ISSN: 2688-8645

Research and Development of Control Strategies for Fuel Cell Systems

Songmao Wei[1], Zihan Xin[1, *], Tian Yang[1], Peng Lu[2] and Ji Liu[2]

[1]CATARC(Tianjin) Automotive Engineering Research Institute Co., Ltd., Tianjin 300300, China

[2]China FAW Group Co., Ltd. Engineering and Technology Department, Changchun 130000, China

*Corresponding Author

Abstract

For the self-developed kilowatt level proton exchange membrane fuel cell system, the control algorithm of the fuel cell system is built in MATLAB/Simulink, and the control models of each subsystem, the entire system control process, and steady-state calibration process are discussed. Data analysis through experiments shows that the system has good performance.

Keywords

Proton Exchange Membrane; Fuel Cell System; System Control; Steady-state Calibration.

1. Introduction

In March 2022, the National Development and Reform Commission and the National Energy Administration jointly issued the "Medium and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035)", which clearly pointed out that hydrogen energy is an important part of the future national energy system and an important carrier to achieve green low-carbon transformation with energy terminals. It`s a strategic emerging industry and the key development direction of future industries.

There are three commercial operation models of fuel cell vehicles: the national demonstration city cluster subsidy model, the wind power photovoltaic resource subsidy model, and the low-cost hydrogen pure commercial mode. According to statistics, the number of fuel cell vehicles in China is about 13,000, and 5009 vehicles was sold in 2023, an increase of 72 % year-on-year. The continuous improvement of fuel cell vehicle ownership has led to the continuous development of the upstream fuel cell system industry. In the past 5 years, the stack has been fully domestic except for a few materials, and the power has been increased from 23kW to 300kW, and the system power has also reached 250kW.

In order to ensure the healthy and rapid development of the hydrogen energy industry, research on control strategies for high-power and highly reliable fuel cell systems is crucial.

The control strategy of fuel cell system includes multiple components, including cathode air transmission loop control strategy, anode hydrogen circulation loop control strategy, coolant transmission loop control strategy, power control strategy, system quantity definition, alarm and fail judgment rules, voltage inspection processing strategy, working mode strategy, etc.

The core of the fuel cell system control strategy is to coordinate the components of the fuel cell system under different conditions, reduce losses at all levels, and achieve optimal performance control in response to the complex operating conditions of fuel cells. Whether it is an air compressor, hydrogen circulation pump, water pump, fan or any other component, there is a working efficiency range. To improve the efficiency of the entire system, it is necessary to keep the vast majority of components working in the efficiency range in order to improve the overall efficiency of the fuel cell system. At present, the industry mainly adopts multiple working condition calibration data combined with PID adjustment control method, and the later development direction of neural fuzzy control system will be.

This article introduces the research and development of control strategies for fuel cell systems based on the fuzzy logic proportional integral differential control (FLC-PID) method.

2. Main Control Model of Fuel Cell System

Figure 1 shows a typical fuel cell system structure. The green part is the fuel cell system, which continuously provides electricity to the load during operation, and the remaining subsystems serve it. The red part represents the hydrogen supply system, which is mainly responsible for the stable supply of fuel to the fuel cell stack. It consists of main components such as hydrogen gas source, pressure reducing valve, solenoid valve, and pipeline. The dark blue part is the air supply system, responsible for the continuous supply of oxidants required for reactions inside the fuel cell. To meet the output performance requirements, an air compressor is needed to pressurize the air. Therefore, it mainly consists of an air compressor, corresponding valve groups, and pipelines. The light blue dashed line represents the omitted temperature/humidity management system. Due to the significant impact of temperature and humidity conditions on the performance of fuel cells, deviation from the target value may even damage internal components of the fuel cell stack. Therefore, these two systems are mainly responsible for humidifying and cooling the supply gas, ensuring that the temperature and humidity of the gas entering the stack meet the requirements, and enabling the system to achieve maximum performance [1,2,3].

