A New Fuzzy Active-disturbance Rejection Controller Applied in PMSM Position Servo System

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Abstract —A new fuzzy active-disturbance rejection position controller of permanent magnet synchronous motor (PMSM) servo system is presented in this paper. The improved position and speed loop controller not only maintains the original features of controller, but also reduces the adjustable parameters ,which makes control performance better. Through the analysis of cross-axis output equation, a new position fuzzy active-disturbance rejection controller (Fuzzy-ADRC) scheme is proposed, ensuring the system dynamic performance, meanwhile improving the ability of the anti-load disturbance. Simulation and experimental results show that compared with classic PID control system the improved Fuzzy-ADRC system has characteristics of fast response, no overshoot and high control accuracy, and the system also has strong robustness to load and parameter changes. Besides, Fuzzy-ADRC runs steadily under high or low speed condition, which realizes higher control accuracy and stronger anti-interference of servo position control system, and makes control effect better.

I. INSTRODUCTION

PMSM with the features of high torque/current ratio, high power density, low loss and convenient maintenance etc.[1], has been widely used in high-performance servo system motor drive control. As a typical nonlinear, strongly coupled and parameter time-varying system, it's hard to use a model to accurately describe PMSM. The traditional control method is the typical PID control based on the model of controlled plant, which has good application in practice[2]. Modern control theories such as adaptive neural network control, robust control and sliding mode control etc. can effectively improve the operation performance of PMSM [4-7].But these approaches each improve different aspects of PMSM control performance, and the computation is heavy.

Active-disturbance rejection controller(ADRC)is a kind of improved nonlinear control technology develops from nonlinear PID control by Chinese Academy of Sciences researcher Han Jingqing[3]. ADRC is combined with nonlinear feedback to realize better control effect, which shows strong adaptability, robustness and operability. However ADRC has many adjustable parameters so that is not easy to operate and adjust[8]. Literature [9-10] uses fuzzy logic control to optimally estimate parameters in a certain range to achieve automatic parameters adjust of control system and improve low speed control performance of motor. No manual tuned active disturbance rejection control (NMT-ADRC) is proposed in Literature [11], where parameter turning is unnecessary, and the speed and torque of system can be well controlled. While when it is applied in high speed control of AC servo system, as the influence of load torque mutation, moment of inertia, and friction etc, the ability of anti-interference is poor.

In this paper, a PMSM position servo control system based on fuzzy active-disturbance rejection is proposed. Introducing fuzzy logic control into the design of ADRC controller, improving the self-tuning of the parameter of nonlinear states error feed-back（NLSEF）, which keeps the original features of controller and reduces the adjustable parameter and enhances the performance of control system. Combined with the speed loop and the position loop, a novel Fuzzy-ADRC position regulator is designed, which improves the robustness and keeps the dynamic characteristics of the system at the same time. Simulation and experiment results suggest that the improved system has the characteristics of fast response speed, non-overshoot, high static precision and strong robustness to load and system disturbance.

II. MATHEMATICAL MODEL OF SLIDING MODE ADRC

A. Mathematical model of ADRC

ADRC is a new nonlinear control technology, which Including: tracking differentiator (TD), extended state observer (ESO) and nonlinear states error feed-back (NLSEF).

Assuming the state equation of two-order controlled object as fallows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_0(x_1, x_2) + w(t) + bu(t) \\ y = x_1 \end{cases} \tag{1}$$

Where b is the amount of gain for the system control; $u(t)$ is the system control volume; $f_0(x_1, x_2)$ is the known part of the system, $w(t)$ is the unknown part of the system, the sum of the two parts of this system are the total disturbance.

The ADRC equation of the two-order controlled object is :

Linear differential-tracker:

$$\begin{cases} \dot{v}_1 = v_2 \\ \dot{v}_2 = -1.76Rv_2 - R^2(v_1 - v) \end{cases} \tag{2}$$

Where v is the input signal; v_1 is the tracking signal of v; R is the speed factor, the greater the R, the faster track the signal.

Nonlinear extended state observer:

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$$\begin{cases}\varepsilon_1 = z_1 - y \\ \dot{z}_1 = z_2 - \beta_{01} fal_1(\varepsilon_1) \\ \dot{z}_2 = z_3 - \beta_{02} fal_2(\varepsilon_1) + bu(t) \\ \dot{z}_3 = -\beta_{03} fal_3(\varepsilon_1)\end{cases} \tag{3}$$

Where y is the system output; z_1 is the track signal of y ; z_2 as the differential signal of z_1 ; z_3 is disturbance of the tracking signal for the system; ε_1 is the error signal; β_{01} , β_{02} and β_{03} is output error correction gain.

