Currently, purging operations are performed immediately after fuel cell shutdown to avoid damage caused by internal water phase change volume expansion when the cell is in a sub-zero environment. Pulsed blast purging is the most basic and widely used purging method, which is used in this paper and the principle of it is to continue to blow air or hydrogen into the stack through the cathode/anode gas supply system after the fuel cell is shut down. Due to the small difference in internal water concentration and the almost capillary structure of the gas diffusion layer, this method is less efficient and requires a long purging time.

Depressurization purging takes advantage of the fact that the gas dissolves more water vapor as the pressure drops by suddenly reducing the inlet pressure. This method requires high mechanical strength of the internal components of the reactor so that the pressure difference does not damage the internal components.

Dielectric purge refers to the method of removing water from the inside of a fuel cell by passing a dry inert gas, such as helium or nitrogen, into it while it is shut down. This method requires carrying additional inert gas and is not suitable for use in on-board systems. The shutdown flow chart designed in this paper is shown in Figure 7.

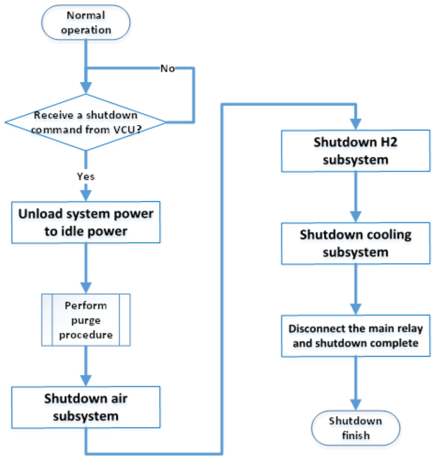

Figure 7. Shutdown flow chart.

When the RCP receives the shutdown command from VCU, it unloads the system power to idle power of 4 kW and then executes the shutdown purge procedure. After the purge, the air subsystem is shut down first, meaning the operation of the air compressor and other components is stopped, and then the hydrogen subsystem and the thermal management subsystem are shut down sequentially until the main relay of the whole system is disconnected [12]. If the hydrogen subsystem is shut down first, excess air penetrates through the proton exchange membrane (PEM) and remains in the anode, which may cause reverse polarity damaging to the stack when the system starting at next time. During the process of shutting down the hydrogen and air subsystem, the electrochemical reaction actually keeps going, so the thermal management subsystem must work continuously to maintain the proper operating temperature. Thus, it is shutdown at last. Part of the control program is shown in the Figure 8.

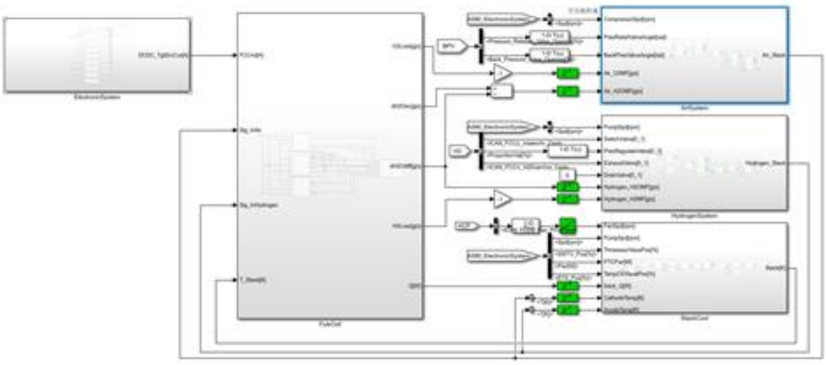

Figure 8. Part of control program.

In this paper, a purge procedure for shutdown is designed. As shown in the Figure 9, the purge valve is opened for pulsed venting with an opening frequency of 1 time/s. When the pressure of hydrogen into the stack is lower than the threshold value of 120 bar, the purge valve is closed for 4 seconds. When the purge time reaches 25 seconds and the pressure of hydrogen into the stack is greater than 130 bar, the shutdown purge is exited and the next state is entered.

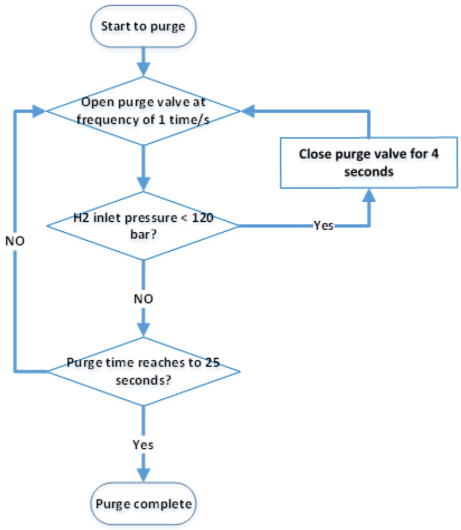

Figure 9. Purge procedure.

