

Research on Permanent Magnet Synchronous Motor Speed Control System Based on Three-Order Linear Active Disturbance Rejection Controller

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Abstract. Linear active disturbance rejection control (three-order LESO+PD control) and fuzzy PID control strategies are used to simulate the same permanent magnet synchronous motor with variable speed (constant load) and variable load (constant speed), by observing and analyzing the oscilloscope waveform data and waveform changes in Matlab/Simulink, we can compare the control performance of the two control algorithms under different conditions. By comparing the waveform changes of the oscilloscope, it is found that LADRC has more advantages in real-time than fuzzy PID, and the fluctuation is smaller after stabilization. However, the linear auto disturbance rejection control algorithm is more likely to cause overshoot, and it is not as easy to master as fuzzy PID in parameter adjustment. The two control algorithms have their own advantages and disadvantages.

Keywords: permanent magnet synchronous motor, linear active disturbance rejection control, linear state observer, fuzzy PID control.

1 Introduction

Permanent magnet synchronous motors (PMSM) are widely used in robots, electric vehicles and machine tools, low-power applications and high-performance drives¹, and have begun to replace brush motors in various application fields. However, the mathematical model of permanent magnet synchronous motor (PMSM) is nonlinear, multivariable and strong coupling², so it is not easy to achieve accurate control. We would like to draw your attention to the fact that it is not possible to modify a paper in any way, once it has been published. This applies to both the printed book and the online version of the publication.

In order to achieve excellent control of permanent magnet synchronous motor (PMSM), because of its weak adaptability to changeable environment and low control precision, many scholars and engineers are constantly exploring control algorithms with more accurate control accuracy and stronger anti-disturbance ability. With the enhancement of the depth and breadth of theoretical analysis, today's PID has become more and more intelligent. At present, the more common intelligent PID control includes fuzzy PID, neural network PID, particle swarm fuzzy PID, etc.^{3,4,5}. Professor Han Jingqing of the Chinese Academy of Sciences started from the principle of traditional PID in the late 1980s, analyzed its advantages and disadvantages theoretically, combined with modern control theory, combined tracking differentiator (TD), extended state observer (ESO), nonlinear State Error Feedback Control Rate (NLSEF) combines a new type of controller-Active Disturbance Rejection Controller (ADRC)⁶. The algorithm proposed by Professor Han Jingqing attracted a large number of scholars' onlookers and research. Active disturbance rejection control absorbs the essence of classic control theory and combines it with modern control theory. The total disturbance is estimated in real time through ESO and eliminated by NLSEF, thereby enhancing the anti-disturbance ability of the system⁷. However, because ADRC itself needs to adjust many parameters, if some parameters are not adjusted well, the control effect is not as good as traditional PID control, and thus it has not been highly recognized by the engineering community. Based on the theory proposed by Professor Han Jingqing, Dr. Gao zhiqiang transformed nonlinear active disturbance rejection control (ADRC) into linear Active disturbance rejection control (LADRC), thus simplifying the technique of active disturbance rejection control (ADRC). The basic idea is: 1. Linearize ESO to simplify the design of ESO; 2. Linearize NLSEF and use a simple PD combination to replace the previous NLSEF⁸. This makes the design of the control system

simple and intuitive, the controller parameters are greatly reduced to three, and the anti-disturbance performance is not worse than the performance of the control algorithm proposed by Professor Han Jingqing, which is becoming a hot spot in engineering applications.

In this paper, through analysis and mathematical modeling of permanent magnet synchronous motor, the ideal stator voltage equation of permanent magnet synchronous motor under d-q axis is obtained. According to the characteristics of the motor, the third-order linear active disturbance rejection control algorithm and the fuzzy PID control algorithm are designed respectively, and the algorithm model is built in Matlab/Simulink. By observing and analyzing the oscilloscope waveform data and waveform changes in Matlab/Simulink, the advantages and disadvantages of the control performance of the two control algorithms under different conditions are compared.

2 PMSM Mathematical Model

Because the permanent magnet synchronous motor system is a complex system, in order to simplify the analysis, in the process of motor simulation, assuming that the PMSM is an ideal type, it is satisfied:

- 1) Ignore the saturation of the motor core;
- 2) The eddy current and hysteresis loss in the motor are negligible;
- 3) The current in the motor is a symmetrical three-phase sine wave current⁹.

