International Journal of Innovative
Computing, Information and Control
Volume 11, Number 3, June 2015

ICIC International ©2015 ISSN 1349-4198
pp. 881–891

ADAPTIVE FUZZY SLIDING MODE CONTROL FOR PMSM POSITION REGULATION SYSTEM

Yue Wang and Juntao Fei

College of IOT Engineering
Hohai University
No. 200, North Jinling Rd., Changzhou 213022, P. R. China
wylucian@163.com

Received August 2014; revised December 2014

Abstract. *This paper investigates the position regulation problem of permanent magnet synchronous motor (PMSM) servo system based on adaptive fuzzy sliding mode control (AFSMC) method. Adaptive fuzzy sliding mode control is designed by using sliding surface as input of fuzzy controller, and adaptive fuzzy controller to approximate the equivalent control law, thus overcoming the impact of model inaccuracy and external disturbances. Then, sliding model controller is designed to compensate the error between the equivalent control law and the fuzzy controller by using adaptive method to estimate the upper bound of approximation error; meanwhile, adaptive fuzzy sliding mode control can weaken the chattering and improve the robustness of the system, make the motor position reach the reference value in finite time, obtaining a better tracking precision. Simulation results illustrate that the proposed control scheme has much better performance than that of conventional PI. Furthermore, parameter uncertainties and external disturbance are considered to highlight the robustness of the proposed control scheme.*

Keywords: Adaptive control, Permanent magnet synchronous motor, Position regulation, Adaptive fuzzy sliding mode control

1. **Introduction.** Permanent magnet synchronous motor (PMSM) plays a crucial part in many applications which have a high demand on fastness and precision due to their compact size, large torque-to-weight ratio, large torque-to-inertia ratio, low rotor losses and so on. The vector PI method is applied to decouple the PMSM, and transfer its mathematical model into the DC motor to be controlled easily, but this control method has some drawbacks in the motor applications [1]: complex coordinate transformation is needed when achieving this transformation. PMSM is largely dependent on the motor parameters, and cannot guarantee to be completely decoupled, then PMSM system using vector controller can be severely affected by a variety of internal and external disturbances, and only good control result can be obtained with appropriately selected parameters. Therefore, PMSM is easily subject to various uncertainties including parameter perturbations, unmodeled dynamics and external disturbances, which bring adverse impacts on performance specifications, furthermore, PMSM control system is time-varying and nonlinear with a strong coupling ability, so the vector control of PMSM cannot achieve high performance in actual circumstance.

In order to obtain better control results, some scholars began to study designing motion controller based on the speed and position control loop of the PMSM. In recent years, with the high development of modern control theory and motion control, many methods have been gradually applied to the nonlinear control theory which exists in PMSM system, such as adaptive control [1,4], disturbance rejection control [2,5,7], inversion control [3], limited time control [6], sliding mode control [7], robust control [8,9], predictive control [10-12], fractional control [13], and intelligent control [4,8]. These nonlinear control methods improve the performance of permanent magnet synchronous motor system. Among those control methods, researchers gradually found that time-varying and external disturbances can be simply dealt by sliding mode control [14]; however, when the structural parameters of the system is uncertain, it is difficult to directly obtain the equivalent control law. Bini and Ghaboussi [15] proposed neural network-based into the control of nonlinear structure. Casciati et al. [16] developed the strategy of the nonlinear control based on fuzzy control algorithm, but the traditional fuzzy control is difficult to be adaptive and largely dependent on the fuzzy control rule which is designed according to the comprehensive understanding of the structure's dynamic properties. The above problems have been solved by Wang et al. [17], who regarded the control system's state variables as input, then used an adaptive fuzzy system to approximate two-stage system, so generated the equivalent control law; however, when this method is used in the third-order system, the number of fuzzy rules will be increased exponentially.

During the past few years, many researchers have paid highly attention on the adaptive fuzzy sliding mode control method which combines the advantages of both sliding mode [18-21] and adaptive fuzzy control, and overcome their shortcomings, and the usage of sliding mode can easily solve impacts brought by the inaccurate model and the disturbance. In this paper, adaptive fuzzy sliding mode control is proposed to solve the position regulation problem of PMSM servo system. The contributions of the paper can be emphasized as follows.

