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Self organizing fuzzy sliding mode controller for the position control of a permanent magnet synchronous motor drive

Yajun Guo *, **Huo Long**

School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

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KEYWORDS

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Abstract In this paper, a self organizing fuzzy sliding mode controller (SOFSMC) which emulates the fuzzy controller with gain auto-tuning is proposed for a permanent magnet synchronous motor (PMSM) drive. The proposed controller is used for the position control of the PMSM drive. The performance and robustness of the control system is tested for nonlinear motor load torque disturbance and parameter variations. It has a novel gain self organizing strategy in response to the transient or tracking responses requirement. To illustrate the performance of the proposed controller, the simulation studies are presented separately for the SOFSMC and the fuzzy controller with gain auto-tuning. The results are compared with each other and discussed in detail. Simulation results showing the effectiveness of the proposed control system are confirmed under the different position changes.

* Corresponding author. Address: Department of Aeronautics and Astronautics, School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China. Tel.: +86 25 15105166003.
E-mail address: gyj198203@163.com (Y. Guo).

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1. Introduction

A mechanism driven by a PMSM is today the most widely used due to the advantageous merits of cost, reliability, and performances. The PMSM is characterized by complex, highly non-linear, time varying dynamics, inaccessibility of some states and output for measurements and hence can be considered as a challenging engineering problem [1]. Some control techniques such as nonlinear control [2,3], sliding mode control [4] and intelligent control [5–7] have been developed to overcome these problems for speed and position control of the PMSM drive.

Fuzzy logic controllers (FLCs) have been used in many areas after fuzzy set theory was first introduced by Zadeh [8]. Fuzzy control (FC) does not need a mathematical model and is more insensitive to plant parameter variations and noise disturbance. Classically, fuzzy variables have been adjusted by expert knowledge. However, the design of FC has relied on trial and error. In practice, a precise knowledge of the plant of the complex systems is often difficult to obtain. So an efficient FC cannot be expected [9]. In recent years, to tackle this problem, the attractive approaches are provided by the neural networks. Generally, this control strategy is called as neuro-fuzzy controllers (NFCs). A NFC is suitable for control of systems consisting of uncertainties and nonlinearities. Although the NFC approaches can also achieve self-learning, it is inappropriate for on-line learning real-time control, since the learning process is time-consuming [10–12].

In addition, the fuzzy rules number will influence the controller accuracy and implementation consideration. Recently, some researchers propose the design methods of fuzzy control system based on sliding-mode approach. These approaches are referred to as fuzzy sliding-mode control (FSMC) design methods. By defining the sliding surface as the input variable of fuzzy inference rules, the number of fuzzy rules can be reduced to a minimum number. In this way, the chattering came out along the sliding surface is solved by FC Huang et al. [13].

A mechanism actuated by a permanent magnet synchronous servo motor using FC with a novel gain auto-tuning and self organizing fuzzy sliding mode control systems are described in this study. The new type of FC system is proposed which contains three sets of fuzzy logic. The rule modifier is a fuzzy learning algorithm that will execute the modification of control rules. Moreover, the SOFSMC system combines the fuzzy learning capability of the FC system, and the robust characteristics of the sliding-mode control technique. By defining the sliding surface as input variable of fuzzy rules, the SOFSMC uses the minimum number of fuzzy rules. In addition, simulated results due to position step and sinusoidal commands are provided to show the effectiveness of the FC and the SOFSMC systems, and the SOFSMC can reduce implementation complexity when compared with FC.

2. Modeling of the PMSM drive system

The mathematical model is similar to that of the wound rotor synchronous motor. Since there is no external source connected to the rotor side and variation in the rotor flux with respect to time is negligible, there is no need to include the rotor voltage equations. Rotor reference frame is used to derive the model of the PMSM [14,15].

The electrical dynamic equation in terms of phase variables can be written as:

$$U_A = R_s i_A + p\Psi_A \tag{1}$$

$$U_B = R_s i_B + p\Psi_B \tag{2}$$

$$U_C = R_s i_C + p\Psi_C \tag{3}$$

where U_A, U_B and U_C are instantaneous phase voltages, i_A, i_B and i_C are instantaneous phase currents, R_s is phase resistant, p is derivative operator, Ψ_A, Ψ_B and Ψ_C are rotor coupling flux linkage.

While the flux linkage equations are:

