



# The Fuzzy Sliding Mode Variable Structure Control for Direct Flux Oriented Vector Control of Motor

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**Abstract.** In this paper, a vector controller based on fuzzy sliding mode variable structure is designed for the influence of nonlinear and variable parameters on the performance of the system. On the basis of establishing the mathematical model of the asynchronous motor in the synchronous rotation orthogonal coordinate system oriented by the rotor flux, a sliding mode variable structure speed regulator using the exponential approach law is designed. The stability of the system is proved by the Lyapunov stability theorem, and the chattering of the system is reduced by the fuzzy algorithm. The simulation results show that compared with the traditional PI controller and the conventional equivalent sliding mode controller, the fuzzy sliding mode variable structure vector control system has better speed regulation performance, smaller torque ripple, and improves the robustness and anti-interference ability of the system.

**Keywords:** Vector control · Sliding mode variable structure · Fuzzy algorithm

## 1 Introduction

For many years, a lot of research has been done about flux observer and PI parameter regulation [1, 2] by the scholars and experts in the scientific research institutes and universities. In reference [3], multi-level inverter is used to attenuate the pulsations from the flux and torque. However the hardware structure of the system becomes complex. The speed observer and flux observer proposed in reference [4] can be applied to the control of the three-phase asynchronous motor direct torque. The references [5] can effectively attenuate of the torque, but PI controller is used in the torque modulate loop to slow down the torque response. Since Utkin applied sliding mode observer to motor control [6], sliding mode observer has attracted much attention [7–9] because of its strong parameter robustness and flexible design. Many scholars introduce a new control method into the motor drive system that has variable structure from the sliding mode and do a lot of research on it. In reference [10], sliding mode control is used to design speed loop and torque loop to reduce the response time and torque ripple of the motor. The application of high-order sliding mode is put forward in reference [11], but these are relatively complex. In reference [12, 13], the chattering phenomenon is effectively reduced by

improving the traditional sliding mode approach law. However induction motor has the characters such as high-order, nonlinear, etc. The research of efficient control scheme of induction motor is still an important research topic because its strongly coupling and multivariable value.

In this research, the control method of sliding mode variable structure and vector technology are combined to reduce torque disturbance and keep switching frequency stable. On this basis, fuzzy control algorithm is used to change the speed of reaching the face of the sliding patterns, so as to weaken the high frequency chattering problem from the process of sliding pattern control. The system has better speed regulation performance, smaller torque ripple, and improves the robustness and anti-interference ability.

## 2 Dynamic Mathematical of Asynchronous Motor

In order to realize the vector control technology, the mathematical model of an asynchronous motor should be established firstly. In the case of neglecting the iron loss and magnetic circuit saturation, assuming that the three-phase winding is symmetrical, the electrical angle difference in the space is  $120^\circ$ , the generated magnetomotive force with the air spacing conforms to the sinusoidal function distribution. And the universal model of the three-phase asynchronous motor is obtained. The altered model in the two-phase static coordinate of the asynchronous motor is obtained through  $3/2$  transformation. Then the mathematical model in d-q coordinate is taken by vector rotation transformation.

The voltage and current equations can be obtained by transforming flux equation and the voltage equation, as shown in Eq. (1):

$$\begin{bmatrix} u_{sd} \\ u_{sq} \\ u_{rd} \\ u_{rq} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_{dqs} L_s & L_m p & -\omega_{dqs} L_s \\ \omega_{dqs} L_s & R_s + L_s p & \omega_{dqs} L_m & L_m p \\ L_m p & -\omega_{dqr} L_m & R_r + L_r p & -\omega_{dqr} L_m \\ \omega_{dqr} L_m & L_m p & \omega_{dqr} L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (1)$$

Where  $i_{sd}, i_{sq}$  are stator current components;  $i_{rd}, i_{rq}$  are rotor current components;  $L_s$  is stator equivalent winding self inductance;  $L_r$  is rotor equivalent winding self inductance;  $L_m$  is the mutual inductance.