Nonlinear states error feed-back:

$$\begin{cases}e_0 = \int e_1 dt \\ e_1 = v_1 - z_1 \\ e_2 = v_2 - z_2 \\ u_0 = \beta_0 fal(e_0) + \beta_1 fal(e_1) + \beta_2 fal(e_2) \\ u(t) = u_0 - [z_3 + f_0(z_1, z_2)]/b\end{cases} \tag{4}$$

Where e_0 , e_1 and e_2 are error, differential and second differential signals; β_1 , β_2 and β_0 are error, differential and second differential gain respectively; $f_0(z_1,z_2)$ is the known part of the system. The feedback of $[z_3 + f_0(z_1,z_2)]/b$ is used to compensate disturbances.

$fal(\bullet)$ is the optimal integrated control function, which was expressed as:

$$fal(\varepsilon) = \begin{cases}|\varepsilon|^a sign(\varepsilon), & |\varepsilon| > \delta, \\ \varepsilon / \delta^{1-a}, & |\varepsilon| < \delta,\end{cases} \delta > 0 \tag{5}$$

In the function, a is the nonlinear factor; δ as the filter factor. Selecting the appropriate parameters, it can achieve small error and large gain or large error but small gain nonlinear control to improve the system control accuracy, which makes the controller with strong adaptability and robustness.

B. Model of Fuzzy controller

In practice, nonlinear feedback control law parameters $\{\beta_0, \beta_1, \beta_2\}$ identified with PID controller parameter tuning is very similar to needs of the different control states, manually adjust the size of each parameter is not conducive to the actual operation and temporary parameter changes. Therefore, This paper introduces the fuzzy logic controller, according to input of the e_1 , e_2 and using fuzzy control rules to change ADRC parameters in real-time and automatic approximating the optimal parameters $\{\beta_0, \beta_1, \beta_2\}$, to meet the e_1 , e_2 parameter requirements of ADRC at different time.

In the controller, the fuzzy variables are e_1 , e_2 , $\Delta\beta_0$, $\Delta\beta_1$, $\Delta\beta_2$, in their domain, five language sets defined as{"Negative Big(NB)", "Negative small(NS)", "Zero(ZO)", "Positive small(PS)", "Positive Big(PB)"}. Select input variables e_1 , e_2 for the Gaussian membership function, output variables $\Delta\beta_0$, $\Delta\beta_1$ and $\Delta\beta_2$ for the triangular membership function. In this paper, the basic domains of e_1 , e_2 are [-3, +3], [-3, +3] , and the basic domains of $\Delta\beta_0$, $\Delta\beta_1$, $\Delta\beta_2$ are [-0.3，0.3] , [-0.3，0.3] , [-0.06，0.06] . The fuzzy reasoning using Mamdani type and defuzzification is weight average method. According to the rules of human mind, fuzzy control rules are worked out by summarizing the engineering staff's technical knowledge and practical experience. For $\{\Delta\beta_0, \Delta\beta_1, \Delta\beta_2\}$ parameter setting, fuzzy control table are established, as shown in TABLE I.

TABLE I $\Delta\beta_0$, $\Delta\beta_1$, $\Delta\beta_2$ FUZZY RULE TABLE

e_1 \ e_2	NB	NS	ZO	PS	PB
NB	NB/PB/ PS	NS/PS/ NS	NS/PS/NB	NS/ PS/ NB	ZO/ZO/ PS
NS	NB /PS/ PS	NS/PS / NS	NS /PS/ NB	ZO/ZO/ NS	PS /NS/ ZO
ZO	NS / PS/ ZO	NS /PS/ NS	ZO/ZO/ NS	PS /NS/ NS	PS /NS/ ZO
PS	NS /PS/ PB	ZO/ZO/ ZO	PS /NS/ ZO	PS /NS/ ZO	PB/NS/PB
PB	ZO/ ZO/ PB	PS /NS/ PS	PS /NS/ PS	PS /NS/ PS	PB/NB/ PB

According to the membership assignment table of fuzzy set and the fuzzy control model of parameters, and with fuzzy synthetic reasoning to design fuzzy matrix, then defuzzification and found correction parameters $\Delta\beta_0$, $\Delta\beta_1$, $\Delta\beta_2$ and substituted it into the equation:

$$\begin{cases}\beta_0 = \beta_0' + \Delta\beta_0 \\ \beta_1 = \beta_1' + \Delta\beta_1 \\ \beta_2 = \beta_2' + \Delta\beta_2\end{cases} \tag{6}$$

Where β_0' , β_1' , β_2' is the NLSEF initial value.