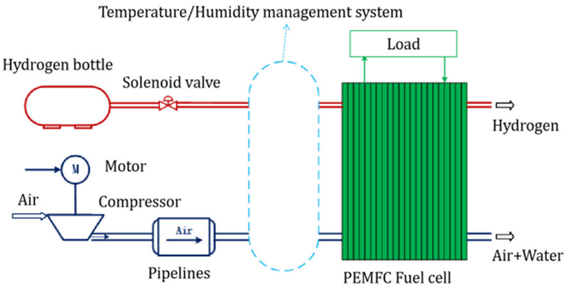


Figure 1. Typical fuel cell system structure

Figure 2 shows the main control model architecture of a fuel cell system, including a state machine processing module subsystem, an air path control module subsystem, a hydrogen path control module subsystem, a cooling path control module subsystem, and a power path control module subsystem. This model mainly divides subsystems according to their functions and handles signal interactions between each subsystem.

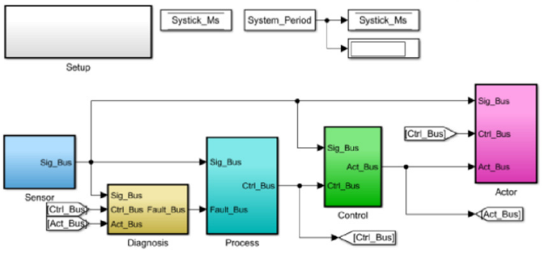


Figure 2. Main Control Model of Fuel Cell System

3. Fuel Cell System Control Strategy

3.1. Air Path Control

3.1.1. Air Flow Control

The air flow is controlled by the air compressor, with the input being the current air flow rate, target air flow rate, and direct control by the air compressor, and the output being the target speed of the air compressor.

The compressor speed is calibrated during open-loop control; PID control is used in closed-loop control, and the parameters are calibrated according to the actual situation of the stack.

The air flow control is shown in Figure 3.

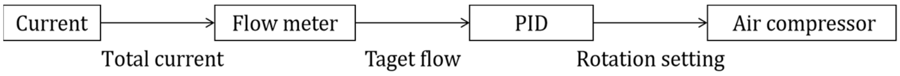


Figure 3. Air flow control

The PID control algorithm calculates the control quantity of the controlled object based on the error between the target value and the measured value. The core formula is:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int e(t)dt + T_d \frac{de(t)}{dt} \right] \tag{1}$$

In the formula: $u(t)$ to control the output value of the quantity, $e(t)$ the error between the target value and the measured value, K_p、T_i、T_d are the proportional coefficient, integral time constant, and differential time constant, respectively.

3.1.2. Air Pressure Control

The air pressure is controlled by the back pressure valve, and the input parameter is the basic opening of the back pressure valve. The basic opening of the back pressure valve is obtained through actual calibration of the fuel cell stack.

During closed-loop control, air pressure PID is used for correction based on the basic opening of the backpressure valve, and the parameters are calibrated according to the actual situation of the fuel cell stack.

The air pressure control is shown in Figure 4.

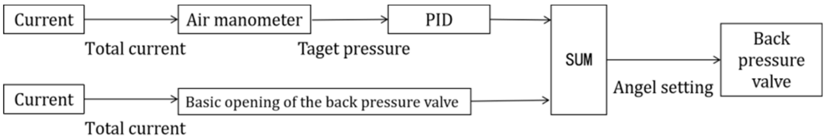


Figure 4. Air pressure control

3.1.3. Bypass Valve Control

To prevent the compressor from surging, it is necessary to adjust the opening of the bypass valve during open-loop control.

The control opening of the bypass valve can be obtained by checking the current meter, and the parameters can be calibrated according to the actual situation of the fuel cell stack.

In addition to the above control strategies, it is also necessary to develop and verify oxygen starvation response algorithms, blowing methods, full electric load reduction strategies, pressure accuracy and response strategies, flow accuracy and response strategies, pressure and flow decoupling algorithms, frequent load variation strategies, bypass logic strategies, etc.