4. RCP configuration and integration

4.1. I/O resources configuration

The task of I/O resource configuration is to match the signals of all sensors and actuators with the interfaces of SCALEXIO. Based on the number of pins required by the control strategy model and the type, the corresponding I/O model is selected using ConfigurationDesk, its acquisition channels and threshold voltages are set, and the model interface is generated in the MATLAB environment to provide input to the control strategy model.

4.2. Sontrol strategy model integration

The interface modules generated by the I/O model are integrated into the signal inputs/outputs of the control strategy model according to the SCALEXIO I/O resource type and compiled in the MATLAB environment using the Simulink Coder toolbox. Figure 10 shows part of this interface.

4.3. Software compilation and download

The integrated model, which includes the fuel cell control strategy model, fuel cell system model and the I/O model, is compiled using ConfigurationDesk. After successful compilation, the executable file is automatically generated and downloaded to the SCALEXIO processor.

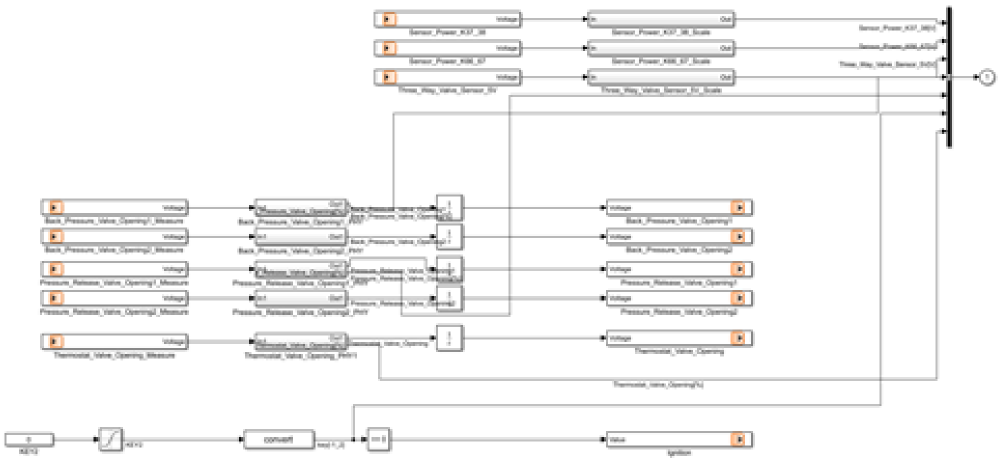

Figure 10. Integration of control strategy model.

5. Simulation and analysis of results

In this paper, a complete fuel cell stack activation condition is selected, as shown in the Figure 11. The power is loaded once every 8 kW, and each time it runs steadily for 3 minutes. The system is shut down when the system power reaches to 72 kW.

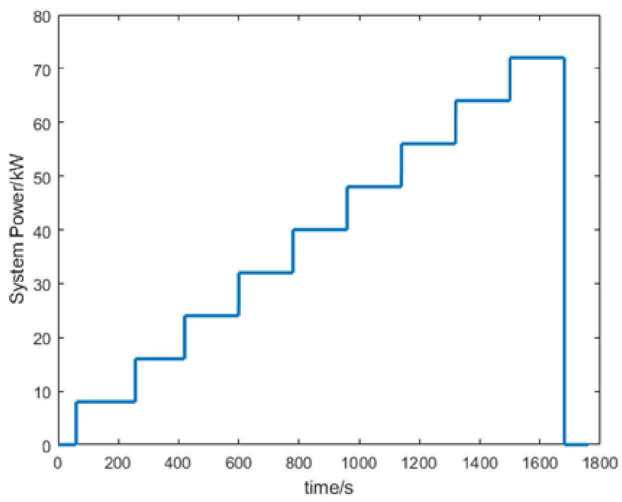

Figure 11. Activation condition used.

ControlDesk can not only observe and record data, but also simulate VCU to send switching commands and demanded power to the RCP system. After receiving the command, the RCP operates according to the aforementioned control strategy and the recorded data is shown in Figure 12. The graph shows that the system is able to follow power request accurately according to the set working conditions.

This paper focuses on the anode purging during the shutdown process which is from 1720 s to 1760 s in Figure 12 after the stack activation is completed. ControlDesk sends the shutdown command, and the system enters the shutdown purge state.

