Research on PMSM Speed Control System Based on Adaptive Fuzzy Control

Shengjian Liu¹*, Jianmin Wang² and Zhiyuan Zheng²
¹Harbin University of Science and Technology, Harbin, China
²Harbin University of Science and Technology, Harbin, China

*Corresponding author e-mail: 1261387616@qq.com

Abstract. PMSM servo system has nonlinear, parameter time-varying, load disturbance and other issues. In the face of these problems, traditional PI control strategies often fail to achieve ideal parameter tracking and load immunity, showing a large degree of limitations. Aiming at this kind of problem, this paper designs a fuzzy PI control method combining PI control and fuzzy control, and uses the vector rotation control method of current speed double closed loop to drive the permanent magnet synchronous motor for control. Finally, the traditional PI control system and fuzzy PI control system simulation model are built in Matlab/Simulink environment. The simulations were carried out in three cases of high speed, medium speed and low speed, and the speed and current waveforms of the two control methods were observed. The simulation results show that the fuzzy PI control system can increase the response rate, reduce the overshoot of the speed and reduce the current fluctuation in the full speed range. The robustness of the system is improved, the adaptability of the system to load changes is enhanced, and the correctness of the theoretical analysis is verified.

1. Introduction

Permanent magnet synchronous motor (PMSM) is widely used in many fields because of its small size, simple structure, wide speed range, etc. However, the control technology of permanent magnet synchronous motor has always been difficult to break through. Traditional PI control The permanent magnet synchronous motor is controlled to a certain extent. Due to its low control precision, slow rotational speed response, large torque ripple, etc., it is difficult to overcome the shortcomings of strong coupling and nonlinearity of permanent magnet synchronous motor, and fuzzy PI control can implement adjustment of PI parameters. The control precision is high; there are better static and dynamic characteristics.

Many documents introduce the fuzzy control system of permanent magnet synchronous motor. In [1], the fuzzy control system of permanent magnet synchronous motor is designed, and the complete fuzzy control rules are developed. The problem of large torque ripple of conventional PID control system is solved, but the rotational speed response is not obvious. The literature [2] designed a kind of research on the control method of permanent magnet synchronous motor based on fuzzy PID controller realizes the control precision and speed regulation effect under ideal conditions, but does not consider the nonlinear situation in reality. The literature [3] proposes a permanent magnet synchronization. The motor vector control method realizes the control of the motor, but the stability of the system is slightly poor, and the rotational speed fluctuates greatly. The motor control system based on STM32 single-chip microcomputer is designed in the literature [4]. The system is robust, but the
realization process. It is too complicated and not suitable for practical application; the literature [5] proposes a control method for permanent magnet synchronous motor, which has high speed control precision, but the torque is obviously shifted; the literature [6] designed the permanent magnet synchronous motor speed servo system. The robust controller achieves good motor control, but the speed response is insufficient.

Aiming at the control method of permanent magnet synchronous motor, this paper proposes a fuzzy PI and vector transformation control method to simulate the operation of permanent magnet synchronous motor in non-ideal state, and measure its speed and torque. Through the MATLAB simulation analysis, the proposed control method is compared with the traditional PID control, and the simulation curve and the implementation data are compared. Experiments show that the control method reduces the time for the motor to accelerate to a given speed; reduces the torque ripple; effectively improves the speed control accuracy; solves the problem of large speed overshoot, long acceleration time, and anti-interference in the traditional PID control method. Weak ability and other issues.