According to the (6), obtaining parameters $\{\beta_0$, β_1 , $\beta_2\}$.Finally, with the principles of ADRC parameters tuning, we can obtain Fuzzy-ADRC. Its structure is shown in Fig.1.

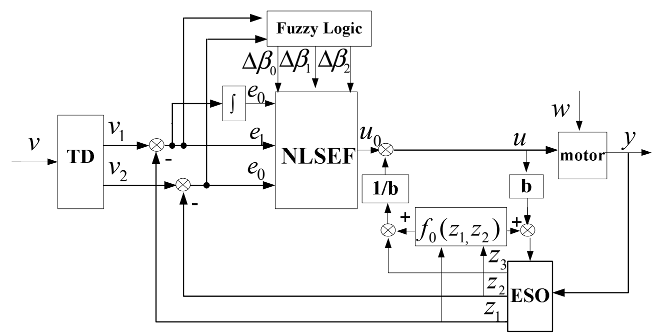


Fig.1 Fuzzy-Self-adapted ADRC structure

III. FUZZY ADRC POSITION CONTROLLER FOR PMSM

In the synchronous rotating coordinate system, using vector control strategies, we can obtain position loop two-order dynamic equation of PMSM:

$$\ddot{\theta} = -\frac{B\omega}{J} - \frac{T_L}{J} + \frac{1.5 p\psi_f}{J} u(t) \tag{7}$$

Let: $f_0(x_1,x_2) = -\frac{B\omega}{J}$, $w(t) = -\frac{T_L}{J}$, $b = \frac{1.5 p\psi_f}{J}$, $u(t) = i_q$, where $f_0(x_1,x_2)$ is the known friction disturbance of system, $w(t)$ is the unknown load disturbances of system, through these two parts can estimate the total disturbance of system and compensate for it, making the system has great robustness to the load and friction disturbance. Under the condition of position sensor, ω is the known quantity, its differential is also a known quantity, and the state equation of position loop is available:

$$\begin{cases} \dot{x}_1 = x_2 = \dfrac{d\theta}{dt} \\ \dot{x}_2 = \dfrac{d^2\theta}{dt^2} = f_0(x_1, x_2) + w(t) + bu(t) \\ y = x_1 = \theta \end{cases} \quad (8)$$

It can be seen, every part of the position Fuzzy-ADRC controller can be designed, Its whole control structure is shown in Fig.2. In it, θ^* is the given rotor position, i_q^* is the given q-axis current, θ is the rotor position feedback signal, v_1 is the tracking signal of θ^* , v_2 is the differential signal of θ^* , z_1 is the tracking signal of θ , z_2 is differential signal for z_1 , z_3 is system observation of the uncertain part of disturbance, that is $w(t)$, $f_0(z_1, z_2)$ as the observation for the certain part, where the differential is different from the differential signal in PID controller, its effect is not amplified, but disincentive to noise signal.

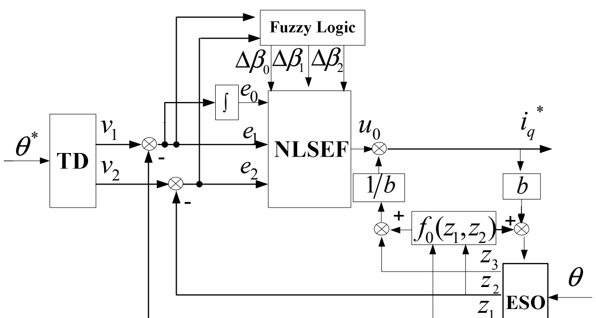


Fig.2 position speed loop fuzzy ADRC controller structure

PMSM position servo system structure diagram is shown in Fig.3. Though tracking differentiator arranging the transient and giving the differential signal of this process, which makes the system realize rapid response and non-overshoot. Though ESO, we can not only obtain the observer value of state variables, but also obtain the observer value of system disturbance, for example: the disturbance caused by variation of moment of inertia, stator resistance, inductance and load disturbance or some other unknown disturbance; though nonlinear error feedback control law, we can not only compensate for various disturbance, but also realize a small error but large gain and large error but small-gain nonlinear control in position loop. The improved controller reduces the adjustable parameters and improves system performance, thereby it can improve control accuracy and adaptability of position servo system.