The part 1 of Figure 13 shows system state changes from 1720 s to 1760 s. Table. I tells the meaning of system states of corresponding values of this part. The system is in normal operation before 1720 s. The system state shifts to shutdown of air, hydrogen and heat management subsystem sequentially after it purges for 25 seconds and then enters to completion of the whole fuel cell system.

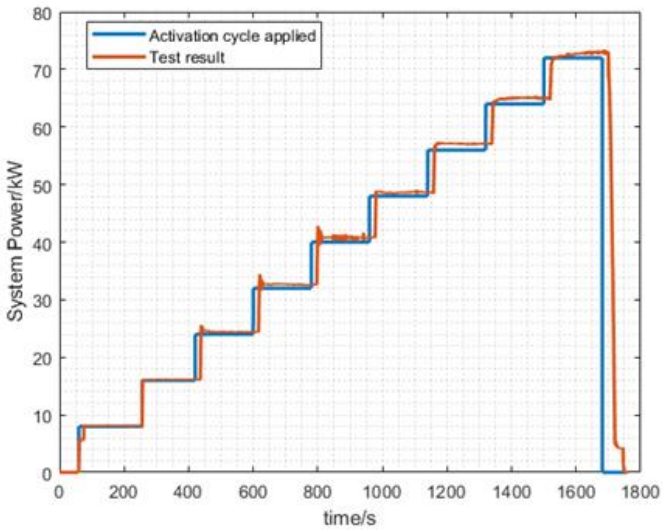

Figure 12. Comparison of observed data and working conditions.

Table 1. Meaning of state value of Figure 12.

Value	Meaning
15	Shutdown complete
17	Normal operation
19	Purge state
20	Shutdown air subsystem
21	Shutdown hydrogen subsystem
22	Shutdown heat management subsystem

Part 2 of Figure 13 shows that at the beginning of the purge, the RCP purges at a frequency of 1 time/s as designed. After 4 impulses of purge, the hydrogen inlet pressure drops continuously until it is below the threshold value of 120 bar, which triggers another procedure designed in Figure 9 that the purge valve is closed for 4 seconds and is executed again from 1729 s.

Part 3 of Figure 13 shows that during the subsequent purges, the hydrogen inlet pressure fluctuated, but did not fall below the threshold again between 1729 s and 1745 s. After 25 seconds of purge process, it was completed and the system shut down subsystems one after another.

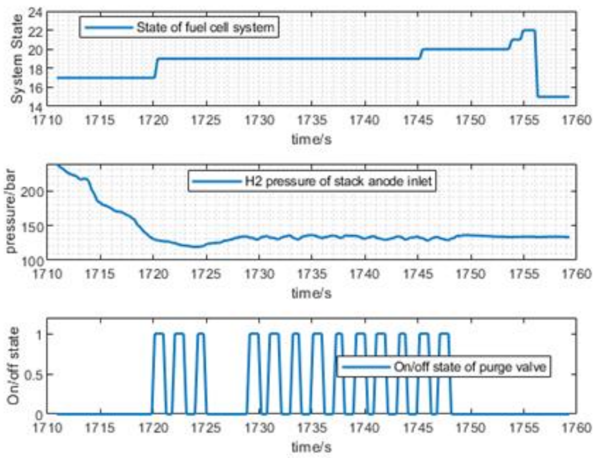

Figure 13. Parameter changes during shutdown process.

6. Conclusions

Hydrogen fuel cell system is an emerging power generation system with great potential for application in the automotive industry. In this paper, a high-power fuel cell system is designed, and the entire process of designing this control strategy based on a rapid control prototype system is comprehensively introduced with the shutdown purge process of it as a case. Finally, the system is verified through experiments of the rapid control prototype to be able to work stably according to the demanded power and to be able to execute the shutdown purge procedure according to the established control strategy.

This development method, which shortens the development cycle, effectively improves the reliability and flexibility of the control strategy development, and has a high value of use. In this research, this most time consuming work is configuration and integration of this system, which cost ten days. Five days of calibration work and debugging were conducted to achieve the target based on the designed strategy. With the improvement of the rapid control prototype system and the accumulation of engineers' experience, the time cost of calibration for every individual strategy would be further reduced. It is estimated that the development period of strategy design and validation of this fuel cell system would be reduced by one third although there was no clear time record to prove it. There are many strategies would be considered while developing a fuel cell system, one of which is the shutdown purge process as a case in this paper. One can see that once the most time consuming work is finished, the rest of job of engineers is to take their time to design and validate their interested strategy in this rapid control prototype system flexibly.

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Conflicts of interests

The authors declare no conflicts of interests.

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