

Application of adaptive stepped PID control with in hydrogen fuel system



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Abstract Hydrogen fuel cells are increasingly being applied in the field of new energy, and corresponding control systems have also been extensively studied. Overshoot is easy to occur during the control of hydrogen inlet pressure in fuel cell system, especially under the special conditions such as shutdown air supplementation and pressure maintenance leak detection. The excessive hydrogen pressure or pressure difference caused by overshoot may cause damage to the fuel cell stack. The hydrogen supply module control in the hydrogen circuit has the characteristics of nonlinear and complex mathematical model, and it is difficult to obtain better control effect with traditional PID control. This paper proposes an adaptive stepping PID hydrogen pressure control method, This paper establishes the pressure flow model of hydrogen circuit, and establishes the algorithm model of adaptive stepping PID and traditional PID in MATLAB/Simulink. The simulation results and experimental comparison prove that the adaptive stepping PID control has excellent control effects on complex systems with large lag, time-variant, and nonlinear characteristics, featuring fast response and the ability to suppress hydrogen pressure overshoot, which can improve the pressure control accuracy of the hydrogen circuit in the hydrogen fuel cell system with significant engineering significance and practical impact.

Keywords: hydrogen fuel cell, hydrogen pressure control, simulink

1. Introduction

The power source of fuel cell vehicles is the proton exchange membrane fuel cell (PEMFC), which generates electricity to drive the vehicle through the chemical reaction of hydrogen and oxygen fuel. Since the hydrogen–oxygen fuel cell reaction only produces water, it achieves true "zero emissions" and "zero pollution." It also has the advantages of low noise, high energy conversion efficiency, and low operating temperature. Therefore, Song et al. (2017) suggested that it is very suitable as a power source for electric vehicles. The fuel cell system consists of an air supply system, a hydrogen supply system, a thermal and water management system, and a control system. The fuel cell obtains hydrogen from high-pressure hydrogen storage equipment and requires the depressurization of high-pressure gas. A too low hydrogen flow rate will lead to an insufficient hydrogen supply, affecting the service life of the fuel cell and causing irreversible damage to the proton exchange membrane, whereas an excessively high hydrogen flow will waste fuel, reduce hydrogen utilization, and pose a safety hazard. Large pressure fluctuations affect the performance of the fuel cell stack and even damage the stack. Therefore, Deng & Liu (2024) noted that research on a stable fuel cell hydrogen supply system is critical for the application of fuel cell vehicles. Pressure stability is an important evaluation factor for the safety and reliability of fuel cells.

In the pursuit of hydrogen supply pressure stability, it is essential to conduct rational modeling of various components within the fuel cell hydrogen system to ascertain their individual impacts on the system's pressure. Liu et al. (2020) established an exhaust valve purge model to effectively facilitate the expulsion of impurities within a fuel cell stack and formulated a corresponding purge strategy to increase the operational efficiency of the stack. In addition, Wu & Lin (2021) subdivided the main controlled objects of a hydrogen system through component modeling methods and constructed a comprehensive simulation model including a gas model and a proportional valve core force model, which provided accurate tools for system analysis. In terms of system modeling, Zhang et al. (2021) combined mechanism modeling and identification modeling techniques to develop a hydrogen fuel cell system model and established a semiempirical model of the output voltage and output power on the basis of the actual operating conditions of the stack. These models not only reveal the impact of varying parameters on the operation of the fuel cell but also provide a theoretical basis for the design of air and hydrogen supply systems. Qin et al. (2023) established a dynamic model of a fuel cell gas supply system and effectively suppressed the chattering phenomenon of traditional sliding mode control by adaptively adjusting the control gain. They also used the Lyapunov method to prove the stability of the control method. Nanadegani et al. (2020) used an ANN to build an empirical model with the gas temperature, excess coefficient, relative humidity and load current as inputs and the stack voltage as the output and predicted the operating conditions corresponding to the maximum output power of the fuel cell under different load current conditions.



As the operating time increases, the performance of the stack decreases, but ANNs lack a memory function and are difficult to apply to the fitting of long time series problems. Zheng et al. (2021) used 600 h of dynamic test data of a fuel cell stack and built a fuel cell stack RNN model by means of long short-term memory (LSTM), realizing the prediction of the polarization curve and fuel cell stack performance degradation. Chen et al. (2017) conducted in-depth research on the modeling and control of the hydrogen common rail system, established a lumped parameter mechanism model of the hydrogen common rail system, analyzed the dynamic response characteristics and working life of the common rail, and provided a theoretical basis for the selection and control research of the common rail.