The system uses double loop vector control structure with $i_d = 0$, that is position loop and speed loop, where position loop is a novel controller that combine position loop with speed loop; d-axis and q-axis current loop using traditional PI regulator. Compared with the traditional active-disturbance rejection control structure, this control system not only reduces the control link, optimizes the control strategy, but also enhances the immunity of the control system, improves the system stability.

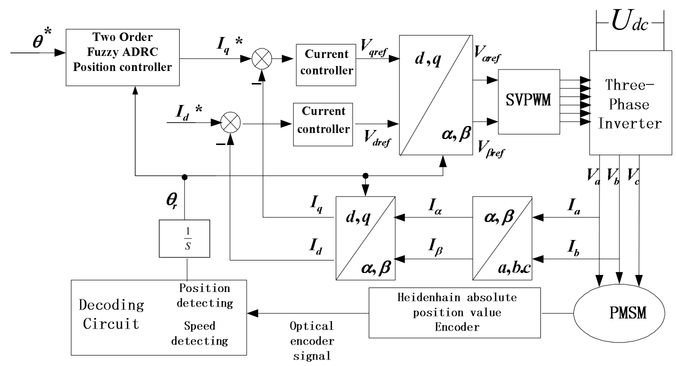


Fig. 3 Fuzzy-ADRC for PMSM servo system

IV. SIMULATION ANALYSIS

To verify the control performance of fuzzy auto-disturbance rejection PMSM, in this paper, we conduct the simulation by using Matlab/Simulink. Under the same condition, using a self-developed frequency conversion control system as the core to control two PMSM. The parameters of PMSM are as follows: rated power PN =1.8kW, rated speed n = 6000r/min, stator resistance R=1.422Ω, d-axis, q-axis inductance respectively Ld= Lq =7.348mH, moment of inertia J = 10.2kg • m^2, number of pole pairs p = 2, rated torque Te = 2.87 N.m, rotor flux ϕ_0 = 0.244T, f_N = 200Hz, position loop cycle is 0.2ms.

In practice, each parts of parameters in the controller need to be adjusted, TD parameters are constant once been set; ESO parameters can be generated automatically in the relationship of the parameters, while NLSEF parameters is automatically adjusted by the fuzzy control. After repeated testing, it's initial parameters value: β_0'= 4.5, β_1'=60.5, β_2'=30.6.

The results are as follows: giving position 0.0001rad, starting the motor without load, adding position disturbance when 1s, and the results shown in Figure 4, it can be seen, the system position tracking is accurate, and the steady tracking accuracy is high and without overshoot, and the system has strong robustness to load disturbance.

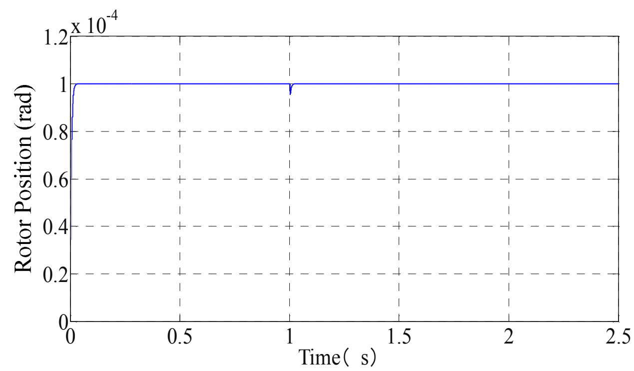
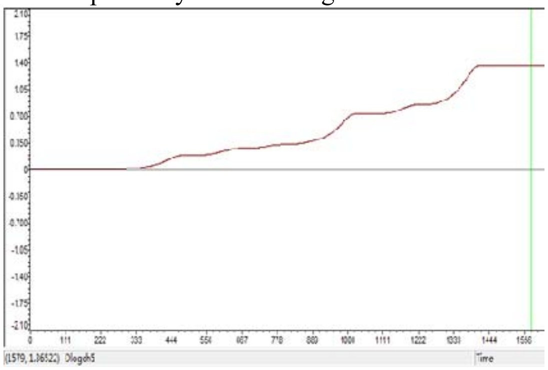


