Adaptive fuzzy control method of hydrogen fuel cell gas supply system

Weidong Wang1,2,3, Jing Chen2, Chun Xiao2 and Nanding Cheng1,2
1 School of Automation, Wuhan University of Technology, Wuhan 430070, P.R. China
2 Foshan Xianhu Laboratory of the Advanced Energy Science and Technology Guangdong Laboratory, Xianhu hydrogen Valley, Foshan 528200, P.R. China
3 E-mail: 1159479896@qq.com

Abstract. This paper takes the hydrogen fuel cell gas supply system as the research object. Firstly, it analyzes the working principle of the hydrogen fuel cell and the control requirements of the gas supply system, then uses the fuzzy adaptive PID control algorithm to regulate the gas pressure of the system. Finally, Matlab/Simulink software simulation platform is used for simulation verification, and the control effects of conventional PID control and fuzzy adaptive PID control are compared. The results show that the gas supply system based on fuzzy adaptive PID control can effectively regulate the gas pressure value and has a good control effect.

1. Introduction
With the depletion of traditional energy sources such as oil, coal and natural gas and the increasingly serious environmental pollution problems, researchers must find suitable alternative energy sources to replace traditional energy sources [1]. As a new energy in the 21st century, hydrogen energy has great development potential and broad application prospects under the current demand. Fuel cells have the advantages of high conversion efficiency, high energy density, short filling time, long endurance mileage, no pollution and environmental friendliness, and very small pollution in the manufacturing and recycling process, which are the future power sources of automobiles. However, due to the delayed response of the gas supply or the uneven current and voltage distribution between different unipolar plates, the hydrogen fuel cell will cause the phenomenon of "hydrogen starvation", that is, fuel starvation [2]. If the degree of hydrogen starvation is mild and resolved quickly, it will only cause performance degradation due to uneven battery current distribution; and if hydrogen starvation occurs for a long time, it will seriously affect the battery life [3]. When the output power of hydrogen fuel cell vehicles increases sharply, the rate of electrochemical reaction inside hydrogen fuel cell will increase accordingly, and the consumption of oxygen will accelerate, and the fuel cell will suffer from "hypoxia" [4], which will cause irreversible damage to the fuel cell electrolyte. On the contrary, when the air supply inside the fuel cell exceeds the actual demand, the phenomenon of "oxygen saturation" will appear [5], which will increase the power consumption of the air compressor and reduce the chemical activity of the catalyst.

In recent years, there have been many researches on the control method of the gas supply system. Literature [6] used a fuzzy PID controller to control the constant pressure gas supply system; Literature [7] used a PID adjustment algorithm to effectively control the converter bottom blowing system; Literature [8] used a PLC-based distributed control method to control the LNG gas supply system; Literature [9] used fuzzy inference-based online adjustment of softening coefficients to improve the...
generalized predictive control algorithm to achieve pressure difference control. At present, most of the control of the gas supply system still adopts the conventional PID control method, which can only effectively control a single state quantity.

In view of the above problems, this paper takes the hydrogen fuel cell gas supply system as the research object, and realizes the real-time adjustment of the gas pressure of the gas supply system through the fuzzy adaptive PID control algorithm. The control algorithm is simulated and analyzed on the Matlab / Simulink software platform, and compared with the conventional PID control.

2. Working principle of hydrogen fuel cell

Hydrogen fuel cell is composed of electrolyte and electrode (anode and cathode), and its principle is equivalent to the inverse process of electrolytic water. At work, hydrogen is ionized into hydrogen ions (H+) and releases electrons (e−) under the action of the anode catalyst. The hydrogen ions (H+) pass through the electrolyte to the cathode, and the electrons (e−) are collected by the current collecting plate, and flows from the external circuit to the cathode; under the action of cathode catalyst, the air is reduced and combined with H+ and electron e− of external circuit to produce emission of only water [10]. In this process, hydrogen fuel cell will produce a certain amount of heat due to its own electrochemical reaction and internal resistance, and the main product is water. The working principle of hydrogen fuel cell is shown in Figure 1.

[Figure 1. Working principle of hydrogen fuel cell.]

It can be seen from Figure 1 that the electrolyte in the battery (such as proton exchange membrane) is the proton transfer channel, and the exchange membrane controls the proton transfer from the anode to the cathode, which together with the electronic transport of the external circuit constitutes a complete circuit. The proton exchange membrane is selective in that hydrogen ions migrate through the membrane to the cathode, while electrons can only be transferred through an external load. The overall chemical reaction formula is as follows:

- anode: \( H_2 \rightarrow 2H^+ + 2e^- \)
- cathode: \( \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \)
- overall response: \( H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Q \) (energy)

3. Mathematical model and control requirements of gas supply system

Based on the analysis of the working principle of the hydrogen fuel cell, it can be concluded that the fuel cell system is mainly composed of a hydrogen supply system, an air supply system, and a cooling system. Since the stable operation of fuel cells requires the respective stable control of hydrogen and air supply systems, the main research content of this paper is the hydrogen and air supply system, which is hereinafter referred to as the gas supply system.