In the domain of hydrogen pressure control for fuel cell systems, researchers have developed a variety of advanced control strategies to enhance system performance and stability. Ding et al. (2019) used a hydrogen subloop pressure control method with feedforward prediction to effectively avoid the hydrogen subloop pressure fluctuations caused by hydrogen consumption and hydrogen exhaust valve switching. Qin et al. (2023) proposed an adaptive superhelical sliding mode control algorithm that can effectively control the hydrogen and oxygen excess ratio and the anode–cathode pressure difference by adaptively adjusting the control gain size and has a strong vibration suppression ability, which can ensure the stable and long-term operation of the fuel cell system. Deng et al. (2018) proposed a method that combines fuzzy feedforward and sliding mode control algorithms to adjust the excess oxygen ratio, which has the advantages of fast response speed and good robustness. Pukrushpan et al. (2004) better controlled the pressure balance between the anode and cathode by adjusting the hydrogen supply and circulation subsystems to ensure the stability and life of battery operation. Lian et al. (2020) applied the model predictive control method to further improve the control accuracy of the cathode excess oxygen ratio, solve the problem of air compressor response lag, and improve the response speed of the cathode flow. The proposal and application of these control strategies not only enhance the performance of fuel cell systems but also provide a solid technical foundation for the commercialization and large-scale application of fuel cells.

Although the above methods can solve some control issues, they also have some drawbacks. For instance, the superhelical algorithm relies on disturbance boundary information when selecting controller parameters, which may lead to unreasonable selection of super-helical gains. Fuzzy PID, as an intelligent controller, has good robustness but cannot adjust the parameters of the feedforward controller. At high speeds and high accelerations, the following error due to inaccurate tuning of the feedforward controller parameters can occur. Additionally, the performance of most algorithms will be greatly reduced if there is a delay in the control process. The adaptive step PID control method effectively reduces computational complexity by limiting the adjustment range of the control output. In terms of dynamic response, it can automatically adjust parameters according to system changes, maintaining good control performance to keep the system stable. Secondly, the adaptive step PID control algorithm also performs well in robustness. This method has a strong ability to resist interference, can quickly reach a stable state under load disturbance conditions, and effectively suppresses the impact of current disturbances on output accuracy.

2. Materials and methods

2.1. Hydrogen subsystem

Hydrogen fuel cell systems typically consist of a cell stack, a hydrogen supply system, an air supply system, a water and thermal management system, and an electrical control system (Lu et al. 2018). Each subsystem has a distinct function, and they work in concert to ensure the normal operation of the fuel cell system. The hydrogen supply system provides the fuel cell system with hydrogen fuel at a stable pressure. The commonly used hydrogen supply system, depicted in Figure 1, consists of a high-pressure hydrogen storage tank, a pressure reduction valve, a proportional valve, and other components. Its function is to deliver hydrogen from the high-pressure storage tank to the fuel cell stack through a pressure regulator, providing the fuel cell stack with hydrogen at the appropriate pressure, humidity, temperature, and flow rate (Zhang, 2019). A portion of the hydrogen is supplied to the fuel cell stack to react with oxygen to produce liquid water, and a circulation pump expels the water to prevent flooding within the stack; moreover, another portion of the unreacted hydrogen is recycled through the circulation pump and re-enters the stack to participate in the electrochemical reaction, increasing the utilization rate of hydrogen (Pukreshpan et al. 2021). The function of the exhaust valve is to release the water produced in the electrochemical reaction and impurity gases such as nitrogen that have permeated from the cathode of the stack into the hydrogen circuit.

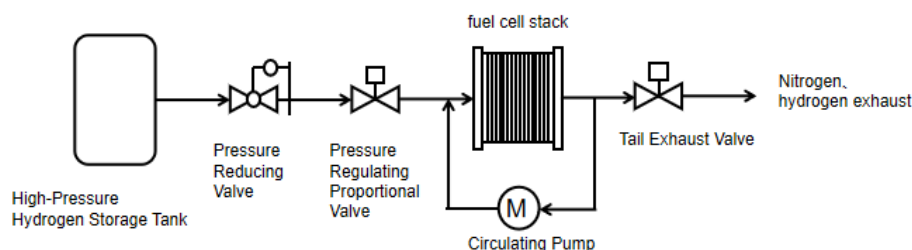
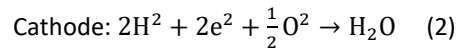
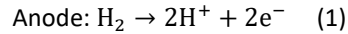


Figure 1 Structure of the hydrogen supply system.

2.2. Principle of Electricity Generation

The mechanism of proton exchange membrane fuel cell (PEMFC) power generation is as follows: the activation energy of hydrogen is reduced under the action of the catalyst layer of the fuel cell stack, and each hydrogen molecule is dissociated into 2 hydrogen ions and 2 electrons. The hydrogen ions pass through the proton exchange membrane, and the electrons travel through the external circuit to the cathode, where they react with oxygen molecules at the cathode catalyst layer to produce water while generating electrical energy. The air that has not reacted completely at the cathode is discharged into the atmosphere through the recirculation channel, and a small amount of excess hydrogen is discharged through the exhaust solenoid valve and recycled. The anode and cathode reactions of the fuel cell are shown in equations (1) and (2).



3. Modeling of the Hydrogen Supply Circuit in a Fuel Cell Power System

3.1. Hydrogen System Model

Improving the utilization rate of hydrogen can significantly increase the economy and efficiency of fuel cells. Therefore, the construction of control strategies for hydrogen circuits in fuel cell systems is highly important for the engineering application of fuel cell system control.

