A Fuzzy Adaptive PID Control Algorithm with Improved Quantification Factor

Yile Shi¹, Zhiyong Qiao¹,², Keqiang Bai¹, Guo Chen¹, Zhigui Liu¹,*

¹Southwest University of Science and Technology, Information Engineering College, Mianyang 621000, Sichuan, China
²Mianyang Vocational and Technical College, Mianyang 621000, Sichuan, China

*Email: liuzhigui@swust.edu.cn

Abstract. The phase-shifting full bridge digital power supply based on Fuzzy PID control is difficult to realize the full mapping from the fuzzy universe to the actual output domain, resulting in the loss of fuzzy control quantity, resulting in the dynamic performance problems of large amplitude and long time output fluctuation. In this paper, a fuzzy adaptive PID control algorithm with improved quantification factor is proposed. The online adjustment function of quantification factor in fuzzy universe is introduced in the quantification link. The function can adjust the fuzzy quantification factor in real time according to the current sampling error and error change rate of the system. In order to verify the effectiveness of the improved algorithm, the traditional PID control, the traditional fuzzy PID control and the quantification factor improved fuzzy PID control are applied to the phase-shifting full bridge small signal disturbance model respectively. The results show that the fuzzy adaptive PID control algorithm with the quantification factor online adjustment function has higher dynamic performance.

1. Introduction

Fuzzy set theory was founded by L.A.Zadeh in 1965, and the definition and related theory of fuzzy control were given in 1973. In 1974, the British scholar E.H. Mamdani took the lead in using fuzzy control statements to form a fuzzy controller, which was applied to the control of boiler steam. With the development of power electronic technology, the fuzzy adaptive PID control which combines fuzzy control with traditional PID control has the advantages of high efficiency, simplicity and easy implementation, and has been widely used in the field of control [1-3].

In order to further improve the control ability of fuzzy adaptive PID control. Some scholars have proposed to increase the fuzzy universe quantification accuracy by adding fuzzy subsets to achieve high-precision control output. However, this method makes the fuzzy rules grow exponentially, which easily leads to the increase of fuzzy decision-making time [4]; In order to make up for the deficiency of fuzzy adaptive PID control ability caused by fuzzy linear quantification, some scholars proposed to use nonlinear membership function to improve the quantification accuracy from fuzzy input to fuzzy output [5]; In order to improve the judgment speed under two extreme sets of fuzzy subset in fuzzy adaptive PID control, some scholars use the method of adding variable judgment to improve the judgment efficiency under two extreme sets [6]; With the arrival of the digital wave of electronic equipment, due to the digital control delay caused by the increase of system adjustment time, some scholars proposed to combine fuzzy adaptive PID with predictive control. Based on the advantages of fuzzy adaptive
PID nonlinear control, the predictive model is used to predict the system output in advance to realize the advanced calculation of the control quantity [7].

In the application of high-power power supply, the phase-shifting full bridge digital power supply, which combines phase-shift control with digital control, has high power density and high intelligence, and has become the first choice in the application field of power supply above 500W [8]. However, the output of high-power phase-shifting full bridge digital power supply has the output characteristics of high voltage or high current. When the input fluctuates, it will cause a wide range of system output fluctuations, and the fluctuation has the characteristics of large amplitude and difficult to predict [9]. The traditional fuzzy adaptive PID control is difficult to realize the full mapping from the fuzzy universe to the actual output domain, resulting in the loss of fuzzy control quantity, resulting in the dynamic performance problems of large amplitude and long time output fluctuation.

In order to improve the dynamic performance of the phase-shifting full bridge digital power supply, reduce the amplitude of output fluctuation and shorten the fluctuation adjustment time. In this paper, a fuzzy adaptive PID control algorithm with improved quantification factor is proposed. The online adjustment function of quantification factor in fuzzy universe is introduced in the quantification link. The function can adjust the fuzzy quantification factor in real time according to the current sampling error and error change rate of the system. In order to verify the effectiveness of the improved algorithm, the traditional PID control, the traditional fuzzy PID control and the quantification factor improved fuzzy PID control are applied to the phase-shifting full bridge small signal disturbance model respectively. The results show that the fuzzy adaptive PID control algorithm with the quantification factor online adjustment function has higher dynamic performance.