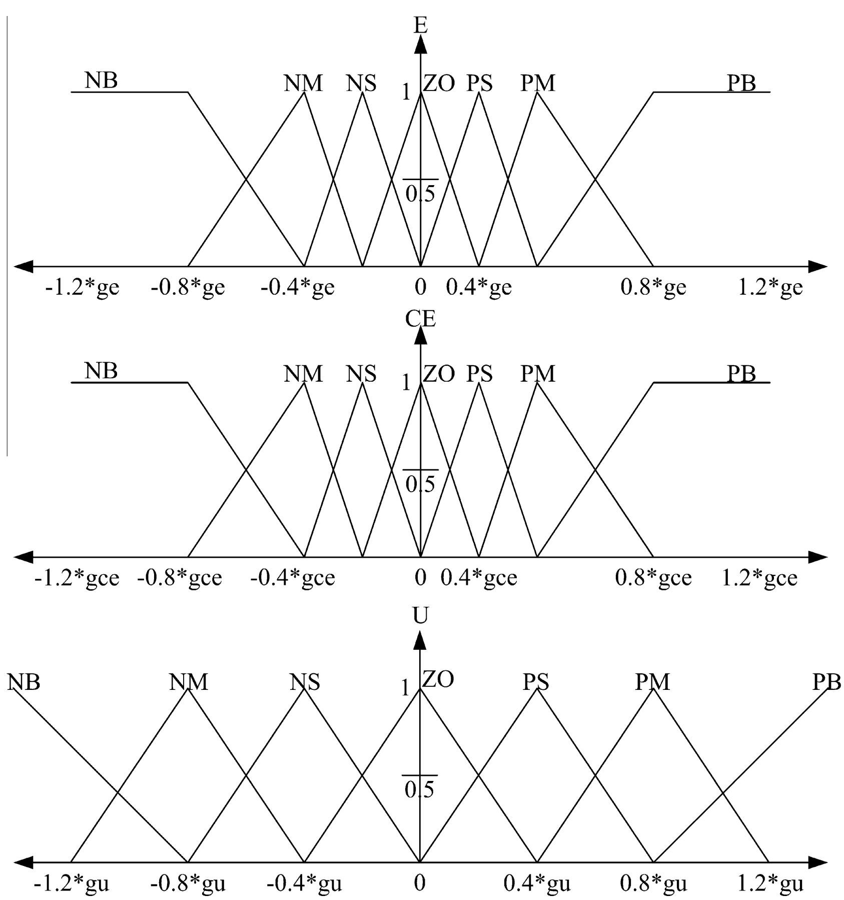


Figure 1 Fuzzy input and output variables membership functions.

Table 1 Fuzzy gains scaling factors.

Gain factor	*ge*	*gce*	*gu*
e > 0.01 degree	5	5	5
0.001 degree < e < 0.01 degree	exp (9e-4×|e|)	exp(9e-4×|ce|)	exp(1.8e-4×|e|)
e 0.001 degree	0.004×|e| + 0.08	0.004×|ce| + 0.04	0.004×|e| + 0.008

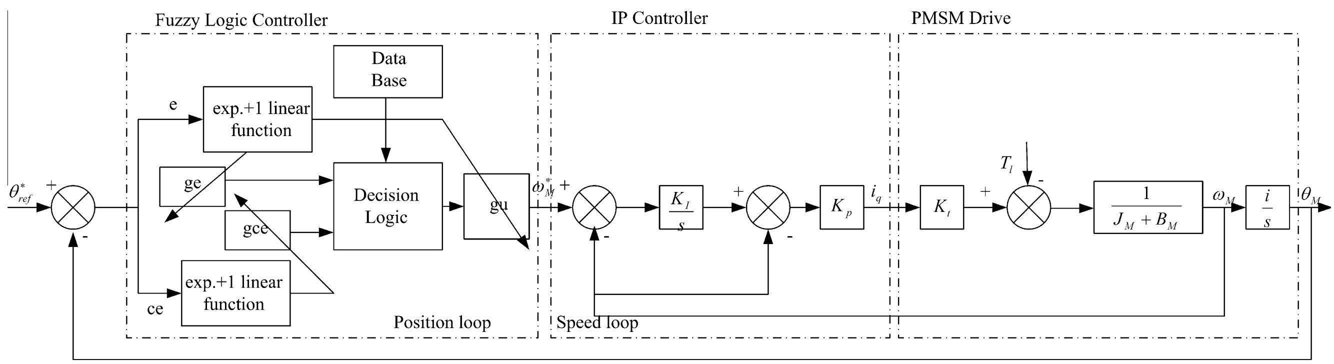


Figure 2 Simplified block diagram of PMSM drive for the fuzzy logic control with gain auto-tuning.

$$\Psi_A = L_s i_A + \Psi_r \cos\theta \tag{4}$$

$$\Psi_B = L_s i_B + \Psi_r \cos\left(\theta - \frac{2\pi}{3}\right) \tag{5}$$

$$\Psi_C = L_s i_C + \Psi_r \cos\left(\theta + \frac{2\pi}{3}\right) \tag{6}$$

where L_s is phase inductance.

The transformation from three-phase to two-phase quantities can be written in matrix form as:

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix} \tag{7}$$

Where U_α and U_β are orthogonal space phasor.

The Park transformation in matrix form can represented as:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} \tag{8}$$

According to the above transformation Eqs. (7) and (8), dq/ABC transformation may be written:

$$\begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} U_d \\ U_q \end{bmatrix} \tag{9}$$

Substituting (7)–(9) in (1)–(3), we get a set of simple transformed equations as:

$$\begin{cases} U_d = R_s i_d + pL_d i_d + p\Psi_r - \omega_r \Psi_q \\ U_q = R_s i_q + pL_q i_q + \omega_r \Psi_d \end{cases} \tag{10}$$

L_d and L_q are called *d*-and *q*-axis synchronous inductances, respectively, ω_r is motor electrical speed.

The produced torque T_e, which is power divided by mechanical speed can be represented as:

$$T_e = \frac{3}{2} p_n (\Psi_r i_q + (L_d - L_q) i_d i_q) \tag{11}$$

where p_n is pole logarithm.

It is apparent from the above equation that the produced torque is composed of two distinct mechanisms. The first term corresponds to "the mutual reaction torque" occurring between i_q and the permanent magnet, while the second term corresponds to "the reluctance torque" due to the differences in *d*- and *q*-axis reluctance [18]. Note that $L_d = L_q = L_s$ for the motor, so an expression for the torque generated by a PMSM is:

$$T_e = \frac{3}{2} p_n \Psi_r i_q \tag{12}$$

In the presence of a *d*-axis stator current, the *d*- and *q*- axis currents are not decoupled, and the model is nonlinear. It can be seen in the torque term Eq. (11). Under the assumption that $i_d = 0$, the system becomes linear and resembles, Thus vector control of PMSM provides approximate desired dynamic characteristics.