The differences in the temperature and humidity of each component are ignored, and the impact of the hydrogen recirculation pump on the flow of the hydrogen system is ignored. According to the composition of the hydrogen circuit and the relationship between hydrogen flow and pressure, a mathematical model of the hydrogen circuit is established. The entire hydrogen system can be divided into two parts: hydrogen supply and hydrogen consumption.

The supply part is controlled by a proportional valve, and the consumption part mainly includes consumption by the fuel cell stack and periodic discharge by the exhaust valve. According to the law of conservation of mass, the hydrogen balance equation of the hydrogen circuit can be derived:

$$M_{\text{supply}} \approx d_m + m_{\text{sta}} + m_3 \quad (3)$$

In equation (3), m_{supply} is the mass of hydrogen entering the fuel system; d_m is the change in the mass of hydrogen in the entire hydrogen circuit consisting of the hydrogen pipeline and the stack anode; m_{sta} is the mass of hydrogen consumed by the system load; and m_3 is the mass of hydrogen discharged periodically by the hydrogen exhaust solenoid valve.

The fuel cell supply pipeline model refers to the lumped volume of the gas supply pipeline, and all pipelines and valve components from the hydrogen gas inlet to the anode of the fuel cell stack are within this model. According to the ideal gas state method, the pressure change in the hydrogen circuit can be described according to the law of conservation of mass as equation (4). The relationship between the hydrogen flow rate and pressure in the pipeline can be expressed as Equation (5).

$$\frac{dP_H}{dt} = \frac{RT_H}{V_H M_H} (W_{H,\text{in}} - W_{H,\text{out}}) \quad (4)$$

$$W_{H,\text{out}} = k_{H,\text{out}}(P_H - P_c) \quad (5)$$

where P_H is the pressure in the hydrogen circuit; T_H is the temperature of the gas in the hydrogen circuit; V_H is the lumped volume of the hydrogen circuit; M_H is the molar mass of the hydrogen gas entering the circuit; $W_{H,\text{in}}$ is the mass flow rate of hydrogen gas at the inlet of the hydrogen circuit; $W_{H,\text{out}}$ is the mass flow rate of hydrogen gas at the outlet of the hydrogen circuit; P_c is the pressure at the anode of the fuel cell stack; and $k_{H,\text{out}}$ is the flow coefficient of the pipeline.

3.2. Proportional Valve Model

The system's hydrogen source is a high-pressure hydrogen cylinder. The actual hydrogen flow into the system is controlled by adjusting the opening of the proportional valve. The hydrogen pressure in high-pressure cylinders is generally much higher than the target hydrogen pressure entering the stack, and the formula for the supercritical state is applicable. Hydrogen supply flow rate Q_{sup} :

$$Q_{\text{sup}} = \frac{257P_1 K_{\text{sup}} D_1}{\sqrt{T\rho_H}} \quad (6)$$

In equation (6), T is the current absolute temperature (K) of hydrogen; P_1 is the medium pressure before the proportional valve in the hydrogen pipeline; K_{sup} is the flow coefficient of the proportional valve selected by the system; D_1 is the opening ratio of the proportional valve (0--1); and ρ_H is the hydrogen density under the index condition, which is 0.089 g/L.

3.3. Hydrogen consumption model in a fuel cell stack

The mass of hydrogen consumed by the stack reaction can be calculated from the stack current (I), which can be obtained by dividing the number of electrons (Q) passing through the conductor cross section by the time[19]. Assuming that the stack consists of n single electrodes, the corresponding hydrogen consumption mass is Q_{sta} .

$$I = \frac{Q}{t} = \frac{2e \cdot n_H \cdot N_A}{t} \quad (7)$$

$$Q_{sta} = \frac{n \cdot n_H \cdot M_H}{t} = \frac{n \cdot I \cdot M_H}{2e \cdot N_A} \quad (8)$$

In the above equations, e is the basic charge (the charge of a single electron), which is taken as $1.6 \times 10^{-19}C$; n_H is the number of moles of hydrogen consumed by the system when the load current is I; and N_A is the Avogadro constant, which is taken as 6.02×10^{23} .

3.4. Hydrogen emission model

During the operation of a hydrogen fuel cell system, the nitrogen from the cathode and water generated from the reaction can partially backdiffuse through the proton exchange membrane into the hydrogen circuit. Therefore, an exhaust valve is integrated at the hydrogen outlet to release waste gases and moisture. In this process, hydrogen is also discharged. For the convenience of modeling, this paper assumes that exhaust emission consists solely of hydrogen.

The emission flow rate of the exhaust valve depends on the internal hydrogen pressure within the stack and the diameter of the flow channel. Under normal operating conditions, the hydrogen pressure inside the stack and pipeline is less than twice the atmospheric pressure. The volumetric flow rate of hydrogen tailpipe emissions can be calculated via the subcritical flow equation (Nie et al. 2021).

$$Q_{pur} = 514K_{pur}D_2\sqrt{\frac{P_4(P_3-P_4)}{T_{PH}}} \quad (9)$$

In equation (9), D_2 is the opening of the hydrogen tail exhaust valve, which takes values of 0 and 1; T is the current absolute temperature of hydrogen (K); P_3 is the pressure of hydrogen before it enters the hydrogen tail exhaust; P_4 is the pressure of hydrogen before it exits the hydrogen tail exhaust; and K_{pur} is the flow coefficient of the tail exhaust valve selected by the system.