2. Fuzzy Adaptive PID Control

Fuzzy adaptive PID control (fuzzy PID) uses fuzzy logic and certain fuzzy rules to optimize PID parameters in real time, so as to overcome the shortcomings of traditional PID control which can not adjust PID control parameters in real time and realize nonlinear control. Fuzzy PID takes system output error and error change rate as control input. Through fuzzy quantification, fuzzy decision-making and clarity, the output of control adjustment quantity acts on the original control value, and realizes the nonlinear adjustment of control quantity.

\[ E = e / k_1 \]  
\[ EC = ec / k_2 \]

Among them, \( e \) and \( ec \) are the actual output error and error change rate of the system; \( k_1 \) and \( k_2 \) are the proportion coefficients of the quantification factor under empirical prediction; \( E \) and \( EC \) are the fuzzy quantities obtained through fuzzy quantification; the quantification link sends \( E \) and \( EC \) after fuzzy quantification into the fuzzy decision-making link. The membership function relationship of fuzzy subsets of \( E \) and \( EC \) is shown in the figure below.

![Figure 1. Fuzzy Adaptive PID control flow.](image-url)
2.2. Fuzzy Decision
The fuzzy decision-making link receives the fuzzy quantity $EC$ and $E$ from the fuzzy quantification link, and completes the fuzzy decision according to the pre-set fuzzy rules and fuzzy reasoning mechanism. Fuzzy decision includes two steps: fuzzy rules and fuzzy reasoning.

In the fuzzy rules, the range of fuzzy quantity is divided into regions according to the number of subsets, and the two-dimensional fuzzy rule table based on fuzzy quantity $EC$ and $E$ is obtained as follows.

Table 1. KP control parameter fuzzy rule table.

| $ec$ | NB | NM | NS | ZO | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| $e$  |
| NB   | PB | PB | PM | PM | PS | ZO | ZO |
| NM   | PB | PB | PM | PS | PS | ZO | NS |
| NS   | PM | PM | PM | PS | ZO | NS | NS |
| ZO   | PM | PM | PS | ZO | NS | NM | NM |
| PS   | PS | PS | ZO | NS | NS | NM | NM |
| PM   | PS | ZO | NS | NM | NM | NM | PB |
| PB   | ZO | ZO | NM | NM | NM | NB | NB |

Table 2. KI control parameter fuzzy rule table.

| $ec$ | NB | NM | NS | ZO | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| $e$  |
| NB   | NB | NB | NM | NM | NS | ZO | ZO |
| NM   | NB | NB | NM | NS | NS | ZO | ZO |
| NS   | NB | NM | NS | NS | ZO | PS | PS |
According to the fuzzy rule table of the three control parameters p, I and D shown in the above table, the fuzzy interval corresponding to the three control parameters p, I and D is obtained. Then, the fuzzy values of the P, I, d control parameters are obtained after the fuzzy reasoning as shown below.

**Table 3.** KD control parameter fuzzy rule table.

| e | ec | NB | NM | NS | ZO | PS | PM | PB |
|---|----|----|----|----|----|----|----|----|
| NB | PS | NS | NB | NB | NB | NM | PS |
| NM | PS | NS | NB | NM | NM | NS | ZO |
| NS | ZO | NS | NM | NM | NS | NS | ZO |
| ZO | ZO | NS | NS | NS | NS | NS | ZO |
| PS | ZO | ZO | ZO | ZO | ZO | ZO | ZO |
| PM | PB | NS | PS | PS | PS | PS | PB |
| PB | PB | PM | PM | PM | PS | PS | PB |

**Figure 3.** Schematic diagram of fuzzy reasoning mechanism.

### 2.3. Clarity

The fuzzy decision-making link is the last link of fuzzy control. The fuzzy values of P, I, d control parameters are obtained by the fuzzy decision-making link. After the fuzzy value is fuzzy, the final real value for PID online adjustment is obtained. Clarity is similar to fuzzy quantification and belongs to the reverse operation of fuzzy quantification. The membership function relationship of PID control parameters is shown in the figure below.
3. Improved Fuzzy Adaptive PID Control