3.2. Hydrogen Path Control

3.2.1. Calculation of Hydrogen Target Pressure

The target pressure of hydrogen is obtained by adding the current pressure and bias of the air path, and the model bias is set to a constant value of 5Kpa.

The calculation of hydrogen target pressure is shown in Figure 5.

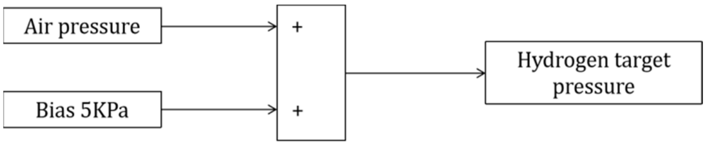


Figure 5. Calculation of hydrogen target pressure

3.2.2. Hydrogen Pressure Control

The hydrogen path control is the hydrogen target pressure control, with input parameters including hydrogen target pressure, current hydrogen pressure, and hydrogen discharge control, and output parameters including proportional valve control percentage and hydrogen discharge valve switch.

The hydrogen pressure control adopts PID control, and the parameters are configured according to the actual situation of the fuel cell stack. The hydrogen discharge adopts a timed hydrogen discharge and drainage strategy based on the current.

In addition to the above control strategies, it is also necessary to develop and verify full electric dense loading and unloading strategies, pressure accuracy and response strategies, pressure difference accuracy and response strategies, anti-interference of hydrogen discharge and load pulling, impact of circulation on pressure and humidity, and validation of the blowing process.

3.3. Cooling Circuit Control

3.3.1. Cooling Control

Cooling path control includes inlet and outlet temperature difference control, and inlet temperature control. The control rate adopts PID control, and the parameters are calibrated according to the actual situation of the fuel cell stack.

The water pump control is shown in Figure 6.

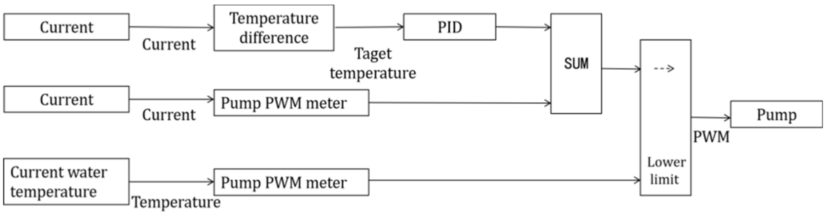


Figure 6. Water pump control

The fan control is shown in Figure 7.

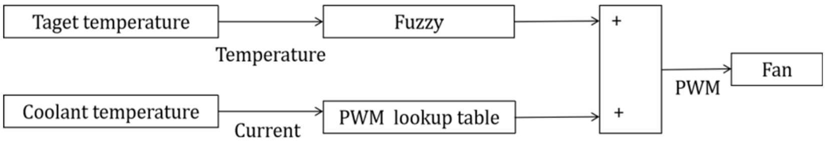


Figure 7. Fan control

3.3.2. Heating Control

Heating control is mainly based on the temperature of the coolant at the outlet of the fuel cell stack, controlling the heating of the water temperature to the specified temperature. The heating control is shown in Figure 8.

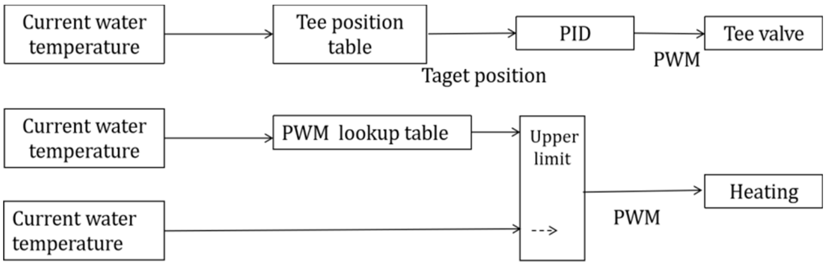


Figure 8. Heating control

In addition to the above control strategies, it is also necessary to develop and verify temperature response for loading and unloading, control of environmental thermal radiation interference, rotational inertia interference of water pumps and fans, algorithm for predicting internal temperature, and pipeline pressure fluctuations.