In general, the mechanical equation of the PMSM can be represented as:

$$T_e = J_M \dot{\omega}_M + T_d + B_M \omega_M \tag{13}$$

Where ω_M is the rotor angular speed, J_M is the motor moment inertia constant, B_M is the total damping coefficient, T_d is the torque of the motor external load disturbance, T_e denotes the

Table 2 Fuzzy logic control rules table.

U		e						
		NB	NM	NS	ZO	PS	PM	PB
ce	NB	NB	NB	NB	NB	NM	ZO	ZO
	NM	NB	NB	NB	NB	NM	ZO	ZO
	NS	NM	NM	NM	NM	ZO	PS	PS
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NS	NS	ZO	PM	PM	PM	PM
	PM	ZO	ZO	PM	PB	PB	PB	PB
	PB	ZO	ZO	PM	PB	PB	PB	PB

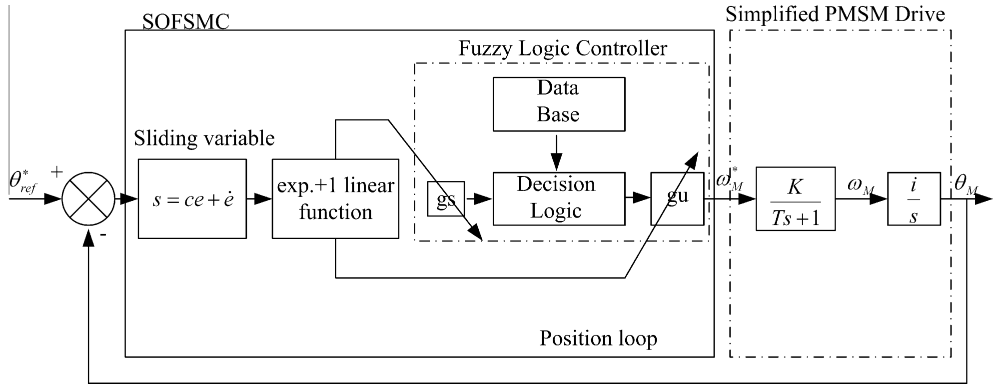


Figure 3 Simplified block diagram of PMSM drive for the SOFSMC.

Table 3 SOFSMC parameters.

Gain factor	*gs*	*gu*
s > 2.5	5	1.5
0.1 < s < 2.5	exp (9.2e-4×|s|)	exp (4e-5×|s|)
s < 0.1	0.0035×|s| + 0.01	0.001×|s| + 0.006

electromagnetic torque, (3/2) $p_n \Psi_r$ can be represented by K_t. Substituting K_t in (12), the torque expression is given by

$$T_e = K_t i_q \tag{14}$$

Substituting Eq. (14) into Eq. (13), the mechanical dynamic of the PMSM drive system can be represented as

$$\ddot{\theta}_M = -\frac{B_M}{J_M}\dot{\theta}_M + \frac{K_t}{J_M} i_q - \frac{T_d}{J_M} \tag{15}$$

3. Fuzzy logic control with gain auto-tuning

The major components of a fuzzy controller are a set of linguistic fuzzy control rules and an inference engine to interpret these rules. Every fuzzy control rule is composed of an antecedent and a consequent, a general form of the rules can be expressed as

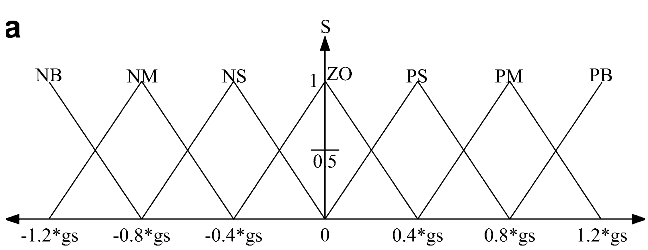
$$\text{IF(antecedent)THEN(consequent)}, \tag{16}$$

Where the antecedent refers to the found out situation concerning the control process dynamics and the consequent refers to the desired dynamics [16].

The output importance of each rule depends on the membership functions of the linguistic input and output variables. In this servosystem, two input indices of the fuzzy controller are position error *e* and error change *ce*, and the output index is control speed u. In order to simplify the computation of fuzzy controller, triangular membership functions and trapezoidal membership function are employed for fuzzy controller input variables *e* and *ce*. They are NB, NM, NS ZO, PS, PM, and PB. The membership functions of these fuzzy variables are shown in Fig. 1. The divisions of this membership functions can be expanded or shrunk by changing the scaling parameter of membership functions. This gain scaling parameter is used to map the corresponding variables into this nominal range. These mapping parameters are specified as *ge*, *gce* and *gu* for the position error, error change and control speed, respectively, whose values are shown in Table 1. The above design method can avoid the phenomenon of control law discontinuous jump of the traditional gain scheduling scheme and simplify the trial-and-error effort for designing the fuzzy rules Table 2. These parameters values are not critical for this gain auto-tuning fuzzy logic controller. The fuzzy logic control block diagram with gain auto-tuning system is show in Fig. 2.