Through the analysis, it is found that the actual output error $E$ and error change rate $EC$ of the phase-shifting full bridge digital power supply are difficult to predict due to the nonlinear, time-varying and high-frequency switching characteristics of the system. According to the fixed quantification factor set by experience, it is impossible to complete the mapping from the output domain to the fuzzy domain, and the input information of the fuzzy control will be partially lost, resulting in the lack of control the system output fluctuates with constant amplitude for a long time. Therefore, in this paper, the on-line adjustment function of quantification factor of error and error change rate will be introduced to construct fuzzy adaptive PID control with adaptive quantification.

3.1. Online Adjustment Function of Error quantification Factor

Considering the system output characteristics of the phase-shifting full bridge digital power supply, the control function idea of bang bang algorithm is combined in the function design from the actual error range to the quantification factor $K_e$ of fuzzy universe. When the current error value is larger than the boundary value of the fuzzy universe range, the quantification factor decreases with the increase of the current error value, and is constant due to the size of the sampling time itself. When the error value is near the steady-state stage, the quantification of error $e(k)$ should increase with the increase of error $e(k)$, and the inverse ratio between the domain boundary value and the quantification factor should be considered. To sum up, the online adjustment function of quantification factor of fuzzy control input error $e(k)$ as shown in the following formula is established.

$$K_e = \begin{cases} \frac{t_s}{e(k)}; & e(k) > M \\ \frac{e(k)}{L}; & L < e(k) < M \\ \end{cases}$$

(3)

where $M$ and $L$ are the upper and lower boundaries of the universe respectively, and $t_s$ is the sampling interval. The improved quantification factor of fuzzy error is shown in the following formula.

$$E = e / K_e$$

(4)

3.2. Online Adjustment Function of quantification Factor of Error Change Rate

It is found that the actual output value of the system is obtained by discrete sampling. According to Xiangnong theorem, the sampling frequency is greater than the switching period. The switching frequency of phase-shifting full bridge with high-frequency switch is more than 100kHz. Therefore, the sampling time interval is short. Combined with the fluctuation of phase-shifting digital power supply error analyzed above, the error change rate $e(k)$ actually ranges to the fuzzy universe the quantification of mapping $ec(k)$ faces the same problem. Compared with the quantification of error, the quantification of error change rate is more affected by the change of sampling time, current error and last error.
Therefore, the design of online adjustment function of quantification factor of error change rate mainly considers the error change rate and sampling time at the current moment. Among them, the quantification factor \( K_{ec} \) should be inversely proportional to the error rate of change, and the number of sampling time is small, so it can be set as a proportional constant to reduce the quantification factor of error change rate in equal proportion. To sum up, the online adjustment function of quantification factor of fuzzy control input error change rate is established as follows.

\[
K_{ec} = \frac{t_s}{(e(k) - e(k-1)) + t_s}
\]

(5)

Where \( t_s \) is the sampling interval, and the quantification factor of the fuzzy error change rate after improvement is expressed in the following formula:

\[
EC = \frac{ec}{K_{ec}}
\]

(6)

4. Simulation and Analysis

In order to ensure the validity of the results, this paper uses the transfer function of the small signal dynamic model of the phase-shifting full bridge digital power supply in reference [10] to construct the small signal disturbance dynamic model from the control signal (duty cycle) to the output signal (output voltage), and transform it as shown in (7) below, and obtain the discrete transfer function as shown in (8).

\[
G_{vd} = \frac{2.073 \times 10^{10}}{s^2 + 1.059 \times 10^5 s + 1.587 \times 10^9}
\]

(7)

\[
G(z) = \frac{11.5z^2 + 23z + 11.5}{z^2 + 1.765z + 0.765}
\]

(8)

Based on the transfer function of the small signal dynamic model of the phase-shifting full bridge digital power supply shown in the above formula, and taking \( P = 0.028 \), \( I = 0.008 \) and \( d = 0 \) as the initial parameters of fuzzy adaptive PID, the traditional PID control, the traditional fuzzy PID control and the phase-shifting full bridge digital power supply with fuzzy quantification factor online adjusted are simulated and verified in MATLAB. The simulation results are shown in the following figure.