3.4. Power Path Control

3.4.1. Power Control

Power control adopts the minimum power limit method, including average voltage power limit, minimum voltage power limit, temperature power limit, fault level power limit, etc.

Control the increase and decrease rates of power based on the calculated target power and actual power.

The power control is shown in Figure 9.

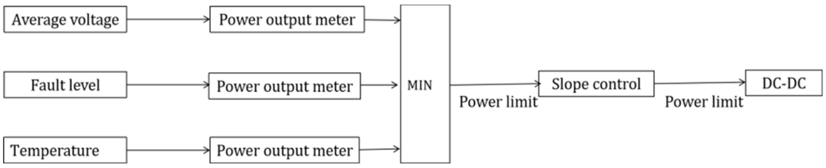


Figure 9. Power control

In addition to the above control strategies, it is also necessary to develop and verify maximum loading logic, lifespan mode, performance mode, optimal hydrogen consumption control, humidity trend prediction, etc.

4. Fuel Cell System Input and Output Modules

4.1. Input Signal Processing

4.1.1. Sensor Input Signal

Sensor information such as hydrogen pressure, temperature, flow rate, position, and switch status is collected by the analog/digital/frequency signal receiving module to the FCU controller. Based on the characteristics of the sensor, the sampled values are converted into corresponding physical values. The conversion methods include table lookup and linear conversion.

4.1.2. CAN Data Reception

The signal transmission of air compressors, water pumps, PTC, CVM, DCDC, etc. all use CAN bus communication. The collection program obtains relevant data through DBC parsing or direct parsing calculation.

4.1.3. Mean Filtering

In this program, the sensor input filtering adopts mean filtering. The filtering method is to record the current sampling value and the previous m sampling values. After removing the maximum and minimum values, the remaining (m-2) data are averaged to obtain the output result.

The calculation formula is:

$$Vt = [\sum_{n=0}^{m} Vn - Max(Vn) - Min(Vn)]/(m-2) \tag{2}$$

In the formula, V_t for filtering values, V_n for sampling values.

4.1.4. Temperature Collection

The temperature sensor uses a voltage signal of 0-5V, and the collection process is as follows: first, the voltage value of the analog interface is collected, and then the analog signal is collected and divided. Then, the resistance value is calculated, and the temperature is obtained by looking up the table.

The temperature collection process is shown in Figure 10.

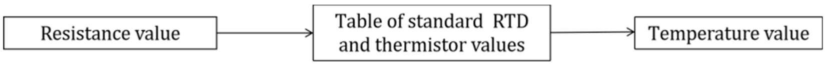


Figure 10. Temperature Collection

4.1.5. Pressure Collection

The pressure sensor uses a voltage signal of 0-5V, and the acquisition process is as follows: first, the voltage value of the analog interface is collected, and the pressure value is converted according to the table lookup.

The pressure collection process is shown in Figure 11.

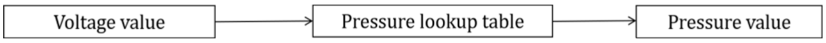


Figure 11. Pressure Collection

4.1.6. Traffic Collection

The flow sensor uses a voltage signal of 0-5V, and the acquisition process is as follows: first, the voltage value of the analog interface is collected, and the flow value is converted according to the table lookup.

The flow collection process is shown in Figure 12.

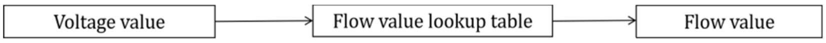


Figure 12. Traffic Collection

4.1.7. Location Acquisition

The position sensor of the backpressure valve uses a voltage signal of 0-5V, and the acquisition process is as follows: first, the voltage value of the analog interface is collected, and the opening value is converted according to the table lookup.

The position acquisition process is shown in Figure 13.