Based on the conservation of matter and the ideal gas equation of state, the gas dynamics of the hydrogen fuel cell stack can be described by the following equation:

\[
\dot{p}_{ca} = \frac{RT_{ca}}{M_{a,ca} V_{in}} (W_{ca,in} - W_{con})
\]
In the formula, $T_{ca}$ represents the temperature of the stack, $M_{a,ca}$ represents the average molar mass of the gas in the stack, and $W_{con}$ represents the rate at which the stack consumes gas, which can be calculated by combining the stack current and the conservation equation of matter:

$$W_{con} = \frac{nI_sM}{4F}$$  \hspace{1cm} (2)

In the formula, $n$ represents the number of single cells in the stack, $I_s$ represents the current value output by the stack, $F$ represents the Faraday constant, and $M$ represents the molar mass of the gas.

The performance parameters of hydrogen fuel cell gas supply system are shown in Table 1.

| Parameter                              | Value       |
|----------------------------------------|-------------|
| Rated power                            | 50kW        |
| Number of single fuel cells            | 450         |
| Operating temperature                  | 348K        |
| Relative humidity of air               | 60%         |
| Water content of proton exchange Membrane | 14       |
| Gas pressure                           | $\leq$0.5MPa |

4. Control system design

Because the fuel cell system is a complex system with multiple inputs and outputs and nonlinearities, it is difficult for conventional control methods to meet the control requirements. According to the working principle of the fuel cell system and the control requirements of the gas supply system, this paper adopts the fuzzy adaptive PID control algorithm to adjust the gas pressure value of the fuel cell gas supply system. The schematic diagram of the specific fuzzy adaptive PID control system is shown in Figure 2.

In Figure 2, $P_g(t)$ is the given gas pressure value, and $P_{r}(t)$ is the output gas pressure value. $H(s)$ is a fuzzy adaptive PID controller, $e(t)$ is the deviation between the collected actual pressure value and the set target pressure value, and $e_c(t)$ is the change rate of the pressure deviation.

The fuzzy controller adopts a dual-input-three-output controller, takes the pressure deviation and the change rate of the pressure deviation as the input, and takes the three parameters of PID change $\Delta K_p$, $\Delta K_i$, and $\Delta K_d$ as the output. The basic domain of the pressure deviation $e(t)$ is [-5,5]; the basic domain of the pressure deviation change rate $e_c(t)$ is [-1,1], and takes the fuzzy domain of deviation $e(t)$ and deviation change rate $e_c(t)$ as [-6,6]; the fuzzy domains of $\Delta K_p$, $\Delta K_i$, and $\Delta K_d$ are [-3,3]. Setting the basic domains of $\Delta K_p$, $\Delta K_i$, and $\Delta K_d$ to [-0.06,0.06], [-0.001,0.001], [-0.003,0.003].
Commonly used membership functions are triangular, normal, trapezoidal, S-type, etc. In this article, the membership functions of \( e \), \( e_c \), \( K_p \), \( K_I \), and \( K_D \) are all selected in the form of a combination of triangular and normal types, namely NB and PB. Choose the normal membership function, and the others choose the triangular membership function. The commonly used methods for clarifying the amount of blur are the maximum membership method, the median method and the center of gravity method. In this paper, the Mamdani algorithm is used for fuzzy inference, and the actual output values of \( \Delta K_p \), \( \Delta K_I \) and \( \Delta K_D \) are obtained by the center of gravity method. The fuzzy control rules of \( \Delta K_p \), \( \Delta K_I \) and \( \Delta K_D \) are shown in Table 2 to Table 4.

**Table 2. Fuzzy control rules of \( \Delta K_p \).**

| \( \Delta K_p \) | NB | NM | NS | ZO | PS | PM | PB |
|------------------|----|----|----|----|----|----|----|
| \( e \)          | NB | PB | PB | NS | ZO | PS | ZO |
| \( e_c \)        | NB | NM | NS | ZO | PS | PM | PB |

**Table 3. Fuzzy control rules of \( \Delta K_I \).**

| \( \Delta K_I \) | NB | NM | NS | ZO | PS | PM | PB |
|------------------|----|----|----|----|----|----|----|
| \( e \)          | NB | NM | NS | ZO | PS | PM | PB |
| \( e_c \)        | NB | NM | NS | ZO | PS | PM | PB |

**Table 4. Fuzzy control rules of \( \Delta K_D \).**

| \( \Delta K_D \) | NB | NM | NS | ZO | PS | PM | PB |
|------------------|----|----|----|----|----|----|----|
| \( e \)          | NB | NM | NS | ZO | PS | PM | PB |
| \( e_c \)        | NB | NM | NS | ZO | PS | PM | PB |

5. Analysis of simulation results

According to the control requirements and control system design of the fuel cell gas supply system, the conventional PID control algorithm and fuzzy adaptive PID algorithm are built in the Matlab/Simulink...
simulation software to build a simulation model. Under the condition of current step input, the simulation results of the two algorithms are analyzed and compared. The conventional PID control simulation model and fuzzy adaptive PID control simulation model is shown in Figure 3.