In this paper, 49 fuzzy rules are employed to manipulate the position control by regulating the PMSM input speed, ω^*_M. Those fuzzy rules are listed in Table 2. the fuzzy controller will automatically calculate the control speed. However, a

a



b

Sliding variable	s						
	NB	NM	NS	ZO	PS	PM	PB
Control rule	NB	NM	NS	ZO	PS	PM	PB

Figure 4 The (a) fuzzy membership function of sliding variable and (b) fuzzy rules.

Table 4 Electromechanical coupling system parameters.

Features	Values
Number of poles (p_n)	4
Friction coefficient (B_M)	0.0001716 Nmsrad
Resistance (R_s)	1.32 Ω
Motor inertia (J_M)	1.034e-3 Nms
Maximum speed (ω_M)	2400 rpm
Winding inductance (L_s)	13.3 mh
Torque (T_e)	25 N.m
Reduction ration (i)	1/190
Horsepower	2.9HP
Max theoretical acceleration	61,300 rad/sec^2
Voltage	230 V

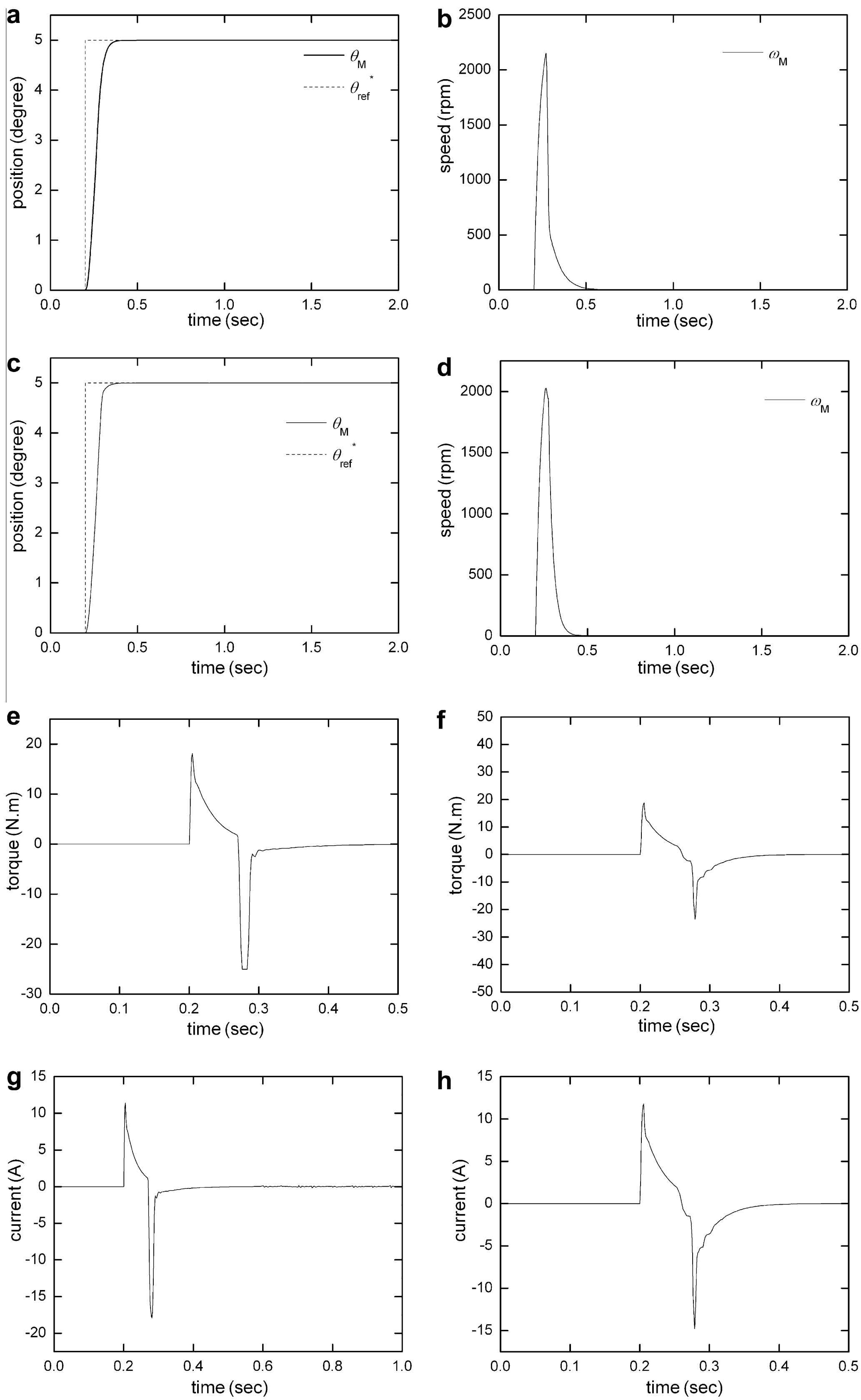


Figure 5 Fuzzy controller: (a) position step performance (b) speed performance (e) torque (h) current i_q. SOFSMC: (c) position step performance, (d) speed performance (f) torque (*i*) current i_q. Fig. 7. The fuzzy controller with the increased (six times) inertia: (a) the 20 degree reference, (b) the speed performance, (e) torque, (h) current i_q. The SOFSMC with the increased (six times) inertia: (c) the 20 degree reference, (d) the speed performance, (f) torque, (i) current i_q.

traditional mode-based controller must accurately identify the mathematical model of system and carefully design the controller parameters of each different step response to achieve position response and steady state accuracy. The height method is employed to defuze the fuzzy output variable for obtaining the control speed of PMSM drive. The relevant equation is

$$u = \frac{\sum_{i=1}^{49} u_i \mu_i}{\sum_{i=1}^{49} \mu_i} \tag{17}$$

Where μ_i is the linguistic value of the fuzzy set variable and u_i is the fuzzy control value of the ith fuzzy rule.