In this way, the stator voltage equation of the permanent magnet synchronous motor in the d-q axis coordinate system can be equivalent to the following form:

$$\begin{cases} u_d = Ri_d + \frac{d}{dt}\psi_d - \omega_e\psi_q \\ u_q = Ri_q + \frac{d}{dt}\psi_q + \omega_e\psi_d \end{cases} \quad (1)$$

The stator flux equation is:

$$\begin{cases} \varphi_d = L_d i_d + \psi_f \\ \varphi_q = L_q i_q \end{cases} \quad (2)$$

Substituting equation (2) into equation (1), the stator voltage equation can be obtained as:

$$\begin{cases} u_d = Ri_d + L_d \frac{d}{dt}i_d - \omega_e L_q i_q \\ u_q = Ri_q + L_q \frac{d}{dt}i_q + \omega_e (L_d i_d + \psi_f) \end{cases} \quad (3)$$

where u_d and u_q are the d-q axis components of the stator voltage respectively; i_d and i_q are the d-q axis components of the stator current respectively; R is the stator resistance; φ_d and φ_q are the d-q axis components of the stator flux linkage; ω_e is the electrical angular velocity; L_d and L_q are the d-q inductance components respectively; ψ_f represents the permanent magnet flux linkage.

The electromagnetic torque equation at this time can be written as:

$$T_e = \frac{3}{2} p_n i_q [i_d (L_d - L_q) + \psi_f] \quad (4)$$

In addition, in the process of building the motor model, we should pay attention to:

$$\begin{cases} \omega_e = n_p \omega_m \\ N_r = \frac{30}{\pi} \omega_m \\ \theta_e = \int \omega_e dt \end{cases} \quad (5)$$

wherein, ω_m is the mechanical angular velocity of the motor, the unit is rad /s; N_r is the speed of the motor, and the unit is r /min.

3 Controller Design

3.1 The Design of Linear Active Disturbance Rejection Controller

The basic structure of LADRC is shown in Figure 1. LADRC is mainly composed of two parts: Linear State Observer (LESO) and Proportional Derivative (PD) linear combination control law.

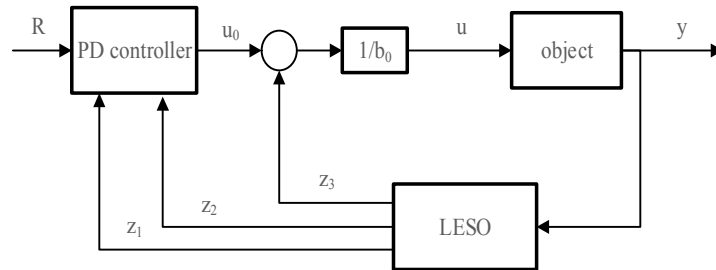


Figure 1. Basic structure of LADRC

Taking the second-order system as an example, the controlled object can be expressed in the following form:

$$\ddot{y} = f(y, \dot{y}, w, t) + bu = -a_1\dot{y} - a_0y + w + bu \tag{6}$$

where y and u are the output and input of the system, and w is the disturbance. a_0, a_1, w are unknown, part b is known (known part is b_0), then (6) can be written as:

$$\ddot{y} = f(y, \dot{y}, w, t) + bu = -a_1\dot{y} - a_0y + w + (b - b_0)u + b_0u = f + b_0u \tag{7}$$

where $f = -a_1\dot{y} - a_0y + w + (b - b_0)u$ is the total disturbance, and the total disturbance includes internal disturbance and external disturbance.

Select state variables:

$$\begin{cases} x_1 = y \\ x_2 = \dot{y} \\ x_3 = f \end{cases} \tag{8}$$

Then the expanded state space of equation (2-2) can be written as:

$$\begin{cases} \dot{x} = Ax + Bu + Ef \\ y = Cx + Du \end{cases} \tag{9}$$

among them

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, D = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, C = [1 \ 0 \ 0]$$

Since f can be estimated according to the correction term, f_0 can be omitted, and the linear extended state observer obtained according to equation (9) is

$$\begin{cases} \dot{z} = [A - LC]z + [B, L]u_c \\ y_c = z \end{cases} \tag{10}$$

where z is the state vector of the observer, and L is the observer error feedback gain matrix, $u_c = [u, t]^T$ is the combined input. y_c is the output, in order to put the poles of the characteristic equation at the same position so that¹⁰

$$\lambda(s) = |sI - (A - LC)| = (s + \omega_0)^3$$

select the gain matrix of the observer $L = [3\omega_0 \ 3\omega_0^2 \ \omega_0^3]$.