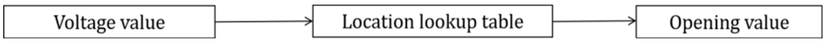


Figure 13. Location acquisition

4.1.8. Angle Acquisition

The electronic thermostat angle sensor uses a 10Hz-15kHz frequency signal, and the acquisition process is to collect the frequency signal feedback from the electronic thermostat and convert the angle value based on a table lookup.

The angle acquisition process is shown in Figure 14.

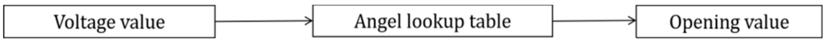


Figure 14. Angle Collection

4.2. Control Output Module

The control output includes the output control of each actuator and the CAN transmission of control signal messages. The output control of the air/hydrogen/cooling/power circuits is carried out in each subsystem, and the control parameters are mapped to the hardware to control the relevant actuators to perform corresponding operations.

The control output module includes air circuit actuators, hydrogen circuit actuators, cooling circuit actuators, and power circuit actuators, as shown in Table 1.

Table 1. Control output module actuator

Number	Subsystems	Actuator
1	Air path	Back pressure valve, bypass valve, air compressor
2	Hydrogen pathway	Heating device for shut-off valve, proportional valve, hydrogen discharge valve, and hydrogen discharge valve
3	Cooling circuit	Water pump, PTC, cooling fan, electronic thermostat
	Power path	DCDC, CVM

*Note: CVM - Fuel Cell Single Chip Voltage Inspection Instrument

5. Fuel Cell System Control Process

The control process of the fuel cell system includes 7 states: Power On, Standby, Start Up, Run, Shut Down, EPO, and Fault.

Figure 15 shows a self-developed fuel cell system.

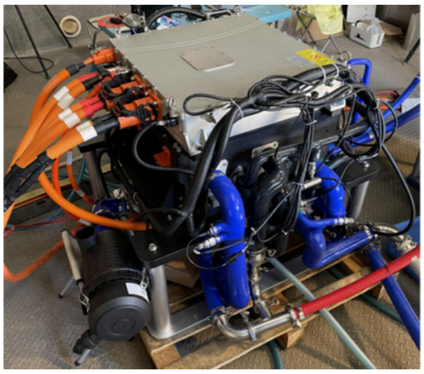


Figure 15. Self-developed fuel cell system

The system control process is shown in Figure 16.

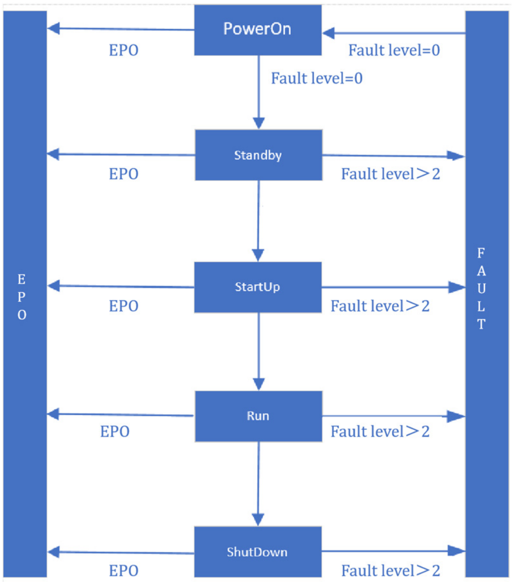


Figure 16. System Control Process

5.1. Power-on Process

(1) Low voltage power on of the system,

(2) Enable MPRD and enable diagnosis,

(3) If there is a fault, enter the fault state,

(4) Open the DCDC output contactor to supply power to the BOP and wait for the voltage to rise>70V,

(5) If the conditions are met, enter standby mode; if the conditions are not met, enter fault mode.

The power on process is shown in Figure 17.