Where  $u_{sd}, u_{sq}$  are respectively the stator voltage components in d-q coordinate system;  $u_{rd}, u_{rq}$  are respectively the rotor voltage components in d-q coordinate system;  $\omega_{dqs}, \omega_{dqr}$  are respectively the stator and rotor angular velocity in d-q coordinate system;  $R_s, R_r$  are respectively the stator resistance and rotor resistance;  $p$  stands for differential operation.

The torque equation is derived and Eq. (2) is get

$$T_e = n_g L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \quad (2)$$

Where  $T_e$  is electromagnetic torque;  $n_g$  corresponds for polar logarithm.

The motion equation of motor references (3):

$$T_e = T_L + \frac{J}{n_p} \times \frac{d\omega}{dt} \quad (3)$$

Where  $J$  corresponds for moment of inertia;  $T_L$  is load torque;  $\omega$  is turning angular speed of asynchronous motor.

### 3 Improved Sliding Mode Controller

#### 3.1 The Sliding Mode Control

The whole motion can be divided into two stages. If the initial position of the controlled trajectory is not considered, the sliding mode control will force the trajectory to move towards the sliding manifold in the first stage. Then the trajectory is kept on sliding manifold by the control function and moves towards the desired equilibrium point.

For any sliding surface (switching surface)  $s = s(x) = s(x_1, x_2, \dots, x_n)$ , the state space can be divided into two parts, namely  $s > 0$  and  $s < 0$ . The control quantity  $u$  of the system is designed:

$$u = \begin{cases} u^+(x), & s(s) > 0 \\ u^-(x), & s(s) < 0 \end{cases} \tag{4}$$

where  $u^+(x) \neq u^-(x), u^+(0) = u^-(0)$ .

The selection of sliding surface is the key to ensure it has good dynamic characteristics and stable performance of sliding mode motion. Select the switch surface function as:

$$s = \omega_r - \omega_r^* \tag{5}$$

Where  $\omega_r^*$  represents the set value of angular speed, and  $\omega_r$  represents the actual value of angular velocity.

The setting of the reaching law determines the dynamic quality of the reaching motion. In the variable structure controller of sliding method, the main reason for chattering is that the reaching law outputs a high frequency signal with a large amplitude, and the state variable still has a certain speed when it approaches the sliding mode surface, which results in its motion path passing through the sliding method face. In the design of sliding method controller, the exponential approach law can reduce the approach speed from a large value to zero, which not only shortens the approach time, but also the speed slows down when the state track approaches the sliding mode face. Thus, the regulation process of the motor speed is accelerated and the chattering of the system is weakened.

The expression of approach law is shown in Eq. (6):

$$\dot{s} = -C s - K \text{sign}(s) \tag{6}$$

In the above formula,  $C$  is the exponential approach rate,  $K$  is the coefficient, and  $C > 0, k > 0$ , so that the derivative between the two sliding surfaces is different and the system is stable. In formula (6), the size of  $C$  should be selected appropriately in the speed of the system's motion track approaching to the sliding surface, and  $K$  determines the motion quality.

In this system, the sliding mode controller is designed by exponential approach law, which can be obtained by combining formula (5) and formula (6)

$$\dot{s} = -C(\omega_r - \omega_r^*) - K \operatorname{sign}(s) \tag{7}$$

From formula (7)

$$\dot{s} = \dot{\omega}_r = \frac{n_p \times (T_e^* - T_L)}{J} \tag{8}$$

Because the input of the speed regulator is  $\Delta\omega = \omega_r^* - \omega_r$  and the output is  $T_e^*$ , so the equation of the speed control is shown.

$$T_e^* = \frac{J}{n_p} [-C(s) - K \operatorname{sign}(s)] + T_L \tag{9}$$

### 3.2 Optimal Sliding Method Controller

In the optimal control system, a most important improvement of the controller design is made. In the process of designing the controller, there are two key links. They are building the fuzzy rule table and determining the structure of the fuzzy control algorithm. In the fuzzy controller structure of the optimal motor control system, input accurate value in the process of fuzzification, and then fuzzify it. Thus, the fuzzy value input logic decision-making function link is generated. Before this link, it is necessary to judge that the logic decision-making function can identify the fuzzy value. The fuzzy value to is processed clearly, so that the accurate value is generated.