Another component of LADRC is the linear error feedback control law (LSEF). Since ESO can estimate and compensate the total disturbance in real time, LESO can be further simplified to the PD combination design, and the integrator in the traditional PID design can be omitted. Therefore, for the second-order system, the form of PD controller used by LDRC is

$$u_0 = k_p (r - z_1) - k_d z_2 \tag{11}$$

Among them, r is the reference value (system setting value), z_1 and z_2 are the states of the LESO observer, and k_p and k_d are the proportional and integral amplification factors in the PD controller, respectively. The model designed this time adopts the LESO of the first order. In this way, in order to make the transfer function of a second-order system without zeros and only poles:

$$s^2 + k_d s + k_p = 0 \tag{12}$$

So we can choose $k_p = w_c^2$, $k_d = 2w_c$, where w_c is the controller bandwidth.

According to the mathematical model of LESO and PD controller, the simulation model of LADRC can be built in Matlab/Simulink as shown in Figure 2:

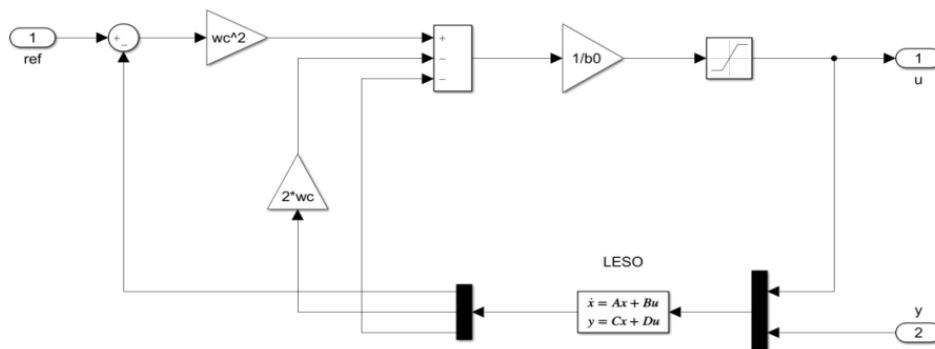


Figure 2. Third-order LADRC Matlab/Simulink simulation model

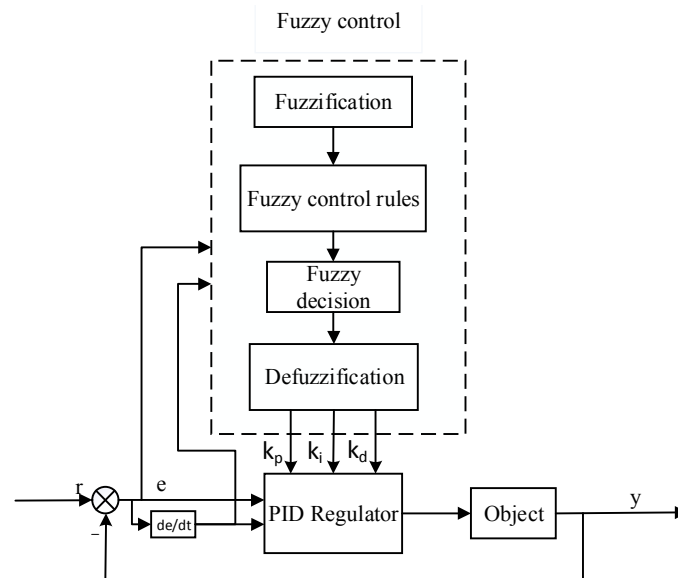


Figure 3. Block diagram of fuzzy PID structure

3.2 Fuzzy PID Controller Design

The fuzzy PID controller is a combination of the PID controller and the fuzzy controller. The input of the fuzzy controller is the deviation e and the deviation change rate e_c . The input is fuzzy, fuzzy

judgment, and de-fuzzy, and finally k_p, k_i, k_d Output, so as to realize real-time modification of PID parameters. Because the three parameters (k_p, k_i, k_d) in the fuzzy PID controller change in real time according to the change of the control environment, it can meet the control requirements under different conditions¹¹. The block diagram of the fuzzy PID controller is shown in Figure 3, where e is the system deviation, which represents the difference between input r and output y , the expressions of $k_p, k_i,$ and k_d are as follows:

$$\begin{cases} k_p = k_{p0} + \Delta k_p \\ k_i = k_{i0} + \Delta k_i \\ k_d = k_{d0} + \Delta k_d \end{cases} \quad (13)$$