![Simulation model of conventional PID control and fuzzy adaptive PID control.](image)

Figure 3. Simulation model of conventional PID control and fuzzy adaptive PID control.

After the simulation model is built, combined with the actual situation of the project, the initial parameters of the PID are tuned by the critical ratio method. The PID initial parameters after tuning in this article are $K_p = 0.7$, $K_i = 0.008$, $K_d = 0.002$. Set the simulation time to 50 seconds and add a step signal. The simulation results of fuzzy PID control and conventional PID control are shown in Figure 4.

![Simulation results of conventional PID control and fuzzy adaptive PID control.](image)

Figure 4. Simulation results of conventional PID control and fuzzy adaptive PID control.

It can be seen from Figure 4 that the conventional PID control method and the fuzzy adaptive PID control method are simulated separately. Under the same input conditions, the gas pressure starts from the initial value 0, and can reach the set value after a certain period of time, becoming steady. The control performance comparison of the two algorithms is shown in Table 5.

| Control method          | Rise time (s) | Peak time (s) | Maximum overshoot (%) | Adjustment time (s) |
|-------------------------|---------------|---------------|-----------------------|---------------------|
| Conventional PID        | 5.5           | 7.5           | 21                    | 9                   |
| Fuzzy adaptive PID      | 11            | 13            | 0                     | 8                   |

Table 5. Comparison of the control performance of the two algorithms.

It can be seen in Table 5 that both conventional PID control and fuzzy adaptive PID control methods can achieve gas pressure control. However, with fuzzy adaptive PID control system, the gas pressure
rise curve is relatively stable, and the overshoot is significantly reduced, and the adjustment time is also shortened.

6. Conclusions
In this paper, hydrogen fuel cell gas supply system as the research object, based on the analysis of the performance index of hydrogen fuel cell gas supply system, a fuzzy adaptive PID control method combining fuzzy theory and PID control is adopted. The simulation experiment is carried out by using Matlab/Simulink software platform, and the simulation results are compared and analyzed. The results show that the fuzzy adaptive PID control algorithm can effectively improve the dynamic response of gas pressure in the hydrogen fuel cell gas supply system compared with the conventional PID control algorithm.

References
[1] Qiang Ma 2018 Analysis of the bottleneck in the development of hydrogen fuel cell vehicles China's Strategic Emerging Industries 46 83
[2] Azuddin M, Choudhury I A and Taha Z 2015 Development and performance evaluation of low-cost custom-made vertical injection molding machine Journal of the Brazilian Society of Mechanical Sciences and Engineering 37 79-86
[3] Ch Santosh Kumar and G Chandra Sekhar 2020 Research progress of power quality algorithm for solar photovoltaic cells based on MMC International Journal of Power and Energy Engineering 2
[4] Mohamer Elgamal, Nikolay Korovkin, Akram Elmitwally and Zhe Chen 2020 Robust multi-agent system for efficient online energy management and security enforcement in a grid-connected microgrid with hybrid resources IET Generation, Transmission & Distribution 14
[5] Woonki Na, Bei Gou, Jonghoon Kim, Felipe Mojica and Po-Ya Abel Chuang 2020 Complementary coop eration dynamic characteristics analysis and modeling based on multiple-inputmultiple-output methodology combined with nonlinear control strategy for a polymerelectrolyte membrane fuel cell Renewable Energy 149
[6] Xiaohui Yu 2015 Research on air compressor constant pressure air supply control system based on fuzzy PID Shandong Chemical Industry 44 159-162
[7] Chengyi Wang, Wei Wu and Libin Yang 2020 120t converter bottom blowing air supply system control model and application effect Special Steel 41 10-14
[8] Xiaolin Zeng, Shangzhi Ding and Jiale Li 2020 Basic design of control, monitoring and safety system of marine LNG gas supply system Mechanical and Electrical Equipment 37 53-56
[9] Haochen Zhang, Xiaohong Hao and Aimin An 2012 On-line adjustment of softening coefficient and improved generalized predictive control applied in gas supply system of proton exchange membrane fuel cell Computers and Applied Chemistry 29 784 -788
[10] Pengcheng Li, Song Gao and Binbin Sun 2021 Simulation and analysis of proton exchange membrane fuel cell voltage Journal of Shandong University of Technology 35 56-62