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Sliding-mode Active Disturbance Rejection Permanent Magnet Synchronous Motor Control System

Ning Chen *

College of Electrical Engineering, Southwest Minzu University. Chengdu, Sichuan 610041, China
* **Corresponding author Email:** chenning@swun.edu.cn

Abstract: Aiming at the permanent magnet synchronous motor with external perturbations and internal uncertainties such as external load, rotational inertia and armature resistance changes, a servo control system based on sliding mode self-immunity controller is designed. By constructing a mathematical model of the servo system of the permanent magnet synchronous motor, considering the internal uncertainty caused by the change of the system parameters and the external random disturbance as the "total disturbance", and designing the transition process and the linear expansion state observer to observe and compensate for it, the system response can track the input signal quickly and without overshooting, and the sliding-mode state feedback makes the closed-loop servo system achieve fast and stable control, and the sliding-mode Active Disturbance Rejection control controller can be used to control the system. The sliding mode state feedback enables the closed-loop servo system to realize fast and stable control, and its consistent stability is proved by the Lyapunov method. Simulations show that this sliding- mode Active Disturbance Rejection control control strategy improves the system response speed and load carrying capability compared with the traditional sliding-mode control.

Keywords: Permanent magnet synchronous motor; Sliding mode control; Self-resilient control.

1. Introduction

Among various types of motors, permanent magnet synchronous motors (PMSM), with the unique advantages of high-performance permanent magnet materials, show remarkable superiority in terms of size, weight, efficiency, transient overload capacity, and power density. In the industrial field, the application of PMSM has significant theoretical and practical significance for the further promotion of industrial automation. High-efficiency, low-noise, and high-precision PMSM can help improve productivity, reduce energy consumption, and minimize environmental pollution, thus promoting industrial upgrading and green development. However, the control of PMSM faces a series of challenges, including factors such as nonlinearity, time-varying parameters, uncertainty and various disturbances [1].

The speed control technology of PMSM has been improving continuously, and researchers at home and abroad have proposed many control strategies based on a large number of studies. Traditional PID control is widely used, but with the advancement of technology, higher requirements are put forward for the control performance of the system. PID control cannot effectively solve the problem of d-q axis physical quantity coupling in the structure of PMSM, and it is not well resistant to noise and interference [2]. As the requirements for system stability, safety and anti-interference performance increase, the traditional PID control no longer meets these needs. Many scholars have done a lot of work on the improvement and optimization of PID based on traditional PID controllers, and have obtained some new control strategies with stronger anti-interference ability and better robustness [3-4]. At the same time, the emergence of modern control theory provides new ideas for improving the performance of the control system. With the continuous

development of PMSM speed control technology, a variety of high- performance control methods have been developed, which are expected to replace the traditional PID controller and gradually applied in permanent magnet synchronous motor control.

Sliding Mode Control (SMC) [5-7] is to enhance the robustness of the system to changes in control parameters and external perturbations by designing a special "sliding surface" on which the system state slides. The advantages of this method are simple structure, strong robustness, applicable to nonlinear systems, and widely used in industrial control and other fields. In order to improve the performance of sliding mode control, a sliding mode control based on fast terminal sliding mode arrival law is proposed in literature [6] to improve the dynamic performance of permanent magnet synchronous motor. The proposed fast terminal sliding mode control can not only effectively suppress the jitter phenomenon, but also improve the system response speed.H. N. Tran et al [7] proposed a robust mechanical parameter estimation and adaptive speed control algorithm based on the dual adaptive sliding mode method for permanent magnet synchronous motor drive system. Yuan Lei et al [8] used a fast non-singular terminal sliding mode control combined with a disturbance observer to improve the accuracy and stability of the system, and it has the advantages of fast response speed and strong anti- interference capability.

Active Disturbance Rejection Controller (ADRC) is a new type of nonlinear robust control technique that does not depend on the precise mathematical model of the object, which is proposed by researcher Han Jingqing of the Chinese Academy of Sciences on the basis of carrying forward the essence of the PID control technique and absorbing the achievements of modern control theory [9]. However, the disadvantages of ADRC are the large number of internal parameters, the weak sensitivity of the parameters, and the coupling relationship between the parameters, which means that it is difficult to select and debug the optimal parameters. Therefore, the parameter tuning method of ADRC has been studied by scholars. Gao [10] proposed a simplified linear

ADRC method, which combines the adjustable parameters of the controller with the bandwidth in engineering, thus reducing the number of adjustable parameters. Baiya Li et al [11] proposed a self immunity control method based on improved sigmoid function. A PMSM speed control system was designed using the improved sigmoid function instead of the traditional nonlinear function, and the improved system has a better response speed fast and stronger anti-jamming ability.Y. Wang [12] proposed a multi-scenario parameter optimization method based on deep reinforcement learning for permanent magnet synchronous motor self- resistant controller. It enables the ADRC to easily achieve the best control results and solves the limitations of current methods.