(1) In order to improve the robustness of the PMSM system, an adaptive fuzzy system is designed by treating the switching function and its derivative as the input variables [22,23], the system controller consists of two parts: the adaptive fuzzy control and switching control, during the design process of adaptive fuzzy control, treat the sliding surface as the input of fuzzy controller, and approximate the equivalent control law by using the adaptive fuzzy controller, switching controller is used to compensate for the error between the equivalent control law and the fuzzy controller, and then use an adaptive method to estimate the upper bound of the approximation error.

(2) The method utilizes the switching controller to ensure the stability of the control system, and designs the adaptive fuzzy controller to adjust the switching controller's parameters, compensate the model uncertainties, thus greatly improving the robustness of the control system and control accuracy, making the motor position reach the reference value in finite time, and obtaining a better tracking precision.

2. **Dynamic Model of PMSM System.** In order to simplify the mathematic model, assume that the conductivity of the permanent magnet material is zero; the core saturation and winding leakage inductance are ignored, and there are no damper windings on the rotor; exclude the eddy current and hysteresis losses that the magnetic circuit is linear; EMF wave of the stator winding is sinusoidal phase, ignoring the higher harmonic of the magnetic field; when the permanent magnet synchronous motor rotor is mounted on the convex structure ($L_d = L_q = L$), the three-phase PMSM system's electrical equation in d-q rotating reference can be expressed as follows:

$$\begin{bmatrix} \dot{i}_q \\ \dot{i}_d \\ \dot{\omega}_\gamma \end{bmatrix} = \begin{pmatrix} -R_s/L & -\omega_\gamma & -\psi_f/L \\ \omega_\gamma & -R_s/L & 0 \\ p_n^2\psi_f/J & 0 & -B/J \end{pmatrix} \begin{bmatrix} i_q \\ i_d \\ \omega_\gamma \end{bmatrix} + \begin{bmatrix} u_q/L \\ u_d L \\ -p_n T_1/J \end{bmatrix} \tag{1}$$

where u_d, u_q, L_d, L_q, i_d, i_q are d, q frame inductance, stator voltage and current respectively; w_γ is speed of the rotor; R_s is stator resistance; p_n is pole number; ψ_f is flux linkage; J is rotor inertia; and T_1 is load torque.

The simulation model of PMSM system usually consists of three closed-loops for position, speed and current. Here two PI controllers, which are used to stabilize the axes current errors and speed error, are adopted in the current and speed loops respectively. According to field oriented vector control ($i_d = 0$) and Clark/Park transformation, a control configuration of the PMSM system is illustrated in Figure 1, and we mainly design a controller for position loop.

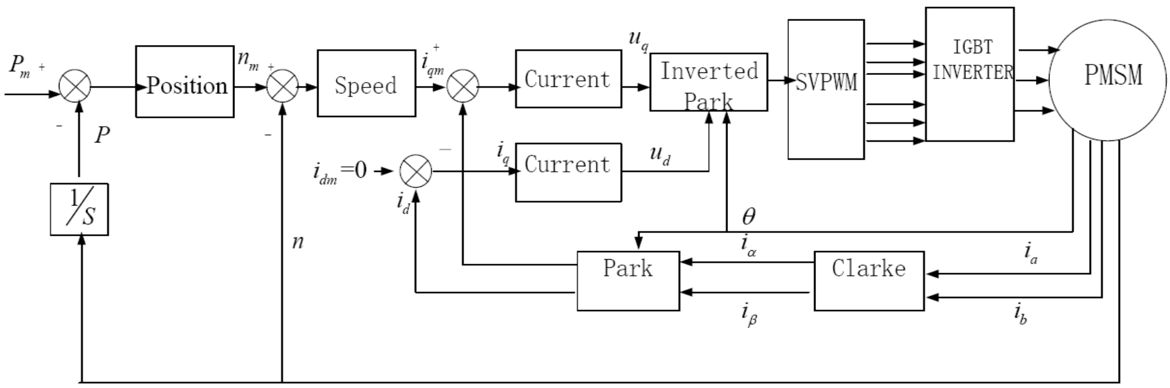

FIGURE 1. Control configuration of the PMSM system

p_m is the reference position; p and n are the position and speed of the rotor measured by encoder.