2. Mathematical Model Analysis of Permanent Magnet Synchronous Motor

The voltage equation of a permanent magnet synchronous motor in a three-phase ABC coordinate system:

\[
u_\alpha = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \\ i_\gamma \end{bmatrix} + \begin{bmatrix} \phi_\alpha \\ \phi_\beta \\ \phi_\gamma \end{bmatrix}
\]

(1)

Where \(u_\alpha, u_\beta,\) and \(u_\gamma\) are three-phase voltages, \(i_\alpha, i_\beta,\) and \(i_\gamma\) are three-phase currents, \(R_s\) is a rotor resistance, and \(\phi_\alpha, \phi_\beta,\) and \(\phi_\gamma\) are three-phase flux linkages. The flux linkage equation is:

\[
\begin{bmatrix} \phi_\alpha \\ \phi_\beta \\ \phi_\gamma \end{bmatrix} = \begin{bmatrix} L_{aa} & M_{ab} & M_{ac} \\ M_{ba} & L_{bb} & M_{bc} \\ M_{ca} & M_{cb} & L_{cc} \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \\ i_\gamma \end{bmatrix} + \begin{bmatrix} \cos \theta \\ \cos(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) \end{bmatrix}
\]

(2)

\(L_{aa}, L_{bb}, L_{cc}\) are the mutual inductance of the three-phase winding, \(M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca}, M_{cb}\) are the mutual inductance between the windings, and the mutual inductance is equal, \(\phi_f\) is the permanent magnet rotor flux, \(\theta\) is the rotor magnetic pole \(N\) The angle between the pole and the A-phase winding. Torque equation:

\[
T_e = \frac{1}{2} P_n \frac{\partial}{\partial \theta_m} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_\gamma \end{bmatrix}^T \begin{bmatrix} \phi_\alpha \\ \phi_\beta \\ \phi_\gamma \end{bmatrix}
\]

(3)

\(P_n\) is the pole number of the motor and \(\theta_m\) is the mechanical displacement of the rotor of the motor.

3. Fuzzy control vector control strategy

3.1. PMSM fuzzy control strategy

The traditional PID has the characteristics of simple stability and high reliability. When the precise mathematical model of the control object is established, the PID controller can achieve its function as long as the parameters \(K_p, K_i\) and \(K_d\) are correctly set, but there are disadvantages in the design that the dynamic response and the overshooting technical index are difficult to be compatible. And because the motor has nonlinear, time-varying and other uncertain factors, the PID control effect is difficult to achieve the expected goal. Although there are optimal PID, such as optimal PID, nonlinear PID and adaptive PID, but fundamentally, the optimization of PID parameters is a compromise between proportional, integral and differential control effects and interference. The trade-off between the tuning and the target value tracking is suppressed, so the tuning parameters are not optimal. That is to say, the PID controller uses different PID parameters for different objects, and the adjustment is inconvenient, the anti-interference ability is poor, and the overshoot is large. Fuzzy control is a kind of language control, which does not depend on the mathematical model of the controlled object. The design algorithm is simple and easy to implement. It can be directly obtained from the operator's experience and optimization, and has good adaptability, strong anti-interference ability and robustness. Good sex. However, fuzzy control also has its limitations and shortcomings. This is because its control function can only be processed according to the file. Generally, when the deviation of the linguistic variable tends to zero, there is oscillation; while the traditional PID control can improve the precision
of the control and eliminate it. Steady-state error. Therefore, this paper proposes to combine the
traditional control method with the fuzzy control technology, combine its advantages, overcome each
other's shortcomings, and form a composite controller, namely fuzzy PID controller. The block
diagram of the fuzzy control system is shown in Fig. 1.

![Figure 1. Fuzzy control system block diagram.](image)

This design uses a composite fuzzy PID controller, namely Fuzzy-PID controller. The control
system block diagram composed of it is shown in Fig. 2. According to different conditions and
requirements, the segmentation is controlled by different modes, that is, when the error is greater than
When a threshold is reached, the switch is transferred to the fuzzy control to improve the response
speed of the system and speed up the response process. When the error is less than a certain threshold,
the switch is transferred to the PID control to eliminate the static error and improve the control
accuracy.

![Figure 2. Fuzzy-PID system control block diagram.](image)

3.2. Fuzzy controller design

The fuzzy PID controller is mainly composed of two parts: a fuzzy controller and a PID controller.
PID control is a widely used control strategy in the industry, and the design method of PID controller
is very mature. This section mainly introduces the design of the fuzzy controller of the brushless DC
motor.