4. Modeling of the Hydrogen Supply Circuit in a Fuel Cell Power System

4.1. Stepped PID Control Method

Traditional PID control, which is composed of proportional, integral, and derivative components, has fixed control parameters. This can lead to a sluggish response and poor disturbance rejection when dealing with complex operating conditions. Stepped PID control does not directly respond to step inputs but instead incorporates a step modulation method on top of traditional PID control. This method allows the input command signal to approach the desired step input gradually, resulting in smoother system operation and reduced overshoot, making it suitable for high-precision tracking systems and offering significant practical value in engineering applications (Liu, 2023).

The expressions for traditional PID control and stepped PID control are given by equations (10) and (11), respectively:

$$e(t) = R(t) - Y(t) \quad (10)$$

$$u(t) = k_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d \frac{de(t)}{dt} \right] \quad (11)$$

In the above equations, R is the input signal after step modulation; Y is the output signal of the controlled object; e is the control deviation; and u is the output of the PID controller.

stepped PID involves initially modulating the input signal, followed by utilizing the output of the stepped modulation to implement PID control on the system. The principle of stepped PID control is illustrated in Figure 2.

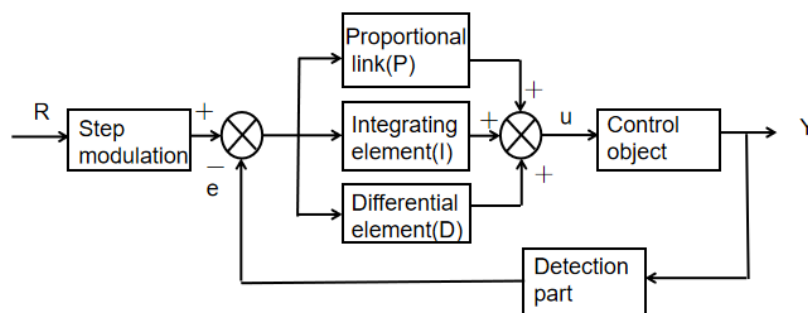


Figure 2 Schematic diagram of the stepped PID control principle.



The setpoint in stepped PID is a provisional value. Upon receiving a new target value, if the setpoint exceeds the target value, the target value is designated the setpoint for the next control cycle. If the setpoint is less than the target value, the subsequent target setpoint is incremented by a fixed offset from the current setpoint, progressively increasing until the setpoint reaches the target value. If the offset is defined as the difference between the target value and the current setpoint, the control performance mirrors that of traditional PID. stepped PID effectively decomposes a single step into multiple incremental steps. This can be articulated as follows:

$$\text{When } Y_{(k)} < Z_{(k)} : Y_{(k)} = Y_{(k-1)} + \Delta b \quad (12)$$

$$\text{When } Y_{(k)} \geq Z_{(k)} : Y_{(k)} = Z_{(k)} \quad (13)$$

In the above equations, $Y_{(k)}$ is the current setpoint, $Y_{(k-1)}$ is the setpoint of the previous cycle, $Z_{(k)}$ is the target value, and Δb is the incremental step size. The flow chart of the stepped modulation process is illustrated in Figure 3 below.

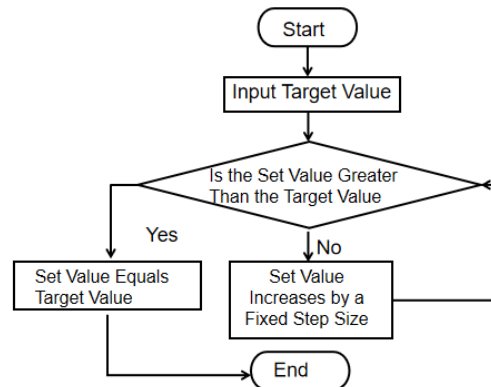


Figure 3 Flowchart of the stepped modulation process.

4.2. The implementation concept of adaptive stepped PID control

If stepped PID increases the setpoint with a fixed step size, the step size is typically derived from numerical simulations. To ensure stability across different environments, this approach can often slow the response speed. This phenomenon is more obvious when the hydrogen target pressure changes greatly. A stepped PID with a fixed step size can achieve stability, but it struggles to meet the demands for rapid response in various complex operating conditions encountered in practical applications. To address these issues, an adaptive stepped PID control method has been designed. This method employs a variable step size, where the step size is a fraction k (ranging from 0--1) of the difference between the actual value and the target value. The step size is larger initially for a rapid approach to the control objective and smaller later to minimize overshoot. When the feedback value is close to the target value and their difference is less than Δt , the setpoint is set to the target value. As illustrated in Equations (14) and (15), $F_{(k-1)}$ is the feedback value.

$$\text{When } F_{(k-1)} < Z_{(k)} - \Delta t : Y_{(k)} = F_{(k-1)} + k(Z_{(k)} - F_{(k-1)}) \quad (13)$$

$$\text{When } F_{(k-1)} \geq Z_{(k)} - \Delta t : Y_{(k)} = Z_{(k)} \quad (14)$$

The flowchart of the adaptive stepped PID is depicted in Figure 4.