$$\dot{p} = w_\gamma \tag{2}$$

As shown in Figure 1, it has an inner loop of current regulation using space vector control for fast tracking the current vector and torque-pulsation reduction, and a speed loop for driving the rotor to the desired speed. The position control loop, which is also the outermost loop for compensating the current and speed loop, is to hold the rotor at desired position. In $i_d = 0$ control mode, from Equations (1) and (2)

$$\ddot{p} = -\mathrm{B}/\mathrm{J}\,\dot{p} + P_n^2\psi_f/Ji_q - P_nT_1/J \tag{3}$$

$$f = -\mathrm{B}/\mathrm{J}\,\dot{p}, \quad g = P_n^2\psi_f/J, \quad d = -P_nT_1/J, \quad u = i_q$$

Then:

$$\ddot{p} = f + gu + d \tag{4}$$

where u denotes the input control parameter.

3. **AFSMC System Design.** Although classical control is able to meet the demands of the system, however, there are still some limitations in classical control system's performance, which is highly dependent on the system's model. Thus, an adaptive fuzzy sliding control system, as shown in Figure 2, is proposed to deal with this problem.

Regard the ideal dynamic characteristics p_m as the reference trajectory.

Tracking error is defined as:

$$e(t) = p(t) - p_m(t) \tag{5}$$

Define the sliding surface s as:

$$s(t) = \dot{p}(t) - \int_0^t \left[\ddot{p_m}(\tau) - k_1\,\dot{e}(\tau) - k_2 e(\tau)\right] d\tau \tag{6}$$

where k_1, k_2 are non-zero positive constants.

If the sliding surface is in the ideal state, then $s = \dot{s} = 0$, and we obtain

$$\ddot{e}(t) + k_1 \dot{e}(t) + k_2 e(t) = 0 \tag{7}$$

It can easily be seen that, by determining the suitable k_1, k_2, a tracking error will exponentially approach zero.

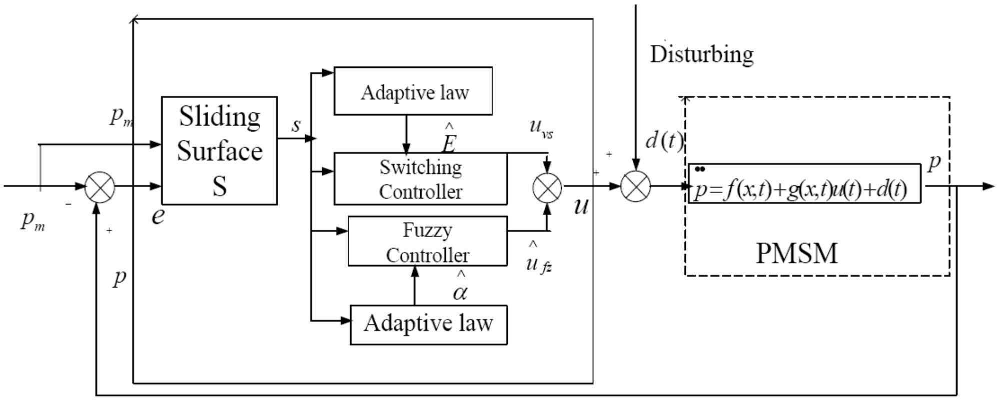

Figure 2. Block diagram of adaptive fuzzy sliding mode control system

Case 1: Assuming that f, g and d are known.

Substituting (7) to (5), the equivalent control law can be obtained as:

$$\overset{*}{u}(t) = {}^{1}\!/_{g}\left[\ddot{\theta}_m(t) - k_1 \dot{e}(t) - k_2 e(t) - f - d\right] \tag{8}$$

Case 2: Assuming that f, g and d are unknown.