Figure 5. Comparison of output response under step signal.
The overshoot of the phase-shifting full bridge digital power supply with traditional PID control is about 40% under the step response, and the adjustment time is about 0.8s, and there is high-frequency oscillation before reaching the steady state; the overshoot of the phase-shifting full bridge digital power supply using fuzzy PID control is about 10% under the step response, and the adjustment time is about 0.15s, and there is high-frequency and constant amplitude oscillation before the steady-state is reached. The phase-shift full bridge digital power supply of the improved fuzzy PID control has almost no overshoot under the step response, and the adjustment time is about 0.1s. The simulation results are compared as follows.

**Table 4. Comparison of simulation results.**

| Control Strategy                        | Overshoot (\( \sigma \% \)) | Adjustment Time (s) | Dynamic Process Description                                      |
|-----------------------------------------|-------------------------------|---------------------|------------------------------------------------------------------|
| PID                                     | 40%                           | 0.80s               | There is a high frequency oscillation before entering the steady state |
| Fuzzy PID                               | 10%                           | 0.15s               | There is a high frequency oscillation before entering the steady state |
| Improved fuzzy PID with quantification factor | No overshoot                  | 0.08s               | There is no high frequency oscillation in the whole process        |

5. Conclusion

Fuzzy adaptive PID control is a kind of nonlinear control strategy which is easy to realize but depends on the subjective experience of the designer. It is widely used in various fields. In the application of high-power phase-shifting full bridge digital power supply, it is difficult to adjust the dynamic performance of system output by traditional fuzzy adaptive PID control prediction because of its large amplitude and difficult to predict. This paper analyzes the control process of fuzzy adaptive PID, and introduces the online adjustment function of fuzzy quantification factor on the basis of traditional fuzzy adaptive PID control. Flexible scaling from the actual output range to the fuzzy quantification interval. Based on the standard small signal disturbance model of phase-shifting full bridge digital power supply, the dynamic performance of traditional PID, traditional fuzzy PID and improved fuzzy PID with quantification factor are simulated respectively, which proves the effectiveness of the improved method proposed in this paper.

**References**

[1] Zeng X, Yan F, Pan Y, et al. 2020 Proportioning control system for zinc pyrometallurgy based on Fuzzy PID algorithm *Metallurgical Automation* 2020 1-11

[2] Zhou Y, Zhuang Y 2020 Application of particle swarm optimization fuzzy PID control algorithm in greenhouse *Computer Measurement and Control* 28(08) 116-9

[3] Hu B, Ying H 2001 Review of research and development of fuzzy PID control technology and some important problems it faces *Acta automatica Sinica* 27(4) 567-84

[4] Wang J 2012 Research on phase shifted full bridge soft switching DC-DC converter (Harbin, China: Harbin Engineering University)

[5] Jiang Q, Zeng W, Yu T, et al. 2020 Core power control of molten salt reactor based on Variable Universe Fuzzy PID *Nuclear Power Engineering* 41(02) 109-13

[6] Qu X, Wang X, Sun H, et al. 2019 Fuzzy adaptive PID control for heating system of FDM 3D printer *Journal of Jilin University (Engineering Edition)* 2019 1-10

[7] Liu X, Ji Z, Niu G et al. 2009 Design of aviation DC / DC converter based on Predictive Fuzzy PID control *Electrical Measurement and Instrumentation* 46(7) 66-9

[8] Ibrahim O, Yahaya N Z, Saad N, etal. 2017 Design and simulation of phase-shifted full
bridge converter for hybrid energy systems International Conference on Intelligent & Advanced. IOP Conference Series:Materials Science and Engineering (2017.6.23. Bangalore)

[9] Murali J K, Chandrasekar V, Udaya S V, et al. 2017 Analysis, estimation and minimization of power loss in CCM operated PSFB converter, IEEE International Conference on Power Electronics, Drives and Energy Systems. (2016.12.01 India)

[10] Liu Y 2019 Design of numerical control switching power supply based on STM32 [D]. Power electronics and power transmission (Xi’an, China: Xi’an University of Science and Technology)