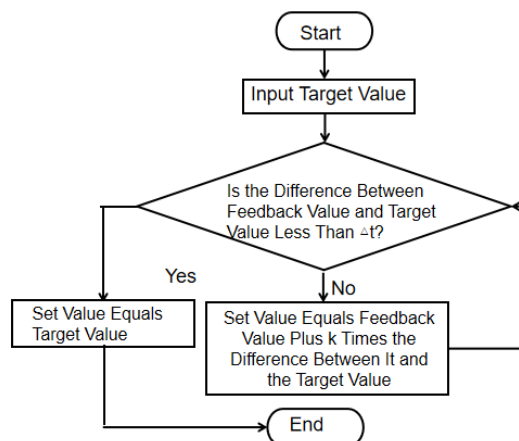


Figure 4 Flowchart of adaptive stepped PID control.

As shown above, the values of the difference coefficients k and Δt directly affect the control effect. Combined with the control of the hydrogen circuit in this paper, ignoring the influence of the exhaust, if for a fixed system, the number of stack sheets, cavity volume, proportional valve flow coefficient and other parameters are fixed and the temperature range is not large, the impact is minimal. It can be assumed that hydrogen consumption is directly proportional to the fuel cell current and that the hydrogen intake is approximately directly proportional to the pressure difference across the proportional valve and the valve opening. For the algorithm to adapt to different operating environments, the difference coefficients k and Δt are adjusted in real time according to the inlet and outlet pressure differences of the proportional valve and the current during fuel cell operation. The pressure upstream of the proportional valve (intermediate pressure) is generally greater than 10 bar, a much higher than the pressure downstream of the valve. Assuming that the intermediate pressure is P_1 , the fuel cell current is I_1 , the hydrogen intake pressure is P , the step coefficient is k_1 , and the PID output target opening of the proportional valve is D_1 . When the intermediate pressure is P_2 and the fuel cell current is I_2 , if the hydrogen intake pressure remains the same as P , then we have:

$$b_1 P_1 D_1 - c_1 I_1 = b_1 P_2 D_2 - c_1 I_2 \quad (15)$$

$$b_1 = \frac{257 K_{sup}}{\sqrt{T_{PH}}} \quad (16)$$

$$c_1 = \frac{n \cdot M_H}{2e \cdot N_A} \quad (17)$$

From the aforementioned equation, the stepped adjustment coefficient is given by:

$$k' = \frac{c_1(I_2 - I_1)}{b_1 P_2 D_1} + \frac{P_1}{P_2} \quad (18)$$

When the intermediate pressure is P_2 and the fuel cell current is I_2 , the step coefficient is kk' . In this equation, to determine the correction coefficient at different target pressures, it is necessary to calibrate the proportional valve opening at different target pressures when the intermediate pressure is P_1 and the fuel cell current is I_1 . The improved stepped PID automatically adjusts the step modulation step size, which not only suppresses overshoot but also accelerates the response speed, achieving a control effect that is both fast and stable.

4.3. Hydrogen supply circuit with the PID control model

According to the above analysis, the hydrogen circuit PID feedback control block diagram can be represented as shown in Figure 5. The hydrogen pressure P serves as the control variable, with the proportional valve acting as the control element. The target opening D_1 of the proportional valve is derived from the PID calculation based on the hydrogen pressure error signal. The fuel cell current I and the switching of the exhaust valve D_2 act as disturbances to the system, influencing the hydrogen pressure.

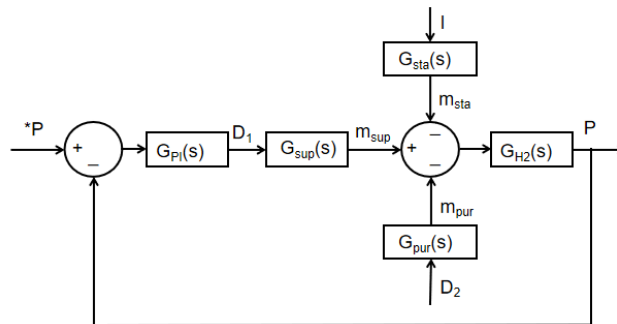


Figure 5 Schematic diagram of hydrogen circuit PID feedback control.