3.2.1. Fuzzy controller structure design. This design mainly completes the speed control of PMSM.
Combined with the effect and realization of fuzzy control, the 2D fuzzy controller is selected to select
the change rate of motor speed and speed as the input precision of the fuzzy controller:

\[
e_k = w_k - w_{k-1}
\]  \( (4) \)

\[
\Delta e_k = e_k - e_{k-1}
\]  \( (5) \)

Among them, \( e_k \) and \( \Delta e_k \) are the deviation of the rotation speed and the rate of change of the
deviation at time \( t=k \), respectively. As shown in Fig. 3, it is a classic two-dimensional control model.
The error \( e \) of the system and the error rate of change \( \Delta e \) are taken as inputs, and then multiplied by
the input quantization factors \( K_e, K_{ec} \) and sent to the input of the controller. The two input quantities
input to the controller are subjected to fuzzy inference to obtain an output fuzzy set, and then
multiplied by the output quantization factors $K_{pu}$ and $K_{iu}$ after defuzzification, and finally the two output quantities $\Delta K_p$, $\Delta K_i$ will be obtained, and finally result is added to the period amount $K_p$, $K_i$. Through the above several steps, the PI parameter adjustment can be finally realized, and finally the new $I_{ref}$ value is calculated to realize the control of the motor.

**Figure 3.** Fuzzy-PID two-dimensional control model.

3.2.2. Fuzzy controller structure design. Considering that the deviation of the rotational speed and the rate of change of the deviation will change in both positive and negative directions, and considering the "zero" state, adopt "Negative Big" (NB), "Negative Medium" (NM), and "Negative Small" (NS), "Zero" (Z), "Posedge Small" (PS), "Posedge Medium" (PM), "Posedge Big" (PB) 7 language values. The method of quantifying the input and output quantities to the fuzzy domain. This design adopts the standardized design method proposed by Mamdani, that is, the fuzzy domain of the variation $e$ and the variation of the deviation $\Delta e$ is set to $[6, +6]$ and discretized. Constructs a discrete set of 13 integer elements: $\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$. Since the controller output has no negative value, it is quantized to $\{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\}$.

The range of the deviation $e$: $e = [-e_{max}, e_{max}]$, which corresponds to the fuzzy domain:

$E=\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$;

The range of variation $\Delta e$ of the deviation: $\Delta e = [-\Delta e_{max}, \Delta e_{max}]$, which corresponds to the fuzzy domain:

$EC=\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$;

Then the quantization factors are:

$$K_e = \frac{6}{e_{max}} \quad (6)$$

$$Kec = \frac{6}{\Delta e_{max}} \quad (7)$$

3.2.3. Establishment of membership function. Fundamentally, membership functions are used to represent fuzzy sets, and membership functions have three forms. Among them, the triangle membership function expression is easy to obtain, and it is very convenient to implement, so this paper uses the triangle membership function to represent the fuzzy set of input and output variables, as shown in Fig 4:

**Figure 4.** Membership function of input and output variables.
The fuzzy logic decision is synthesized by max-min of Mamdani algorithm, and the direct product is calculated by the fuzzy set of error $e$ and error change rate $ec$. The result is fuzzy vector product operation with fuzzy operator to obtain the control output of the system.

3.2.4. Establishment of control rules. The fuzzy rule table and the surface model of the $\Delta kp$ setting are as shown in Table 1 and Fig.5, and the fuzzy rule table and the surface model of the $\Delta ki$ setting are shown in Table 2 and Fig.6. When the response rises, $kp$ needs to be increased to speed up the response process, but when the response overshoots, $kp$ needs to be reduced to increase the system damping, so that the response quickly enters the steady state; when the rotational speed error is large, $ki$ can take To be 0, as the error decreases, $ki$ will gradually increase to eliminate the system static difference. For parameter tuning, the response and relationship of the two parameters must be considered comprehensively. The fuzzy rules are used to perform fuzzy reasoning, and the fuzzy matrix table is queried for parameter adjustment.