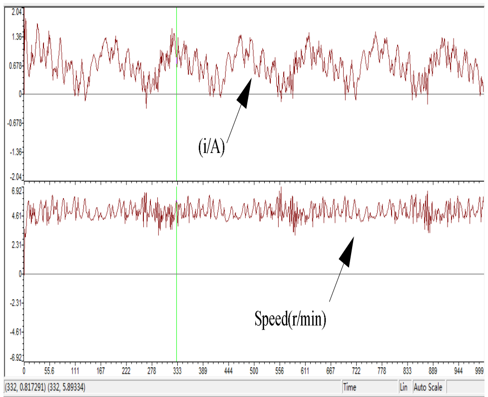
Fig. 4 Rotor position waveforms

V. EXPERIMENTAL RESULTS

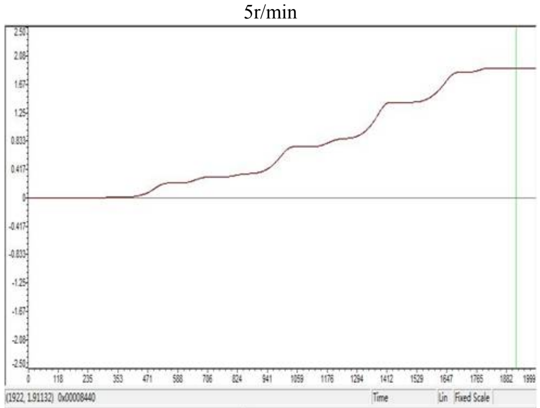
In experimental comparison, PID control is used to compare with the novel Fuzzy-ADRC. The system is given a mechanical angle of 200° , and non-load start the motor with a speed of 5r/min, the position , speed and current experimental waveforms using PID control and Fuzzy-ADRC control are respectively shown in Fig.5.



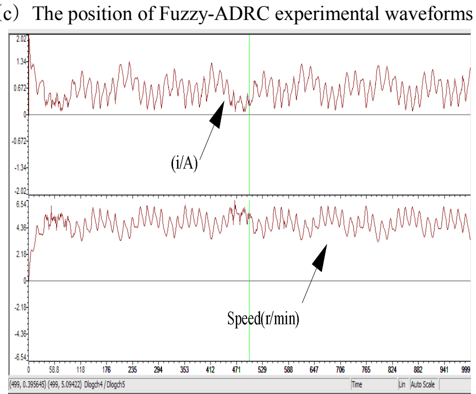
(a) The position of PID controller experimental waveforms at 200°



(b) The speed and current of PID controller experimental waveforms at 5r/min



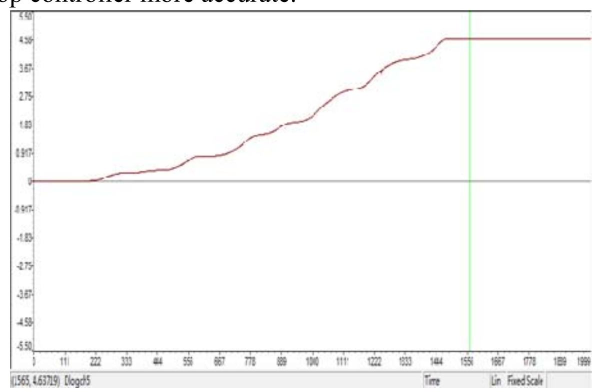
(c) The position of Fuzzy-ADRC experimental waveforms at 200°



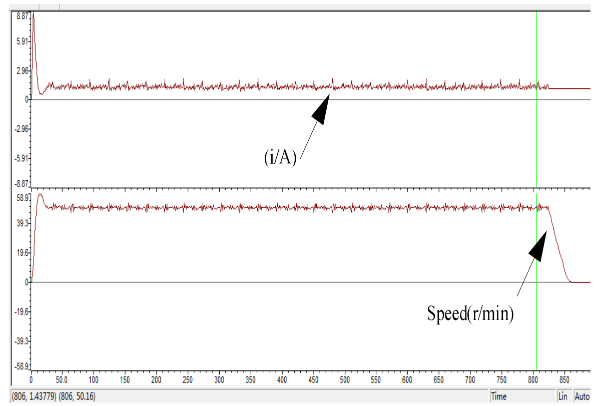
(d) The speed and current of Fuzzy-ADRC experimental waveforms at 5r/min