From equations (4), (6), (8), and (9), the transfer functions of the hydrogen pressure, proportional valve opening, fuel cell current, and tailpipe valve opening with respect to the hydrogen flow rate can be obtained.

$$G_{H_2}(s) = \frac{P(s)}{\Delta m_H(s)} = \frac{R_a T}{sV} \quad (19)$$

$$G_{sup}(s) = \frac{Q_{sup}(s)}{D_1(s)} = \frac{257 P_1 K_{sup}}{\sqrt{T_{PH}}} \quad (20)$$

$$G_{sta}(s) = \frac{Q_{sta}(s)}{I(s)} = \frac{n \cdot M_H}{2e \cdot N_A} \quad (21)$$

$$G_{pur}(s) = \frac{Q_{pur}(s)}{D_2(s)} = 514 K_{pur} \sqrt{\frac{P_4(P_3 - P_4)}{T_{PH}}} \quad (22)$$

5. Simulation experiment and analysis

According to the design concept of hydrogen pressure control and the established transfer functions from the aforementioned text, a simulation model for fuel cell hydrogen circuit pressure control is constructed in MATLAB/Simulink. This model is used to simulate and compare the control effects of hydrogen pressure. The simulation model is shown in Figure 6.

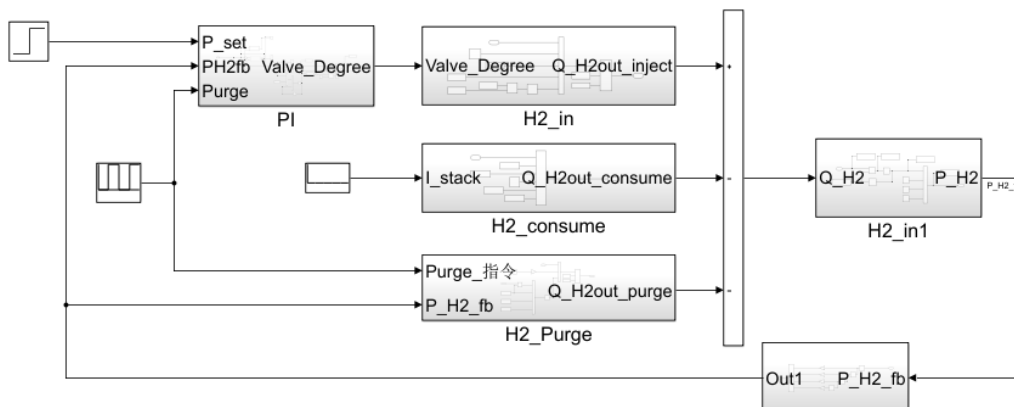


Figure 6 Simulation model diagram.

The model inputs a target hydrogen pressure of 0–200 kPa steps, a fuel cell output current of 200 A, and a hydrogen purge pulse with a duty cycle of 80% and a period of 5 s. The hydrogen pressure control models based on traditional PID and adaptive stepped PID are run, and the simulation results are shown in Figures 7 and 8, respectively.

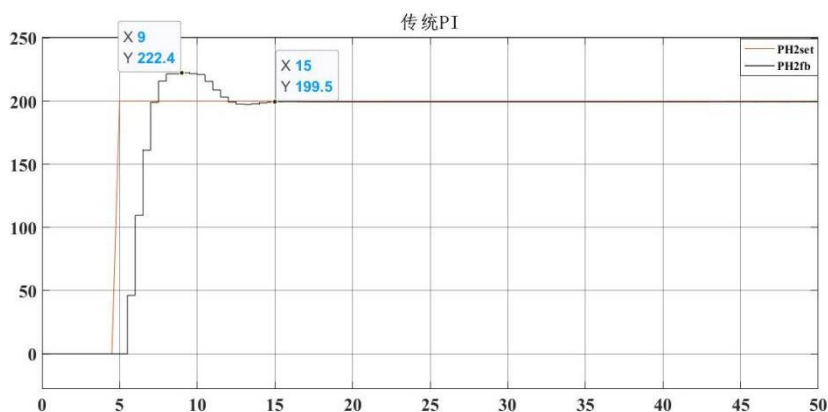


Figure 7 Simulation curve of traditional PID control.

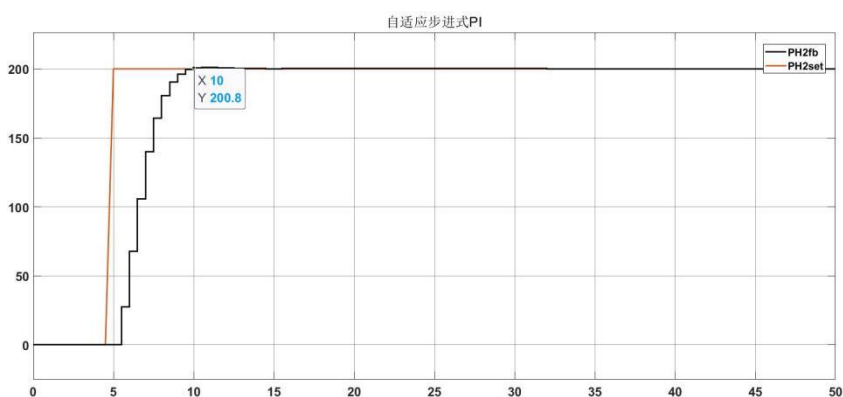


Figure 8 Simulation curve of adaptive stepped PID control.