### Table 1. $\Delta kp$ fuzzy rule table.

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

### Table 2. $\Delta ki$ fuzzy rule table.

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

### Figure 5. Kp surface model. 

### Figure 6. Ki surface model.

3.2.5. Fuzzy quantity defuzzification. In the paper, the anti-fuzzification method uses the smoother center of gravity method. The method calculates the weighted average of each element in the fuzzy output and its corresponding membership degree, and rounds it up to obtain the accurate output control quantity. as follows:

$$
\Delta u(t) = \frac{\sum_{k=1}^{n} b_k \int_{\Delta u} u'_k(\Delta u)d\Delta u}{\sum_{k=1}^{n} \int_{\Delta u} u'_k(\Delta u)d\Delta u} \tag{8}
$$

Where $u(t)$ is the output of the defuzzification, where $n$ is the total number of rules of the fuzzy controller, which is the area center corresponding to the output membership function, and is the area enclosed by the output membership function.
4. Simulation Analysis of Matlab/Simulink for PMSM Control System

4.1. PMSM model construction.

In order to verify the control effect of the fuzzy control system described above on the permanent magnet synchronous motor, the fuzzy PI control system and the traditional PI control system are respectively constructed in Matlab/Simulink for simulation comparison. The system simulation structure is shown in Fig.7, Fig.8 It is the block diagram of fuzzy control structure: First, the system parameters of PMSM selected in this paper are shown in Table 3:

| Parameter       | Numerical value |
|-----------------|-----------------|
| Number of pole Pairs | 2              |
| Rated Current I  | 5A              |
| Rated Voltage U  | 24V             |
| Rated Speed n    | 1000r/min       |
| Rated Torque T   | 10N·m           |

**Table 3. PMSM model parameters.**

![Figure 7. Conventional PID Control system structure diagram.](image)

![Figure 8. Fuzzy Control chart.](image)

4.2. Simulation results

The motor is operated with torque T=5N·m, and t=0.2s for sudden load T=15N·m. Fig. 9-11 shows the waveforms of the traditional PI adjustment and fuzzy PI adjustment for the motor when the motor speed is n=500r/min, 1000r/min, 1500r/min.

![Figure 9. Speed waveform of 500r/min under Traditional PI Conditions and Fuzzy PI Condition.](image)
When the motor is running at 500r/min, it can be seen from the waveform of the speed. Under the traditional PI control, the motor overshoot has reached 20%, and when t=0.2s suddenly increases the load, the speed fluctuation reaches 7.6%. That is, the rotational speed drops by nearly 40r/min, and it can be clearly seen in the figure that the time taken for the rotational speed to decrease from the beginning to the return to the speed before the fall is relatively long. There is a slight fluctuation in the speed during steady operation. Observing the waveform 7 under fuzzy control, we can see that the first time is only 4.8% in overshoot, and at t=0.2s, the speed will only be about 1%, and it will return to 500r/min in a short time. It can be seen from the above analysis that when the counter electrode is controlled by the fuzzy PI, the fluctuation of the sudden load is superior to the conventional PI regardless of the overshoot of the rotational speed. For the speed of 1000r/min, 1500r/min, the waveform of the speed under fuzzy control is better than the control of traditional PI.

The motor is operated with torque T=5N·m, and t=0.2s for sudden load T=15N·m. Fig.12-14 shows the current torque waveforms of the conventional PI adjustment and fuzzy PI adjustment for the motor when the motor speed is n=500r/min, 1000r/min, 1500r/min.