4. SOFSMC

Due to the velocity loop response is faster than the position loop response, that is, the cut-off frequency of the position loop is far less than inverse of the time constant of the velocity loop, so the velocity loop can be equivalent to the first-order inertia link as analytic system [17]. The simplified structure diagram of position control system based the designed SOFSMC controller is described in Fig. 3.

Let $x_1 = \theta_M$, $x_2 = \omega_M = \dot{\theta}_M$, state space equation of position servo system is:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{T} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{Ki}{T} \end{bmatrix} u \tag{18}$$

Where T is L_s/R_s, K is the system gain, i is reduction rate.

The position error is

$$e = \theta^*_{ref} - \theta_M \tag{19}$$

Switching surface is designed as:

$$s = ce + \dot{e} \tag{20}$$

Where c is set as a positive constant.

The equivalent control method of the sliding mode state space equation is expressed as:

$$\dot{s} = c(\dot{\theta}^*_{ref} - \dot{\theta}_M) + \ddot{\theta}^*_{ref} - \dot{\omega}_M = 0 \tag{21}$$

According to Eqs. (21) and (18) is obtained as:

$$u_{eq} = \frac{1}{Ki}[Tc\dot{\theta}^*_{ref} - T\ddot{\theta}^*_{ref} + (1 - Tc)\dot{\theta}_M] \tag{22}$$

Based on the developed switching surface, a switching control law satisfies the hitting condition. The switching control function is indicated as:

$$u_s = \varepsilon \mathrm{sgn}(s) \tag{23}$$

Where ε is set as a positive constant.

A sliding mode controller can be express as:

$$u = u_{eq} + u_s \tag{24}$$

According to above equations, we obtain

$$s\dot{s} = s\left(-\frac{Ki}{T}\varepsilon \cdot \mathrm{sgn}(s)\right) = -\frac{Ki}{T}\varepsilon|s| < 0 \tag{25}$$

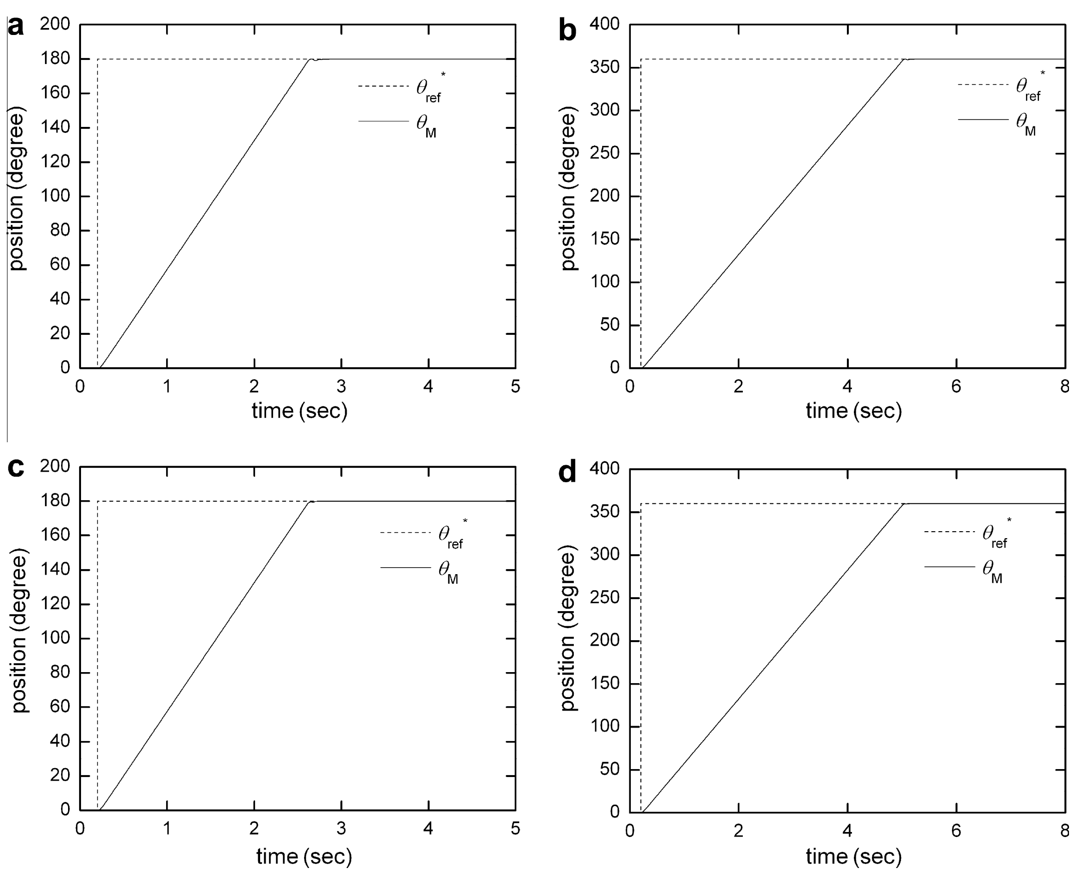


Figure 6 The increased (six times) inertia for the fuzzy control: (a) the 180 degree position reference, (b) the 360 degree position reference. The increased (six times) inertia for the SOFSMC: (c) the 180 degree position reference, (d) the 360 degree position reference.