In the sliding mode variable structure control, the coefficient  $K$  of the symbolic function in the switching control quantity determines the motion quality of the system in the sliding stage. Further optimization can reduce the chattering of the system in the sliding stage.

In the two-dimensional fuzzy controller, the derivative  $ds/dt$  and the sliding surface  $s$  are taken as the input. The value  $K$  is adjusted in real time by combining the fuzzy control rules. The obtained  $\Delta K$  plus the initial value of  $K_0$  is used to adjust the value of  $K$  in real time, attenuated the vibration of the variable structure motor drive system, and prepare for the movement quality of the system.

The input  $s, ds/dt$  and output  $\Delta K$  in the domain of fuzzy controller are defined in the following forms:

The output and input fuzzy subsets are  $\{-B, -M, -S, ZO, +S, +M, +B\}$ .

The fuzzy subset is divided into seven segments.  $-B, -M, -S$  stand for negative big, negative middle, and negative small separately.  $ZO$  is the symbol for zero.  $+S, +M$  and  $+B$  are similar, except they are positive. The continuity domains of input  $s, ds/dt$  and output  $\Delta K$  are all defined in  $[-3, 3]$ , and the triangle membership function is adopted in the input and output of the controller. Its expression is shown in formula (12)

$$f(x, m, n, k) = \begin{cases} 0 & x \leq m \\ \frac{x-m}{n-m} & m \leq x \leq n \\ \frac{k-x}{k-n} & n \leq x \leq k \\ 0 & x \geq k \end{cases} \tag{10}$$

The system uses the barycenter method to calculate the output variables according to “If A and B then C” the rule statements. Based on the distance between status position and the sliding face in the process of movement, a fuzzy rule table is constructed. The corresponding rule table of the fuzzy control system established in this system is shown in Table 1. In the actual operation of the system, if the movement status track get close to the sliding face, then the output value  $\Delta K$  has a smaller value. when the distance away the switching face is far, the output value  $\Delta K$  has a larger value.

**Table 1.** Rule table

$\Delta K$	$s$							
	$-B$	$-M$	$-S$	$ZO$	$+S$	$+M$	$+B$	
$ds/dt$	$-B$	$-B$	$-B$	$-B$	$-M$	$-M$	$-S$	$O$
	$-M$	$-B$	$-B$	$-M$	$-S$	$-S$	$O$	$O$
	$-S$	$-M$	$-M$	$-S$	$O$	$O$	$+S$	$+S$
	$O$	$-S$	$-S$	$-S$	$O$	$O$	$+S$	$+S$
	$-S$	$-S$	$-S$	$O$	$+S$	$+M$	$+M$	$+M$
	$+M$	$-S$	$O$	$O$	$+M$	$+M$	$+B$	$+B$
	$+B$	$O$	$O$	$+S$	$+M$	$+B$	$+B$	$+B$

### 4 System Simulation Analysis

This design simulation model of sliding method optimized by fuzzy algorithm is established in Matlab environment. In this design, traditional PI controller and fuzzy sliding method optimization controller are applied to the speed regulator of the asynchronous motor control system, and the simulation dynamic response curve is obtained. Specific system simulation parameters are as follows:  $U_n = 1140\text{ V}$ ,  $f = 50\text{ Hz}$ ,  $P_n = 40\text{ kW}$ ,  $R_s = 0.435\ \Omega$ ,  $L_s = 0.2\text{ mH}$ ,  $R_r = 0.816\ \Omega$ ,  $L_r = 0.2\text{ mH}$ ,  $L_m = 0.194\text{ mH}$ ,  $J = 0.19\text{ kg}\cdot\text{m}^2$ .

The simulation result of velocity and torque running curve of traditional PI control is shown.

When the motor is started,  $T_L = 35\text{ N}\cdot\text{m}$ , and the given speed of the system  $n = 500\text{ r/min}$ . At 0.2 s, 0.4 s and 0.6 s, the system simulation response curves of torque and speed under different control strategies are obtained under sudden load and sudden load reduction.