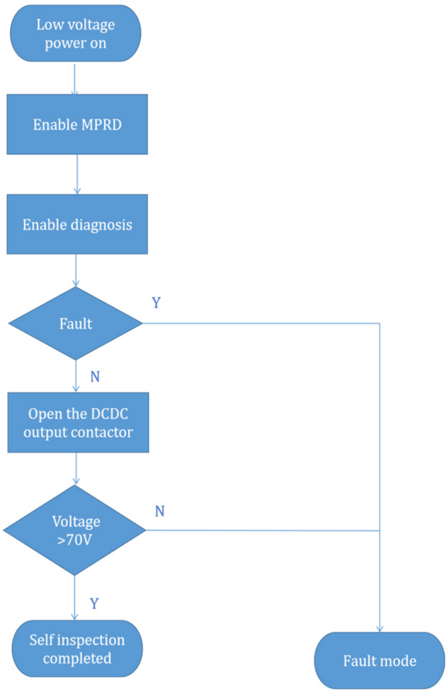


Figure 17. Power on process

5.2. Self Inspection Completed

During the power on process, enable the fault diagnosis function. If there is a fault in the high and low voltage equipment, enter the fault mode.

If there are no faults in the high and low voltage equipment during self check, the self check is completed and enters standby mode.

5.3. Standby

Wait for the system startup command, if there is one, enter the startup state.

5.4. Start-up Status

In the start-up state, perform the start-up operation :

(1) Open the power lock,

(2) Turn on temperature control, set the target temperature, open the DCDC output contactor, and open the shut-off valve,

(3) Start the purge and start the hydrogen pressure,

(4) Turn off blowing and start hydrogen discharge,

(5) Open the throttle valve and turn on the air compressor,

(6) The power limit is at the starting power, turn on the stack output flag, and turn on the DCDC output contactor,

(7) Enable DCDC, enable temperature control, set target temperature based on current, set air target flow rate based on current, set throttle opening based on current, and set air and hydrogen pressure,

(8) Enter the running state.

5.5. Operating Status

During operation, calculate and execute air flow rate, throttle opening, target temperature, and power limit release based on current.

5.6. Normal Shutdown

(1) Limit the output power to idle power,

(2) Turn on the waterway to cool down, set the target temperature and air flow rate based on the current, and set the throttle valve opening,

(3) Open the throttle valve, blow air, and shut down to cool down;

(4) Hydrogen purging,

(5) Turn off air blowing and hydrogen blowing, and start discharging,

(6) Supplementing hydrogen gas at 20kpa,

(7) Turn off the output of the fuel cell, turn off the DCDC input, turn off the power limit, turn off the discharge, and continue to perform shutdown and cooling,

(8) Turn off temperature control, turn off diagnostic enable, and turn off DCDC output contactor,

(9) Shutdown completed.

5.7. Emergency Shutdown

(1) Determine whether to enter the power reduction stage based on the current air flow rate,

(2) Power limitation, target flow rate is 0, throttle valve is fully open, shut-off valve and proportional valve are closed, hydrogen gas is purged, and shutdown for cooling,

(3) Turn off the air compressor and wait for the air flow rate and hydrogen pressure to decrease,

(4) Close the throttle valve, turn on the power, and close the DCDC output contactor,

(5) Close the DCDC input contactor, set the power limit to 0, turn off hydrogen gas blowing, turn off DCDC enable, and wait for the water temperature to decrease,

(6) Turn off temperature control and diagnosis,

(7) Emergency shutdown completed.

5.8. Fault Shutdown

(1) Turn on the power, fully open the back pressure valve, fully open the bypass valve, close the hydrogen circuit, open the normal hydrogen discharge, shut down and cool down, and wait for the air flow rate to decrease,

(2) Close the back pressure valve and wait for the stack voltage to decrease,

(3) Turn off the DCDC output contactor,

(4) Close the air and hydrogen circuits, turn off hydrogen discharge, turn off DCDC enable, turn off diagnostic enable, and wait for the water temperature to decrease,

(5) Turn off temperature control,

(6) Shutdown completed.

The shutdown and power-off process is shown in Figure 18.