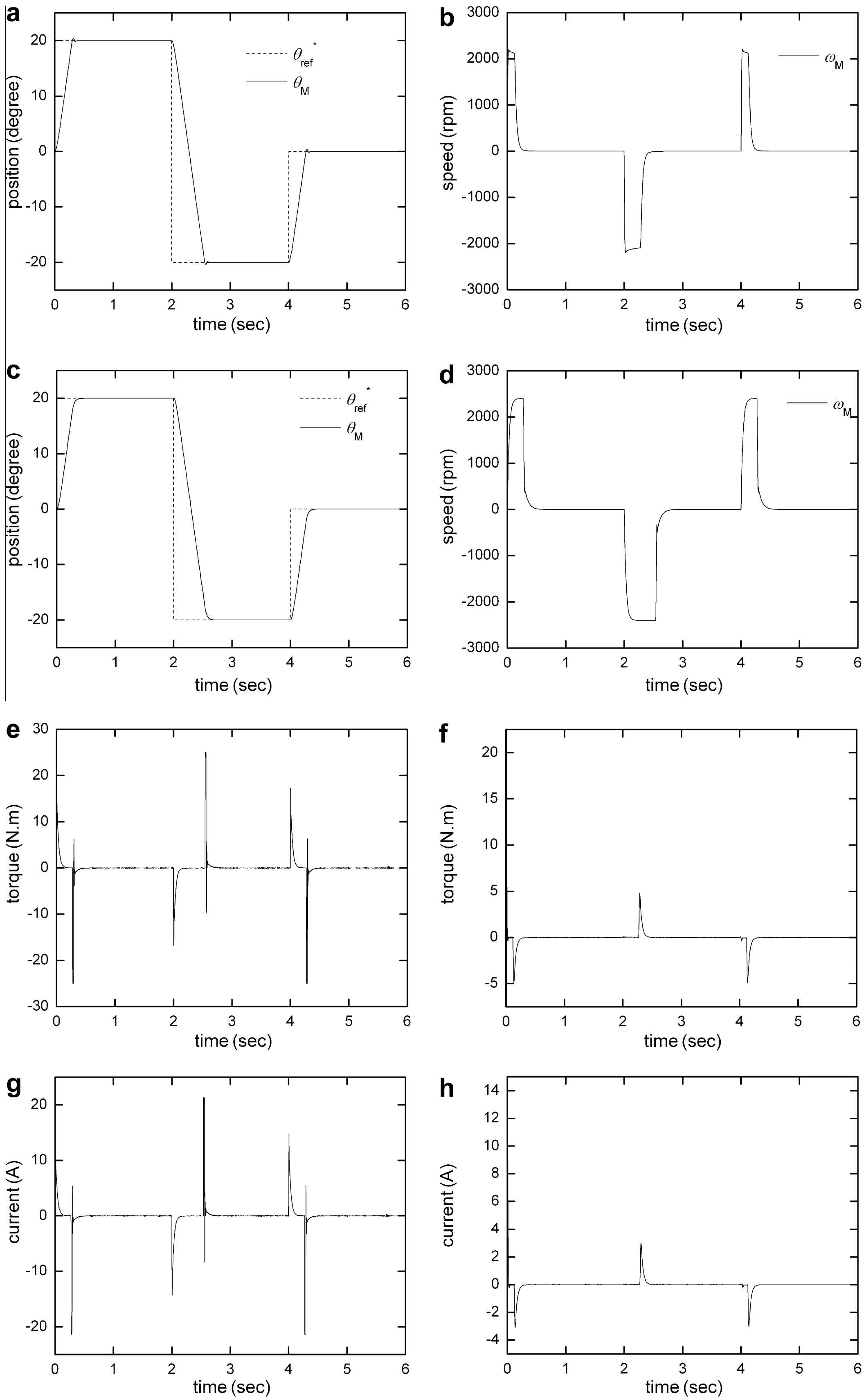


Figure 7 The fuzzy controller with the increased (six times) inertia: (a) the 20 degree reference, (b) the speed performance, (e) torque, (h) current i_q. The SOFSMC with the increased (six times) inertia: (c) the 20 degree reference, (d) the speed performance, (f) torque, (i) current i_q.

Based on the Lyapunov theorem, the sliding surface reaching condition is $s\dot{s} < 0$. Therefore, the system is globally stable. If a control input u can be chose to satisfy this reaching condition, the control system will converge to origin of the phase plane. The relating theory about the convergence and stability of adaptation process on the basis of the minimization of $s\dot{s}$ can be found in Ref. [18].

Here, a fuzzy logic control is employ to approximate the nonlinear of equivalent control law. The control speed for each step is derived from fuzzy inference and defuzzification calculation instead of the equivalent control law derived form the nominal model at the sliding surface. The proposed SOFSMC scheme does not need the robust term to compensate the system mathematical model uncertainty. Hence, it can eliminate the chattering phenomenon of a traditional sliding mode control. Membership functions of fuzzy input and output variables, and the fuzzy rules of the SOFSMC are shown in Fig. 4a and b, respectively.

The membership functions can be expanded or shrunk by changing the scaling parameters of the membership function. The gain self organizing parameter is used to map the corresponding variables into this nominal range. These parameters are specified as gs and gu respectively. Whose nonlinear functions are shown in Table 3. These gain scaling parameters are continuous functions of state control error during the whole control history, this design method can avoid the control law discontinuous jump of a traditional gain scheduling scheme and simplify the trial-and-error effort for designing the fuzzy rules table. The values of these parameters are not important for this gain self organizing fuzzy sliding mode controller. The same gain self organizing functions are suitable for various position responses. They can be determined by simple simulation tests. Then the same values can be employed for different position step value to achieve appropriate speed performance and tracking error.