Compared with the step responses of the above hydrogen pressure, the hydrogen pressure controlled by the traditional PID method reaches a peak value of 223 kPa at 8.5 s, then decreases and oscillates, stabilizing at the target value after 15.5 s. The hydrogen pressure controlled by the adaptive stepped PID stabilizes at the target value at 10 s with virtually no overshoot. The simulation results indicate that adaptive stepped PID control can effectively suppress hydrogen pressure overshoot and



stabilize at the target value in a shorter time, thereby reducing the impact of hydrogen pressure overshoot on the fuel cell and providing better protection for the fuel cell.

6. Comparative Analysis of Actual Data

To verify the control algorithm and integrate it more effectively with practical applications, a hydrogen pressure test bench was built. A test program is subsequently written to compare the control effects of hydrogen pressure under different operating conditions. The test bench is shown in Figure 9.



Figure 9 Hydrogen pressure testing bench.

6.1. Data comparison for pressure maintenance and gas supplementation

In the actual operation of a fuel cell system, it is often necessary to conduct pressure maintenance tests on the hydrogen circuit of the fuel cell system to eliminate the risk of hydrogen leakage. Alternatively, hydrogen is replenished in the hydrogen circuit after the system is operated to exhaust the remaining oxygen on the cathode side. Under these two special working conditions, the hydrogen exhaust valve is in a closed state, the system does not generate electricity, hydrogen is not consumed, and the overshoot part cannot be consumed.

Under these conditions, the hydrogen pressure control waveform based on the traditional PID is shown in Figure 10 below. The target hydrogen pressure is 1.4 bar. a, and the actual hydrogen pressure has exceeded 1.6 bar. a. Moreover, owing to the current state of the system where there is no consumption of hydrogen, the hydrogen remains in an overshoot state for an extended period, which is highly likely to cause damage to the fuel cell stack.

The hydrogen pressure control waveform using adaptive stepped PID is shown in Figure 11. When the target hydrogen pressure is set to 1.4 bar. a and 1.6 bar. a, the actual hydrogen pressure feedback shows virtually no overshoot.

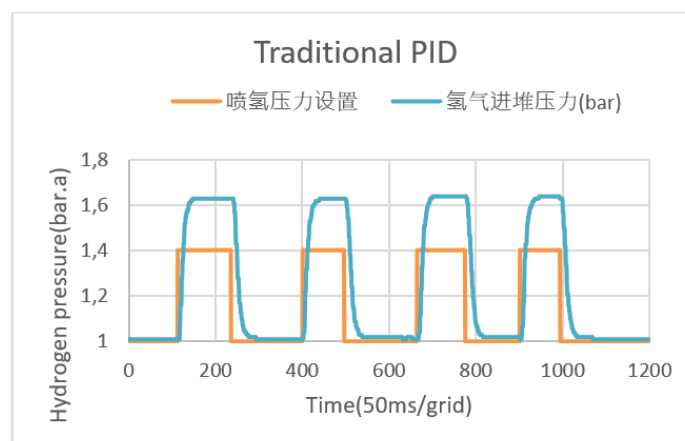


Figure 10 Hydrogen pressure control waveform of the traditional PID.

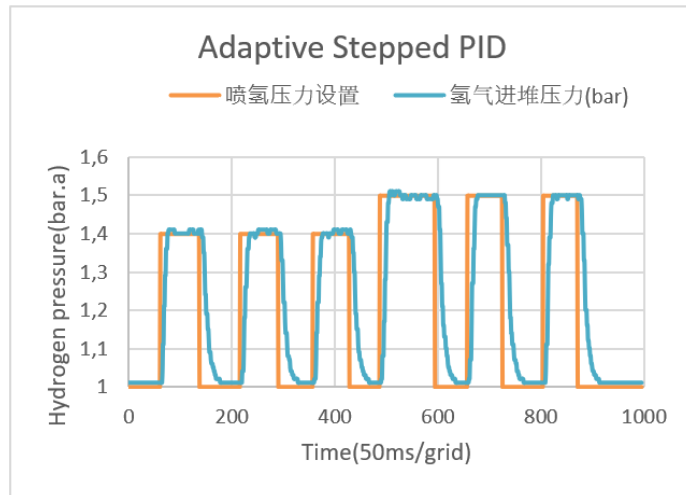


Figure 11 Hydrogen pressure control waveform of the adaptive stepped PID.

6.2. Data comparison during operation

In practical operation, fuel cell systems operate at various power levels. Different system powers correspond to different hydrogen demand flows and pressures. By adjusting the manual ball valve of the hydrogen pressure test bench, the hydrogen consumption of the fuel cell stack at different power levels can be simulated. Different target hydrogen pressure values are set, and hydrogen pressure feedback is obtained via traditional PID control and adaptive step PID control, as shown in Figures 12 and 13. A comparison of the test data indicates that traditional PID control results in a significant overshoot in the hydrogen pressure feedback when switching between target values. The adaptive step PID control effectively suppresses overshoot, significantly improving the control performance. This reduces the occurrence of faults such as excessive hydrogen pressure differentials caused by overshoot and secondary damage to the fuel cell stack caused by corresponding fault protection measures.