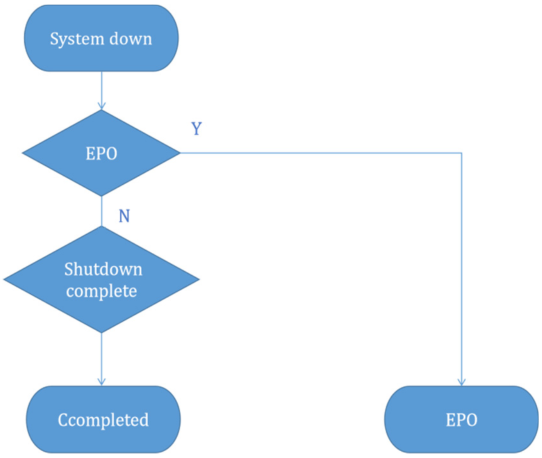


Figure 18. Shutdown and power-off process

6. Calibration of Steady-State Operating Conditions

6.1. Calibration at a Rate of 1A/s

Gradually increase the power to a certain power at a rate of 1A/s, and calibrate the control parameters of each electrical density at idle speed to that power.

6.1.1. Minimum Current Operation

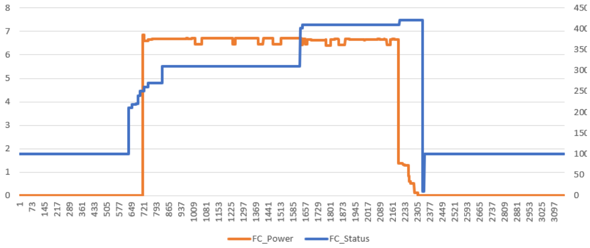


Figure 19. Steady-state operation calibration curve

Operating at a minimum current of 26A, the fuel cell system outputs 6.8kW, and the calibration curve under steady-state operating conditions is shown in Figure 19.

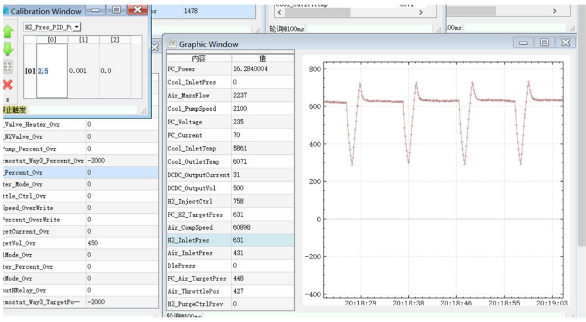
According to the loading rate of 1A/s, the power is gradually increased to a certain power, and the control parameters of each electric density at idle speed to this power are calibrated.

6.1.2. Calibration of Hydrogen Proportional Valve PID

The front-end pressure is 150kPa, and the hydrogen pressure decreases by about 30kPa during hydrogen discharge.

Adjust the front-end hydrogen pressure to 250kPa, and during hydrogen discharge, the hydrogen pressure will decrease by about 2kPa. Determine the PID parameter value.

The calibration of the hydrogen proportional valve is shown in Figure 20.



H2_Pres_PID_P

	[0]	[1]	[2]
[0]	2.5	0.001	0.0

_Valve_Heater_Ovr	0
_N2Valve_Ovr	0
ump_Percent_Ovr	0
rmostat_Way3_Percent_Ovr	-2000
_Percent_Ovr	0
ter_Mode_Ovr	0
ttle_Ctrl_Ovr	0
Speed_OverWrite	0
ercent_OverWrite	0
getCurrent_Ovr	0
getVol_Ovr	450
lMode_Ovr	0
ter_Percent_Ovr	0
Mode_Ovr	0
outHRelay_Ovr	0
rmostat_Way3_TargetPo···	-2000

内容	值
FC_Power	16.2840004
Cool_InletPres	0
Air_MassFlow	2237
Cool_PumpSpeed	2100
FC_Voltage	235
FC_Current	70
Cool_InletTemp	5861
Cool_OutletTemp	6071
DCDC_OutputCurrent	31
DCDC_OutputVol	500
H2_InjectCtrl	758
FC_H2_TargetPres	631
Air_CompSpeed	60898
H2_InletPres	631
Air_InletPres	431
DlePress	0
FC_Air_TargetPres	448
Air_ThrottlePos	427
H2_PurgeCtrlPrev	0