5. Simulation

To give the further comparison, the proposed SOFSMC and fuzzy controller with auto-tuning will be used to control the following PMSM drive system, respectively. The parameters of the motor are given in Table 4. The proposed SOFSMC parameters are chosen as follows:

$c = 35, K_s = 0.01, K_u = 28.$

Where K_s and K_u are input and output parameters, respectively.

The simulation for the SOFSMC is run under the assumption that the system parameters and the nonlinear functions are unknown. And the inverter topology in this paper is AC–DC–AC, which is ignored for impact on motor.

In this section, a step change is specified to evaluate the control performance of these controllers described in previous section. The gain auto-tuning parameters are listed in Tables 1 and 3. The position response and the speed reference values are shown in Fig. 5. It can be observed that the position response can achieve good response, but the speed change, torque change and current i_q may be complicated for the fuzzy controller.

In electrical drives, the most important parameters affecting the robustness are inertia (J_M) and load torque of the motor. Therefore, the robustness of the servo system is tested under inertial variation and unwanted disturbances. First, inertia of the motor is increased approximately six times of the nominal inertia. The simulation result given in Fig. 6 displays the position step performance for the different step value with the increased (six times) inertia between the fuzzy controller and the SOFSMC. It should be noted that the good performance is obtained under the SOFSMC. The overshoot is not seen in low reference and high reference for the SOFSMC.

Position tracking performance for the fuzzy control and the SOFSMC are given in Fig. 7 under the same conditions in Fig. 6 and the similar performances are observed. Fig. 8 shows the sine position tracking performances of the fuzzy control

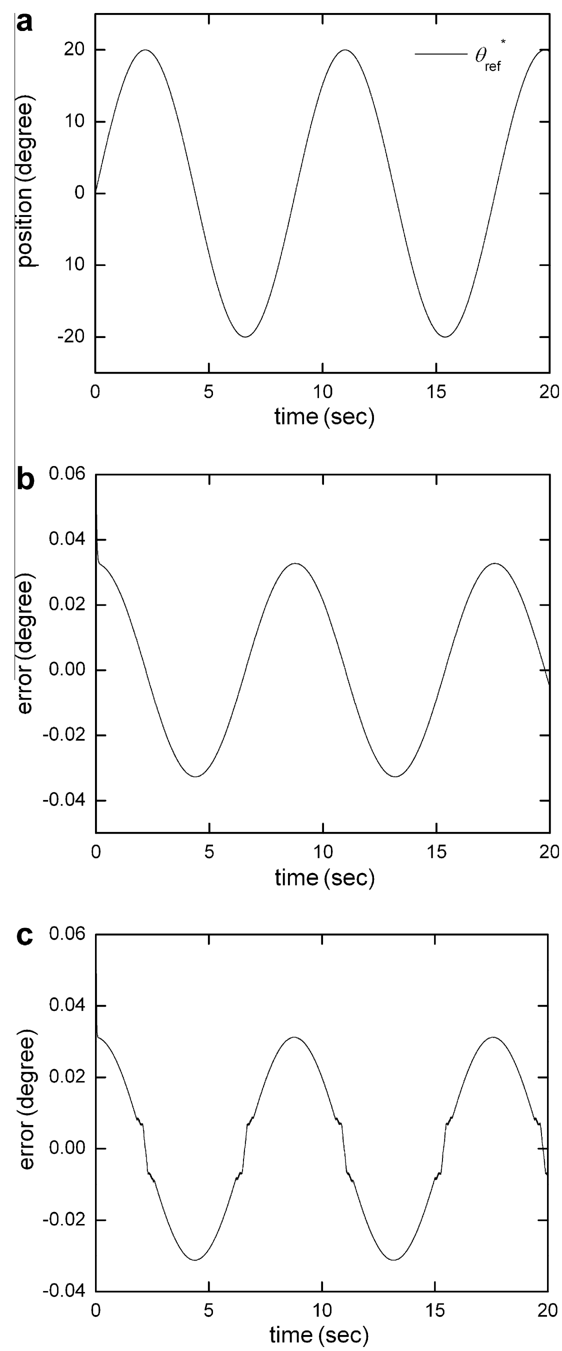


Figure 8 (a) The tracking reference, (b) the tracking error of the fuzzy control, (c) the tracking error of the SOFSMC.

and the SOFSMC for the nominal inertia. In can be observed that the tracking error of both intelligent fuzzy controllers are kept within 0.04 degree. In addition, all the step position response dynamic performance of both controller for the increased (six times) inertia are listed in Table 5 for comparison.

It can be concluded that the proposed self organizing fuzzy sliding mode control can be used to monitor different position step changes for nominal inertia and the increased (six times) inertia with almost zero overshoot. It has satisfied the data requirement of PMSM drive and industry applications.

Table 5 Performance comparison of the fuzzy control and the SOFSMC for increased (six times) inertia.