The simulation result of velocity and torque running curve of the fuzzy sliding method is in Fig. 2.

Compared with Fig. 1 and Fig. 2, the fuzzy sliding mode control system takes less time from the start to the rated speed stability stage, and the overshoot of the system is significantly reduced. At 0.2 s and 0.6 s, the system increases and decreases the load respectively, the response curve of PI control is more fluctuant than that of optimization

controller, and the recovery time is slightly shorter, but the regulation of optimization controller is relatively smooth. When the system increases the load again and the speed decreases in 0.6 s, the overshoot of fuzzy sliding mode control is about 10 r/min less than that of PI control, and the regulating time of fuzzy sliding method control is a little less. When the system reduces the load torque and the system increases the speed in 0.8 s, there is almost no overshoot in fuzzy sliding mode control, while the overshoot of PI control is about 5 r/min.

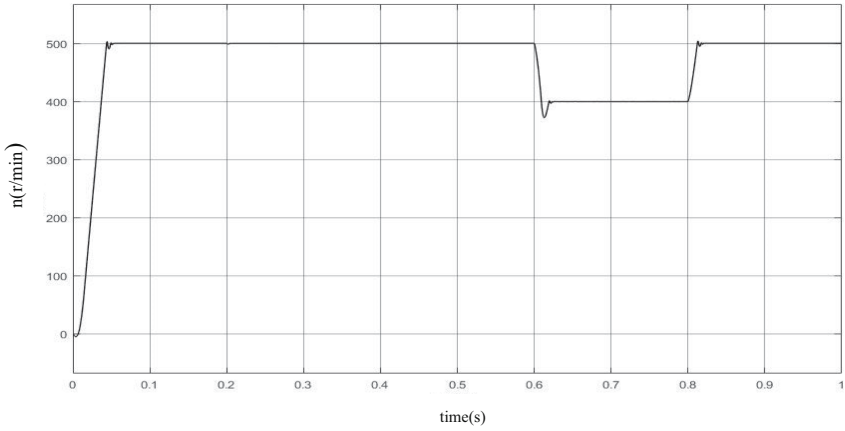


Fig. 1. Speed response curve of traditional PI control

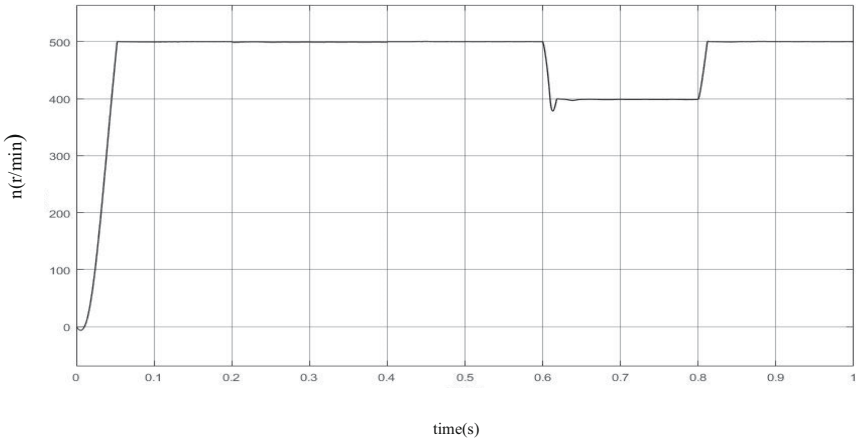


Fig. 2. Optimization controller

## 5 Conclusion

In this paper, through the theoretical analysis of the advantages and disadvantages of the asynchronous motor control system, combined with the asynchronous motor mathematical model, fuzzy and sliding method control theory, the simulation model of the frequency conversion speed control system of the shearer's traction unit based in fuzzy sliding mode control is established. Matlab tools are used to simulate the actual running of asynchronous motor, and then the simulation curves are analyzed theoretically. The results show that the fuzzy sliding mode control system is faster than the traditional PI algorithm system, which proves the correctness and feasibility of the design.

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