Figure 20. Calibration of hydrogen proportional valve

6.2. Calibration at a Rate of 5-10A/s

Gradually load to peak power at a rate of 5-10A/s, and calibrate the control parameters from idle to peak power:

(1) Air path PID to optimal,

(2) Hydrogen PID, water separation and hydrogen discharge are optimized,

(3) Calibrate the cooling control to the optimal level,

(4) Polarization characteristics to optimal:

Test the logical relationship and time of intake valves 1 and 2, and see if there is any improvement in the performance of the fuel cell stack,

Test whether there is a difference in the performance of the fuel cell stack between the hydrogen inlet discharge valve and the hydrogen outlet discharge valve;

Calibrate the start of the refrigeration unit, calibrate the thermal management valve, optimize the performance of the fuel cell stack at each power point, and calibrate the temperature limit power curve.

6.3. Evaluation Results

The calibration results are shown in Figure 21-25.

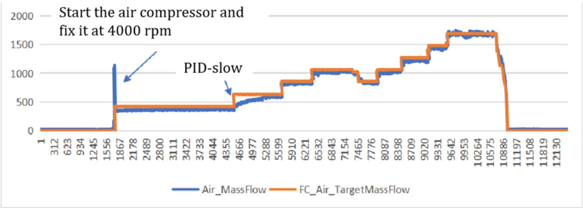


Figure 21. Air flow PID curve

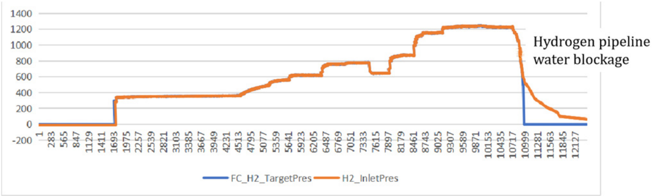


Figure 22. Hydrogen Pressure PID Curve

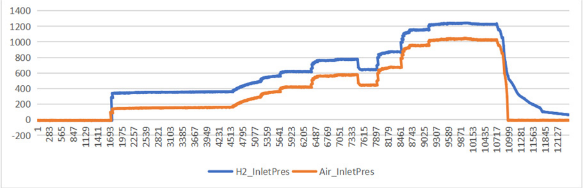


Figure 23. Hydrogen Air Pressure Curve

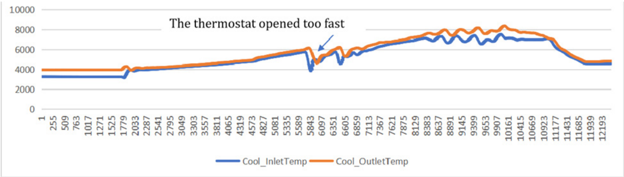

The thermostat opened too fast

Figure 24. Water Temperature Curve

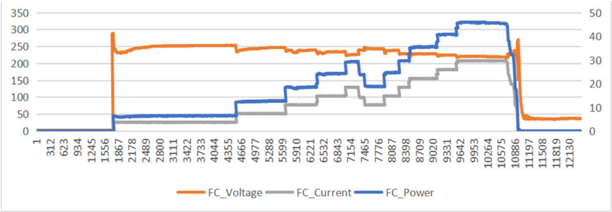


Figure 25. FC Power Curve

7. Conclusion

We have achieved a maximum efficiency of 52% and a rated point efficiency of over 45% for our independently developed fuel cell system through precise BOP selection, system low flow resistance design, optimization of working conditions, and multi parameter coupling of operating conditions and FC power targets.

Hydrogen energy is currently recognized as a practical and feasible solution for sustainable development of clean energy. It is foreseeable that hydrogen energy will be applied in various fields of industry and daily life in the future, and the research and development of high specific power stacks and high-power integrated systems will be a top priority.

Acknowledgments

Supported by the key R&D program of China Automotive Technology and Research Center Co., Ltd. (No.23253403).

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