Sliding Mode Active Disturbance Rejection Control (SM-ADRC), an improved sliding mode active disturbance control algorithm is proposed to address the problems of overshooting and response time contradiction as well as the lack of disturbance estimation in sliding mode control based permanent magnet synchronous motor control. It can not only retain the advantages of self-immunity without overshoot and strong resistance to load perturbation, but also improve the dynamic steady-state performance of the permanent magnet synchronous motor speed control system [13]. Zhao Ximei et al [14] proposed a sliding mode self-immunity control scheme for permanent magnet synchronous motor based on the improved gray wolf optimization algorithm to address the problem of the deterioration of the system robustness of the servo system of permanent magnet synchronous motor under the influence of external perturbations, parameter variations, and other uncertainty factors. This method can effectively track the given speed, overcome the influence of parameter changes, load disturbances and other uncertainty factors, and ensure the strong robustness of the PMSM servo system. Qingxue Liu et al [15] proposed a non-singular fast terminal sliding-mode self-immunity composite controller based on fixed- time convergence for the problems of jitter phenomenon and poor performance of self-immunity control trajectory tracking accuracy in the speed control system of permanent magnet synchronous motor using sliding-mode control. The jitter phenomenon of the system is attenuated, and the tracking performance and immunity performance of the system are enhanced.

Currently, the traditional PID control strategy is still a widely used control method in PMSM servo control systems. However, PID control is less adaptable to system parameter and load variations, and is difficult to cope with internal uncertainties and external perturbations, and thus often fails to meet the demand for high-performance control. To improve the performance and robustness of PMSM drive systems, more powerful control strategies are needed. Self-robust control has been widely used in complex environments due to its advantages of simple structure, fast response speed, and almost no dependence on the model. Sliding mode control is an effective method to deal with uncertain systems with strong robustness and fast response. These two control methods have shown excellent performance in PMSM control system studies. However, ADRC has limited robustness to parameter variations, while SMC tends to cause control system jitter when switching near the sliding mode surface. Therefore, in order to improve the resistance to uncertainties and external disturbances as well as the overall robustness of the PMSM system, a new control method, the sliding mode Active Disturbance Rejection control control, is proposed to address these challenges.

Based on this the study of this composite control strategy is of great theoretical and practical significance to improve the immunity and robustness of PMSM systems.

2. PMSM Mathematical Model

The system studied in this paper is a permanent magnet synchronous motor (PMSM) with a stator powered by a three-phase alternating current (AC) with star (Y) connection and a flat rotor. The following assumptions are made: the magnetic circuit is not saturated, the magnetic field is sinusoidally distributed in space, the hysteresis and eddy current losses are not taken into account, i.e., the effects of hysteresis and eddy current can be neglected; the inductance of the alternating and direct axes of the PMSM is equal, i.e., L=Ld=Lq. At this time, the permanent magnet synchronous motor system model is:

$$\begin{cases} \mathrm{u}_d = R_s i_d + L_d \dfrac{di_d}{dt} - \omega_e \varphi_q \\ \mathrm{u}_q = R_s i_q + L_q \dfrac{di_q}{dt} - \omega_e \varphi_d \end{cases} \tag{1}$$

Where ud and uq are the d-q axis components of stator voltage;； id and iq are the d-q axis components of stator; Rs and ψd are the stator resistances; ψq is the d-q axis component of the stator magnetic chain; ωe is the electrical angular velocity; Ld and Lq are the d-q-axis inductance components, respectively; ψq represents the magnetic chain of the permanent magnet; Te is the electromagnetic torque; Pn is the number of pole pairs of the motor; J is the moment of inertia; B is the coefficient of friction.