Fig.5 The position of Fuzzy-ADRC and PID comparison experimental waveform at 200°

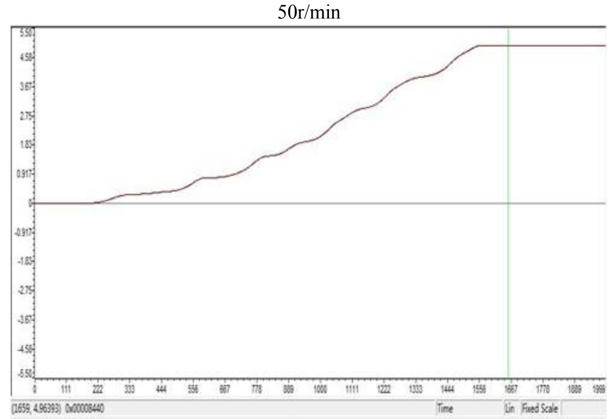
By comparison of the motor starts at an ultra-low speed of 5r/min in Fig.5, when motor responds at a position of 200° ,using Fuzzy-ADRC controller can reach accuracy of 0.01° . Comparing with PID, the speed and current control effect of Fuzzy-ADRC is better while the position respond speed is slower. As the current torque pulsation is low, Fuzzy-ADRC has more stable control effect and stronger anti-interference performance at 5r/min, which makes position loop controller more accurate.



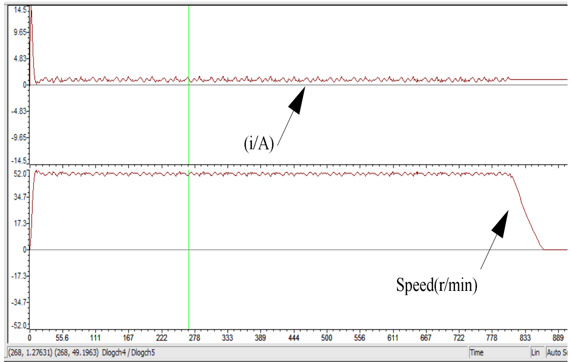
(a) The position of PID controller experimental waveforms at 500°



(b) The speed and current of PID controller experimental waveforms at 50r/min



(c) The position of Fuzzy-ADRC controller experimental waveforms at 500°



（d） The speed and current of Fuzzy-ADRC controller experimental waveforms at 50r/min

Fig.6 The position of Fuzzy-ADRC and PID comparison experimental waveform at 500°

Fig.6 shows the position, speed and current experimental waveforms if motor non-load start at a speed of 50r/min when a position of 500° is given to the system. We can see low speed and iq-axis current when motor responds position signal from the figure; Fuzzy-ADRC uses ESO to estimate the state variables and internal/external disturbance real-time action of controlled object, besides, compensates for it, and designs a reasonable state error feedback control law. Therefore it has strong robustness than PID controller. Using $i_d = 0$ vector control strategies, we can see from practical data that current harmonic component is low, which makes current torque pulsation small. Though PID controller improves the position accuracy, there are some oscillations during position respond. Besides, Fuzzy-ADRC has better position respond, and as the enhancement of anti-interference performance, the position accuracy is more precise.

VI. CONCLUSION

According to practical requirements, this paper applies Fuzzy -ADRC theory to high performance AC permanent magnet servo system, and designs two-order Fuzzy-ADRC position regulator to enhance anti-interference ability of the system, and using ESO to estimate the disturbance, which achieving high precision control of servo motor with position sensor. Simulation and experiment results show that Fuzzy-ADRC has good dynamic and static performance for IPMSM. The system not only realizes high performance servo drive and reduces the adjustable parameters but also has strong robustness to system disturbance. Form the contrast experiment with PID, Fuzzy-ADRC has lower current torque pulsation under ultra-low and low speed. It also has stronger anti-interference performance which makes the motor realize fast locating under low speed when using position loop control and Fuzzy-ADRC operates more stable under high speed. In the servo position control contrast experiment, it's obvious that Fuzzy- ADRC control has faster position response, better rapid dynamic response performance, higher control precision, stronger disturbance rejection performance and better control performance.

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