When designing a fuzzy PID, the first thing to determine is the structure of the fuzzy controller, the fuzzy processing of input and output parameters, where the input is the error e and the error change rate e_c , and the output is $k_p, k_i,$ and k_d .

The language value of input and output and the choice of membership function are shown in Figure 4 and Figure 5 below:

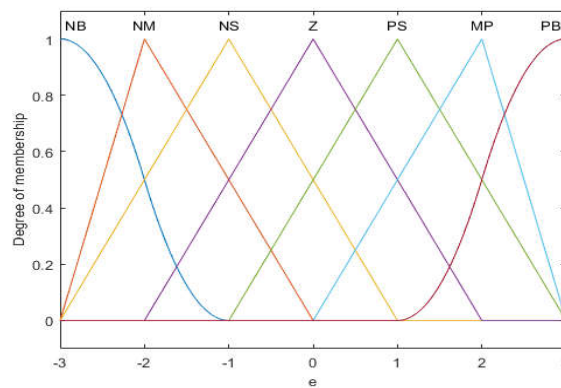


Figure 4. Linguistic value and membership degree of e and e_c

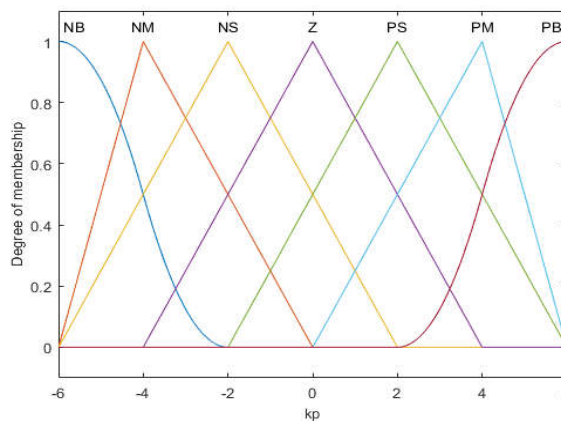


Figure 5. Linguistic value and membership degree of PID parameters

Fuzzy rule is a control rule condensed after a large amount of control strategies and control experience are refined. Each fuzzy conditional statement gives a control rule. The control rules in the fuzzy controller this time use Mamdani control rules, and a total of $7 \times 7 = 49$ rules are formulated. The fuzzy rules of $\Delta K_p, \Delta K_i$ and ΔK_d are shown in Table 1~Table 3.

Table 1. Fuzzy rule table of ΔK_p

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

Table 2. Fuzzy rule table of ΔK_i

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

Table 3. Fuzzy rule table of ΔK_d

| e | e_c | | | | | | |
|-----|-------|----|----|----|----|----|----|
| | 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 |

The output of the fuzzy controller is a fuzzy set, and a de-fuzzy method needs to be used to determine an exact output. The "area halving method" is used in this article¹². Use Simulink tools to establish a system simulation model composed of fuzzy controllers as shown in Figure 6 below:

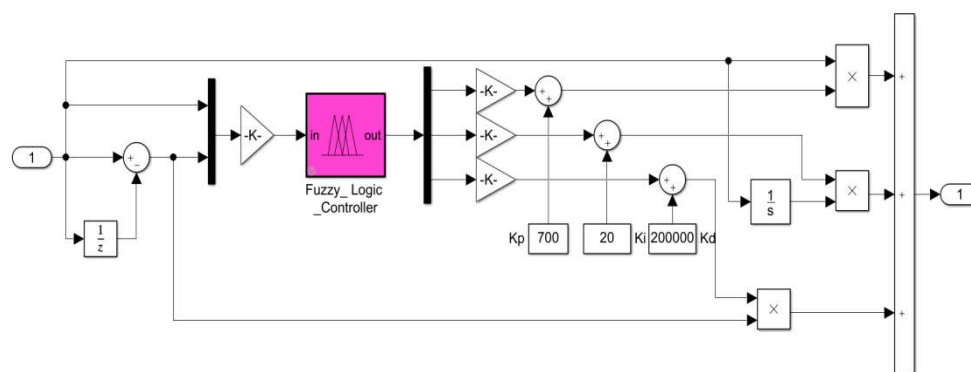


Figure 6. Fuzzy PID controller simulation model

4 Simulation Research

Through the simulation in Matlab/Simulink, we can get the speed control effect of the two controller schemes in PMSM. The parameter configuration of the permanent magnet synchronous motor model selected in this simulation is shown in Table 4.

Table 4. Fuzzy rule table of ΔK_d

| Parameter | Parameter Value |
|---|-----------------|
| Phase | 3 |
| Back EMF waveform | Sine wave |
| Stator resistance R/Ω | Salient |
| L_d/mH | 0.25 |
| D phase winding inductance (L_q/mH) | 0.00545 |
| Permanent magnet flux (Ψ/Wb) | 0.00635 |
| Number of motor pole pairs | 4 |
| Moment of inertia $J/(Kg \cdot m^2)$ | 0.005 |

In order to compare the LADRC controller and the fuzzy PID controller, simulations were carried out under three conditions. The total simulation time is 0.5s, and the simulation settings are as follows:

- (1) 0-0.2s, at 0s, given a step Signal, set the initial target speed to 400r/min, the motor is no-load, and the load is 0N.
- (2) 0.2-0.4s, at 0.2s, add a 10N load to the motor, and the target speed remains 400r/min. The simulation waveform verifies the anti-load disturbance ability of the two control algorithms.
- (3) 0.4-0.5s, at 0.4s, the target speed changes from 400r/min to 200r/min, and the load is still 10N.

The simulation results using LADRC controller and fuzzy PID controller are shown in Figure 7 and Figure 8 below:

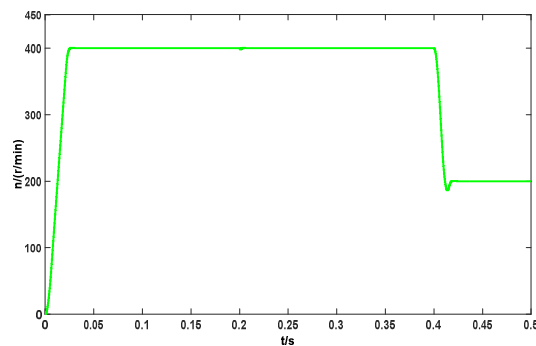


Figure 7. Simulation results based on LADRC controller

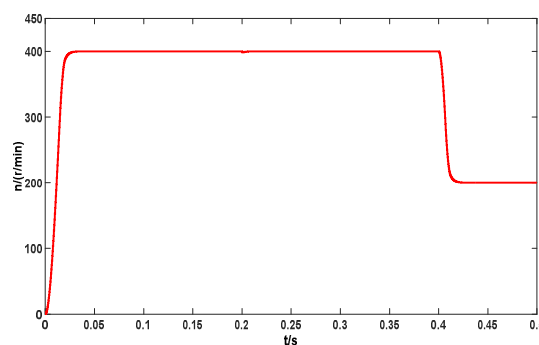


Figure 8. Simulation results based on PID controller

It can be seen from the simulation results:

(1) At 0-0.2s, using LADRC control, the speed is from the initial 0r/min to the steady state 400r/min, the adjustment time is 0.034s, the overshoot is 1r/min, the overshoot is 0.25%, and the maximum torque is 65.5 Nm; When using fuzzy PID control algorithm, the adjustment time is 0.045s, the overshoot is 0.03r/min, the overshoot is 0.0075%, and the maximum torque is 96.78Nm. It can be seen that under no-load conditions, LADRC reaches a stable speed faster, takes less time, and torque fluctuations are smaller, but the overshoot is larger than the fuzzy PID control.