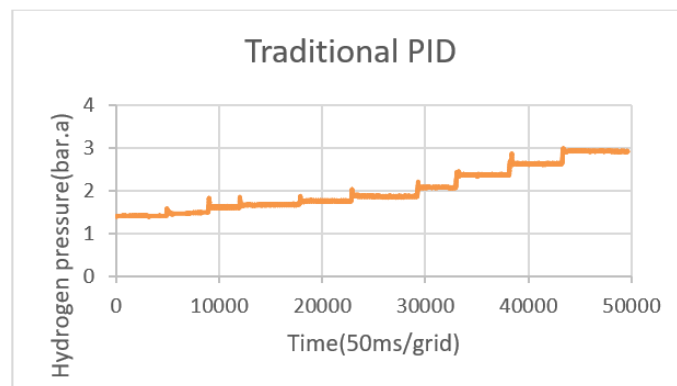


Figure 12 Hydrogen pressure feedback diagram of traditional PID.

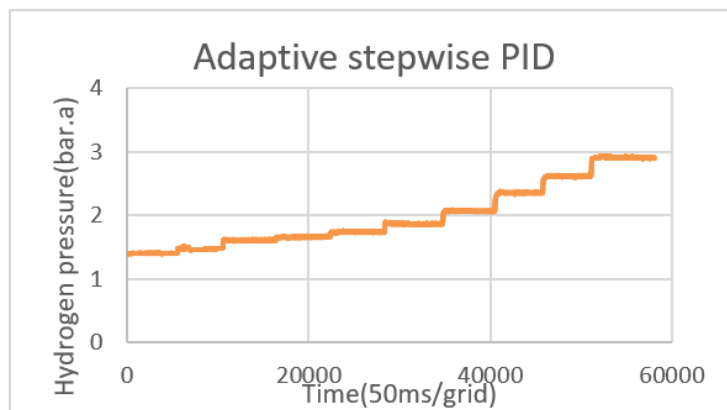


Figure 13 Hydrogen pressure feedback diagram of the adaptive stepped PID

5. Results and Discussion

This paper analyzes the principle of the hydrogen circuit in a hydrogen fuel cell system and the flow characteristics of each component and establishes a corresponding mathematical model. To address the overshoot issue in hydrogen pressure control, an adaptive stepped PID control method is proposed. The control algorithm is verified through simulation in MATLAB/Simulink, and an experimental bench is constructed for testing. The simulation results and test results show that the adaptive stepped PI control algorithm can reduce the overshoot by about 0.2 bar compared with the traditional PI control algorithm under the system pressure holding or common operating conditions, and effectively solve the overshoot problem of hydrogen pressure in the system; Moreover, compared with traditional PI control, this control algorithm can shorten the time to stabilize to the target pressure value by nearly 30%. It can well avoid the damage of hydrogen overpressure and repeated overshoot shocks to the fuel cell over-formation under specific working conditions. Research on hydrogen pressure control in hydrogen fuel cells is highly important.

This view is also supported by a related study by Dong et al. (2019), which stated that the method of stepping PID control has the advantages of small overshoot at startup, fast system response and small control amount.

In a prospective study in 2021, Chang et al. (2021) in order to extend the service life of the proton exchange membrane fuel cell (PEMFC), a model for PEMFC including its cathode and anode supply system is established, control strategy for both cathode and anode pressures is designed. The pressure difference between cathode and anode can be maintained at a very low value even under complex working conditions, significantly extending the service life of proton exchange membrane.

Qiu et al. (2022) use particle swarm optimization algorithm to adjust PID parameters to improve PID control performance of temperature control system. The simulation results show that the control system after particle swarm tuning can reduce the overshoot by 30% and shorten the adjustment time, which can overcome the shortcomings of the traditional PID control that can not guarantee the control effect.

Stepwise PID control is an improved control strategy developed on the basis of traditional PID control. The traditional PID controller calculates the control amount according to the current error signal, while the step PID control is to divide the control process into several small step stages, and gradually adjust the control parameters according to the change of the error in each stage to achieve more accurate control. Compared with the traditional PID control, the stepping PID control has stronger adaptability and robustness, and can better cope with the change of system parameters and external interference.

In order to improve the dynamic performance of air flow and pressure cooperative control, Xue et al. (2024) proposed an air mass flow and pressure control strategy based on feedforward PID, conducted offline simulation tests and applied it to 86 kW class fuel cell engines, and conducted experiments under different load requirements. The results show that both the reference values of air flow and cathode inlet air pressure have short transient response time and stable following effect.

6. Conclusion

Adaptive step PID control for hydrogen pressure in fuel cell systems holds significant potential for industrial applications, particularly in the realm of vehicle systems where real-time implementation is crucial. This method's ability to dynamically adjust parameters in response to system changes is not only essential for maintaining stability but also for optimizing performance under varying conditions. The integration of such control systems in vehicles is part of a broader technological transformation in the automotive industry, which aims to enhance vehicle stability, efficiency, and connectivity.

In conclusion, the adaptive step PID control method for hydrogen pressure in fuel cell systems is a compelling area for future research, with significant implications for the advancement of vehicle control systems and the broader scope of industrial process control.

Ethical considerations

Not applicable.

Conflict of interest

The authors declare that they have no conflicts of interest.

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