Step reference	Response performance	Fuzzy control with auto-tuning	SOFSMC
20 degree	Settling time (s)	0.42	0.42
	Overshoot (degree)	0.38	0
180 degree	Settling time (s)	2.64	2.56
	Overshoot (degree)	0.03	0
360 degree	Settling time (s)	5.05	4.93
	Overshoot (degree)	0	0

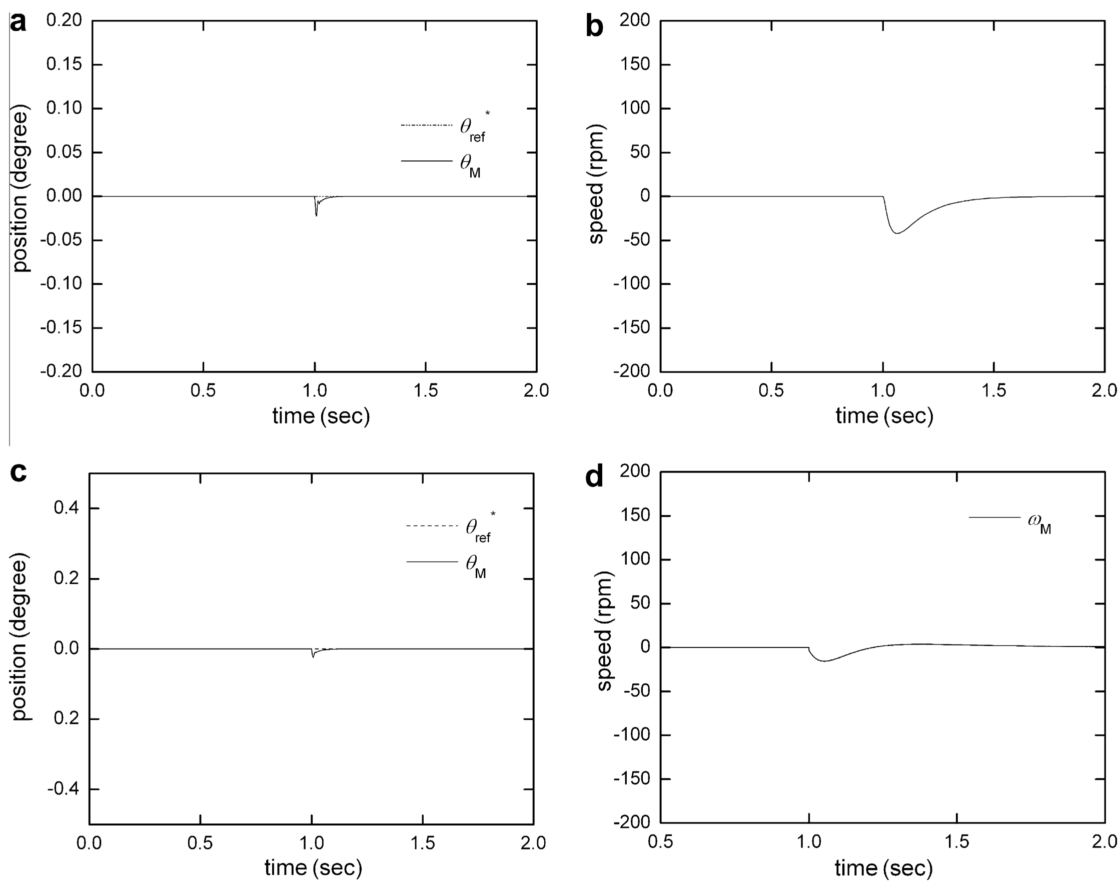


Figure 9 The fuzzy control with the load torque disturbance: (a) the 0 degree position, (b) the speed performance. The SOFSMC with the load torque disturbance: (c) the 0 degree position, (d) the speed performance.

Table 6 Summary of the simulation results.

Controllers	Position response for nominal inertia	Position response for increased (six times) inertia	Speed reference chattering in control position	Load disturbance on position	Position tracking error
The fuzzy controller with auto-tuning	Good	Good	High	Good	Good
The SOFSMC	Good	Very good	Low	Good	Good

Finally, Fig. 9 shows the performance of the fuzzy control and the SOFSMC when 60% load disturbances is applied. Load torque is applied to the system at the zero position reference as shown in Fig. 9a and c. In order to have a better view, the speed performances are given in Fig. 9b and d. It can be seen from the figures that the robustness of the two control system are acceptable, the change of the speed reference in the SOFSMC is less sensitive to the external load disturbance than that of the fuzzy controller.

Although, the fuzzy controller has good transient response and the small tracking error, it needs a 2-order fuzzy rules table to calculate the control law. Its computation effort may be complicated for a single chip embedded control system application. Hence, a 1-order SOFSMC with fuzzy rules is designed for this purpose.

The simulation results obtained from two controller are briefly summarized in Table 6. As shown in Table 6, the performance of the SOFSMC is better than the fuzzy control under different conditions.

6. Conclusion

Based on fuzzy technique, self organizing fuzzy sliding mode control scheme is proposed to control PMSM drive system. The nonlinear of the servo motor system is difficult to model and estimate. This speed reference is directly compensated by the fuzzy control rules. Both quick transient response and accurate tracking error can be achieved by using this novel approach compared to the fuzzy control with gain auto-tuning. The performance of the proposed controller is verified by the computer simulations. The simulation results show that the speed chattering or discontinuous jump behaviors of the control speed reference in the SOFSMC is less than the fuzzy control with gain auto-tuning. It can be concluded that the SOFSMC produces acceptable overshoot under the inertial variations and load disturbance between the low and high position references. In addition, the fuzzy rules of the fuzzy sliding mode controller are reduced from 49 to 7 for simplifying the implementation problem.

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Guo Yajun is Ph.D. at Department of Aeronautics and Astronautics, School of Mechanical Engineering, Nanjing University of Science and Technology.

Huo Long is Master at Department of Aeronautics and Astronautics, School of Mechanical Engineering, Nanjing University of Science and Technology.