It is proportional to. By this control method, the main idea of decoupling of PMSM is realized. The system state variables of the permanent magnet synchronous motor are:

$$\begin{cases} e = \omega_{ref} - \omega_m \\ \dot{e} = -\dot{\omega}_m = \dfrac{1}{J}(T_L - \dfrac{3p_n\varphi_f}{2} i_q) \\ \ddot{e} = -\ddot{\omega}_m = -\dfrac{3p_n\varphi_f}{2J} \dot{i}_q \end{cases} \tag{2}$$

3. Sliding mode self-immunity controller design

3.1. Linear Expansion State Observer Design

The self-immune controller draws on the essence of the observer theory in modern control theory, and uses the expanded state observer to observe the system state and feedback suppression. The system parameter variations, internal uncertainties and external disturbances of the permanent magnet motor are regarded as total disturbances, which are observed and compensated by the expanded state observer to dynamically compensate for the effects of the disturbances. The expanded state observer makes the closed-loop system much more resistant to disturbances.

In order to improve the permanent magnet synchronous motor is control performance, design an expansion state observer based on fal function to observe the total disturbance of the system. the system state equation can be expressed as:

$$\begin{cases} \dot{z}_1 = z_2 + b_0 i_q \\ y = z_1 \end{cases} \tag{3}$$

Then the system expansion state observer is designed as follows:

$$\begin{cases} e_1 = z_1 - \hat{z}_1 \\ \dot{\hat{z}}_1 = \hat{z}_2 + b_0 i_q - \beta_3 e_1 \\ \dot{\hat{z}}_2 = -\beta_4\, fal(e_1, \alpha_3, \delta_1) \end{cases} \tag{4}$$

3.2. The tracking differentiator is designed

The tracking differentiator is designed as follows:

$$\begin{cases} e = z_1 - y^* \\ \dot{z}_1 = -rfalfal(e_1, \alpha_4, \delta_2) \end{cases} \tag{5}$$

where the fal function is a nonlinear function with the following functional expression:

$$fal(e, \alpha, \delta) = \begin{cases} \dfrac{e}{\delta^{\alpha-1}}, |e| \le \delta \\ |e|^{\alpha}\operatorname{sgn}(e), |e| > \delta \end{cases} \tag{6}$$

3.3. Sliding mode controller design

First, select the sliding surface:

$$s = ce + \dot{e} \tag{7}$$

Here, e= is the system given value, the input signal and fankuixinhao difference, c is a constant, according to the system state adjustment so as to achieve the purpose of system stabilization. In the design of the convergence law design is to choose the exponential convergence law to ensure that the system convergence speed at the same time also reduces the system jitter vibration jitter vibration problem. The convergence law design is shown below:

$$\dot{s} = -\varepsilon \cdot sign(s) - ks \tag{8}$$

Where: ε is the isochronous convergence constant, k>0;(8) sign() is the sign function;$\varepsilon \cdot sign(s)$ is the isochronous convergence term, andks is the exponential convergence term.At this point, the design state feedback control has three parameters ε, k, c The parameter k directly affects the response speed and the time to reach the sliding mold surface; in the phase trajectory approaching the switching surface, the main role of is the speed of approaching; c affects the speed when approaching the origin on the sliding surface.

4. Simulation experiment verification

In order to verify the effect of the controller designed in this paper, the PMSM control system is built in the MATLAB/Simulink environment, and the ADRC-SMC composite controller is designed for the phase current loop, which is analyzed by numerical simulation, and the values of the PMSM parameters are shown in Table 1.

In order to validate the performance of the sliding mode self-immunity controller, the superiority of the proposed algorithm is experimentally verified by comparing it with the conventional sliding mode control.

Table 1. Motor Parameters

parameter variable	numerical value
polar logarithmPn	4
Stator resistance R/Ω	2.875
d-q-axis inductance L/mH	0.0085
Magnetic chains for PMSM φf/W	0.175
Damping factor B/N-m-s	0.008

In order to verify the control performance of SM-ADRC, the initial value of the motor speed is given as 800r/min, and at the same time, in order to verify the motor's ability to carry loads as well as anti-disturbance ability, the motor is given a 10N.m load at 0.1s, and the performance is observed when the PMSM withdraws the load after stabilizing the operation. The motor speed response performance curve is shown in Fig. 1:

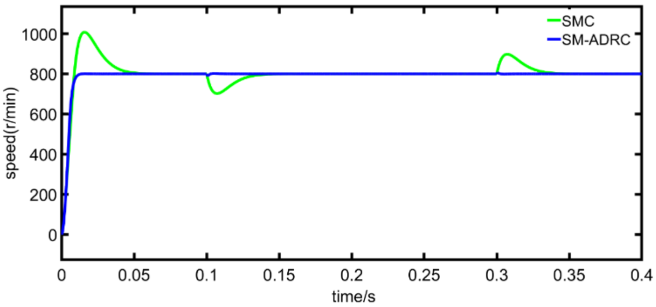

Figure 1. Speed response performance curve

As can be seen from Fig. 1, under the sliding mode Active Disturbance Rejection control control, the PMSM can quickly reach the given speed of the system, the system overshoot is 0, and the rotational speed error is 0. The introduction of the tracking differentiator solves the contradiction between the response speed of the traditional sliding mode control and the system overshoot, and meanwhile, in the process of adding loads to the motor suddenly, it can be seen that the speed fluctuation of the SM-ADRC is the smallest, which is 10r/min, and that of the sliding mode control is 100r/min. The fluctuation of speed is 100r/min, and its speed fluctuation is only 10% of the traditional sliding mode control, which greatly improves the system's ability to carry loads as well as anti-disturbance ability. When the system removes the load, the speed of SM-ADRC jumps by 7r/min, while the traditional sliding mode self- immobilizing speed jumps by 95r/min, and the method proposed in this paper greatly reduces the performance of the motor control in the case of the system's sudden removal of the load. It not only reduces the fluctuation of the motor but also improves the motor's ability to carry loads as well as anti-disturbance ability.

Its three current waveforms are shown below in Fig. 2, Fig. 3:

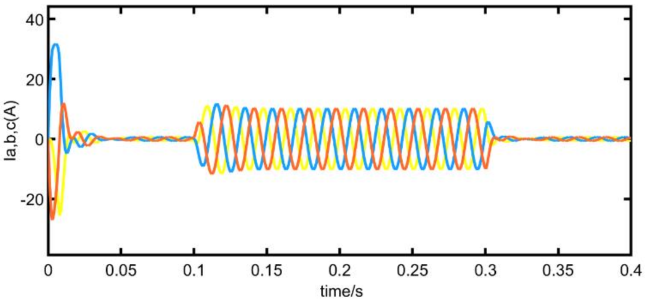

Figure 2. Sliding mode control triple current waveform

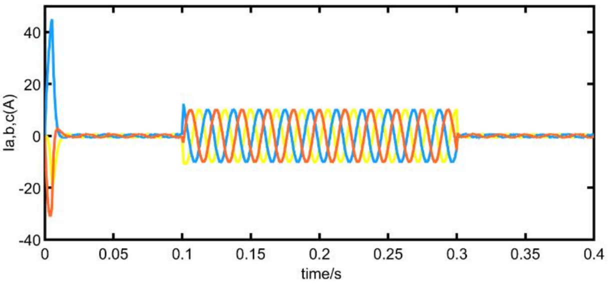

Figure 3. SM-ADRC three current waveforms

From Fig. 2, Fig. 3, it can be seen that the three current waveforms of the traditional sliding mode control fluctuate more and the response time is slower, while its current ripple is smaller, while the SM-ADRC current waveform fluctuates less, which results in a larger current ripple due to its accelerated response time, leading to a larger system jitter. Current with load, with the increase in load leads to an increase in system current,while the current ripple is smaller and slow to change.

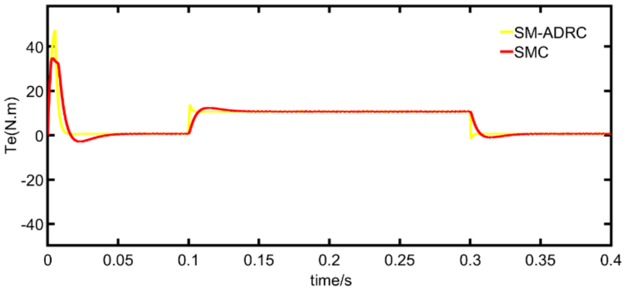

Figure 4. Torque variation waveform

The torque change waveform of the two control methods is shown in Fig. 4, which leads to a larger starting torque under the premise of faster response speed, but it can be stabilized faster, and at the same time, the system can also be stabilized in a shorter period of time at the torque required for the steady state of the motor under the condition of adding and subtracting loads, and it can be stabilized faster under the condition of carrying loads.

5. Conclusion

In this paper, a composite control method based on sliding mode and self-oscillation is applied to vector-controlled PMSM speed control system to improve the control performance of permanent magnet motor. The sliding-mode self-oscillation control inherits the advantages of the traditional linear self-oscillation and sliding-mode control, and can estimate and compensate the disturbances in real time, with fast dynamic response performance and strong robustness. It can not only suppress the influence of system internal uncertainty and load change disturbance. It has strong adaptability to parameter changes. Moreover, its algorithm is simple. Its superior performance is verified through simulation experiments, and compared with the traditional sliding mode control, its response speed is accelerated, no overshooting and its ability to carry load is greatly improved.

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