When the motor is running at 500r/min, it can be seen from the waveform of the speed. Under the traditional PI control, the motor overshoot has reached 18%, and when t=0.2s suddenly increases the load, the speed fluctuation reaches 5.7%. That is, the rotational speed drops by nearly 35r/min, and it can be clearly seen in the figure that the time taken for the rotational speed to decrease from the beginning to the return to the speed before the fall is relatively long. There is a slight fluctuation in the speed during steady operation. Observing the waveform 7 under fuzzy control, we can see that the first time is only 2.4% in overshoot, and at t=0.2s, the speed will only be about 1%, and it will return to 500r/min in a short time. It can be seen from the above analysis that when the counter electrode is controlled by the fuzzy PI, the fluctuation of the sudden load is superior to the conventional PI regardless of the overshoot of the rotational speed. For the speed of 1000r/min, 1500r/min, the waveform of the speed under fuzzy control is better than the control of traditional PI.

The motor is operated with torque T=5N·m, and t=0.2s for sudden load T=15N·m. Fig.12-14 shows the current torque waveforms of the conventional PI adjustment and fuzzy PI adjustment for the motor when the motor speed is n=500r/min, 1000r/min, 1500r/min.
The analysis of the motor running at 500r/min is carried out. The comparison analysis between Fig. 12 and Figure 14 shows that when the motor is under the traditional PI control, the starting current of the motor is too large (although the relative starting torque is also large, this will The motor speed response is fast. Since the motor is started with a load of T=5N·m, the torque is too high and the speed response will only increase a little). Moreover, the three-phase current waveform of the motor is not sinusoidal, and torque ripple occurs in the current commutation. On the other hand, under the control of the current and torque under the fuzzy PI control, it can be clearly seen that the sinusoidality of the current waveform is smoother, so that the torque ripple of the motor during commutation is weakened or even completely eliminated. For the motor at 1000r/min and 1500r/min, the torque and current waveforms under traditional PI control are worse with the increase of the speed. At 1500r/min, the motor torque is greatly affected by the load. t=0.2s gives the motor a sudden load, and the motor torque will shake for a long time, and the load torque cannot be balanced. Under fuzzy control, the current and torque waveforms are significantly better than the traditional PI control regardless of the motor running at low speed, medium speed and high speed.

5. Conclusion
The Traditional PI Control system and Fuzzy PI Control system simulation model are built in Matlab/simulink environment. The simulations were carried out under three conditions of high speed, medium speed and low speed, and the speed, current and torque waveforms under the two control methods were observed. It can be seen from the simulation results that the fuzzy PI control system can be better in the running performance of the motor at low speed, medium speed or high speed. For the speed, the overshoot is greatly reduced, and the load can be quickly returned after loading. Given the speed. For current and torque, the current waveform is closer to sinusoidal than the conventional PI adjustment over the full speed range, which makes the torque ripple much smaller and makes the motor run more stable. It enhances the system's ability to adapt to load changes and verifies the correctness of theoretical analysis.

References
[1] SUAN TAN, TIM ABRAHAM, DON FERENCE, et al Macosko. Rigid polyurethane foams from a soybean oilbased polyol. [J] Polym,2011,52 (13), 2 840 -2846.
[2] Du Juan, Guo Zhonghua, Ma Huajie, Brushless DC Motor Speed Control System Based on Adaptive Fuzzy PID Control[J]. Electronic Technology and Software Engineering, 2016, (3):139-141.
[3] Li Shihua, GU Hao, Fuzzy Adaptive Internal Model Control Schemes for PMSM Speed-Regulation System [J]. IEEE Transactions on Industrial Informatics,2012,8(4):767-779.
[4] Huang Ping, Wang Ying, Jiang Xianzhi. DC motor fuzzy-PID control system based on STM32[J]. Mechatronic Engineering,2017,34(4):380-385.
[5] LAI C K, SHYU KK. A novel motor drive design for incremental motion system via sliding-mode control method [J]. IEEE Transactions on Industrial Electronics,2005,52(2):499-507.
[6] Du Xue. Research on Direct torque Control algorithm for permanent Magnet synchronous Motor[D]. Hebei University of Science and Technology,2018.