(2) In 0.2-0.4s, suddenly increase the load of 10Nm. When using LADRC control, the minimum speed drops to 398.23rpm, the maximum speed change rate is 0.44%, the adjustment time is 0.011s, and the maximum torque reaches 16.18Nm; When using the fuzzy PID control algorithm, the minimum speed is reduced to 398.32r/min, the maximum speed change rate is 0.42%, the adjustment time is 0.04s, and the maximum torque is 12.5Nm. It can be seen that when the load disturbance is suddenly increased, it takes less time for the LADRC control algorithm to reach the steady state, but the torque and speed change range is larger than that of the fuzzy PID.

(3) In 0.4-0.5s, when the load remains unchanged, the target speed is reduced from 400r/min to 200r/min. When the LADRC controller is used for control, the adjustment time is 0.025s, and the minimum speed is reduced to 186.3r/min, speed change rate is 6.85%; when the fuzzy PID controller is used for control, the adjustment time is 0.04s, the minimum speed is reduced to 199.96r/min, and the speed change rate is 0.02%. It can be seen that when there is a load, the speed drops suddenly, and the adjustment time is shorter when the LADRC control algorithm is used, but the overshoot is larger than the fuzzy PID control algorithm.

5 Conclusion

Due to the poor adaptability of traditional PID and weak anti-disturbance ability, the fuzzy PID control algorithm derived from it with better anti-interference ability greatly improves the anti-disturbance ability of the system, but it does not fundamentally A big problem with changing PID (The way to eliminate errors based on error feedback is very passive, lags behind the influence of disturbance, and may cause system oscillation or severe overshoot due to excessive control force); The core idea of the LADRC control algorithm is to treat the part of the system that is different from the standard type as total disturbance, and use LESO to estimate the total disturbance in real time and eliminate it with NLSEF. From the experimental simulation results, it can be seen that the anti-disturbance ability of LADRC is better in terms of adjustment time and steady-state error. However, in the process of parameter adjustment, the change law of parameters is not as easy to grasp as fuzzy PID. It is relatively difficult to adjust and exceed Tuning is larger than fuzzy PID, and the two algorithms have their own advantages and disadvantages.

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References

1. JIAN YANG. Research on Sensorless Control of Interior Permanent Magnet Synchronous Motor in Zero and Low Speed[D]. Hefei University of Technology, 2018.
2. Wang Ruiming. Study on AC Servo Driven System and It's Novel Control Strategy[D]. ZheJiang: Zhejiang University, 2005.
3. ZhengWei Zhu, JianWei Zhu. Simulation Study On the Permanent Magnet Synchronous MotorSpeed Control System Based On Fuzzy Control.[J]. Journal of Changzhou University, 2012 (24): 61-65.
4. WenShuang Ding, YuWen Hu, WenQi Lu, JiaoYan Liang. Fuzzy PID Parameter Self-Turning Control for PMSM Servo System[J]. Small & Special Electrical Machines, 2011, 39 (05):17-21.
5. Yi Zhi-An, Mu Chun-Miao, Sun Yin-Ping. Fuzzy Neural Network Based on Improved Particle Swarm Algorithms[J]. Computer Systems & Applications, 2014, 23 (06): 135-140.

6. Han Jing-Qing. From PID Technology to "Auto Disturbance Rejection Control" Technology[J]. Control Engineering of China, 2002 (03):13-18.
7. Xiong Cheng-Lin. Practical Research on Vector Control System of Induction on Motor Bsaed on Optimizing ADRC[D]. Southwest Jiaotong University, 2006.
8. Gao Zhiqiang. On the foundation of active disturbance rejection control[J]. Control Theory & Application, 2013, 30 (12): 1498-1510.
9. Xiao Wei-Wen. Study on Direct Torque Control System of Permanent Magnet Synchronous Motor[D] .Hunan university, 2009.
10. Guo Bin, Shan Qingxiao, Xiao Changyan, Yang Jun, Liu Guohua. A Study of Beidou and GPS Dual -mode Synchronization Technology For Electric Power System Clock[J]. Computer Systems & Applications, 2011, 19 (01): 139-141.
11. Wang Shuyan, Shi Yu, Feng Zhongxu. A Method for Controlling a Loading System Based on a Fuzzy PID Controller[J]. Mechanical Science and Technology for Aerospace Engineering, 2011, 30 (01): 166-172.
12. Zhang Jinhuan. Study and Comparison on PID Control and Fuzzy Self-Adapting PID Control Syetem[J]. Journal of Wuhan University of Technology (Information & Management Engineering), 2005 (05): 286-290.