Because f, g and d are unknown, it is difficult to use $\overset{*}{u}(t)$ in some practical needs, and we use fuzzy systems to approach $\overset{*}{u}(t)$.

Taken a_1 as adjustable parameters, and then anti-fuzzy the fuzzy control, the fuzzy controller's output is:

$$u_{fz}(s, a) = a^T \xi \tag{9}$$

where $a = [a_1, a_2, \ldots, a_m]^T$, $\xi = [\xi_1, \xi_2, \ldots, \xi_m]^T$.

Define ξ_1 as

$$\xi_1 = \frac{w_i}{\sum_{i=1}^{m} w_i} \tag{10}$$

According to the universal approximation theory, there exists an optimal fuzzy control system to approach $\overset{*}{u}(t)$.

$$\overset{*}{u}(t) = u_{fz}(s, a^*) + \varepsilon = a^{*T}\xi + \varepsilon \tag{11}$$

where ε is approximation error, and meets the condition: $|\varepsilon| < E$.

Use the fuzzy control system to approach $\overset{*}{u}(t)$

$$u_{fz}(s, \hat{a}) = \hat{a}^T \xi \tag{12}$$

where $\hat{a}$ is the estimated value of a^*.

The total control law is designed as follows:

$$u(t) = u_{fz}(s, \hat{a}) + u_{vs}(s) \tag{13}$$

where $u_{vs}(s)$ is the switching control law, by using it to compensate for the approximation error.

Substituting (14) into (5) yields:

$$\ddot{p}(t) = f + g\left[u_{fz}(s,\hat{a}) + u_{vs}(s)\right] + d \tag{14}$$

By differentiating (7) with respect to time and using (9) and (13), we obtain that:

$$\begin{aligned}\dot{s} &= f + g\left[u_{fz}(s,\hat{a}) + u_{vs}(s)\right] + d - f - d - g\,\overset{*}{u}(t)\\ &= g\left[u_{fz}(s,\hat{a}) + u_{vs}(s) - \overset{*}{u}(t)\right]\end{aligned} \tag{15}$$

According to (12), we obtain

$$\tilde{u}_{fz} = \hat{u}_{fz} - u^* = \hat{u}_{fz} - u^*_{fz} - \varepsilon \tag{16}$$

with the assumption that $\tilde{a} = \hat{a} - a^*$, (17) becomes

$$\tilde{u}_{fz} = \tilde{a}^T\xi - \varepsilon \tag{17}$$

For AFSMC, it needs the system to satisfy the reaching condition and the sliding condition, considering a Lyapunov function in the following form:

$$V_1(s(t),\tilde{a}) = \frac{1}{2}s^2(t) + \frac{1}{2\eta_1}\tilde{a}^T\tilde{a} \tag{18}$$

where η_1 is a positive real parameter.

By differentiating (19) with respect to time and using (16), we obtain:

$$\begin{aligned}\dot{V}_1(s(t),\tilde{a}) &= s(t)\,\dot{s}(t) + \frac{1}{2\eta_1}\left(\tilde{a}^T\,\dot{\tilde{a}} + \dot{\tilde{a}}^T\tilde{a}\right)\\ &= s(t)\left[u_{fz}(s,\hat{a}) + u_{vs}(s) - \overset{*}{u}(t)\right] + \frac{1}{\eta_1}\tilde{a}^T\,\dot{\tilde{a}}\\ &= s(t)\left[\tilde{a}^T\xi + u_{vs}(s) - \varepsilon\right] + \frac{1}{\eta_1}\tilde{a}^T\,\dot{\tilde{a}}\\ &= \tilde{a}^T\left(s(t)\xi + \frac{1}{\eta_1}\dot{\tilde{a}}\right) + s(t)\left(u_{vs}(s) - \varepsilon\right)\end{aligned} \tag{19}$$

where $\tilde{a}^T\,\dot{\tilde{a}}$ are scalar, therefore, $\tilde{a}^T\,\dot{\tilde{a}} = (\tilde{a}^T\,\dot{\tilde{a}})^T = \dot{\tilde{a}}^T\,\tilde{a}$, which also means that $\tilde{a}^T\,\dot{\tilde{a}} + \dot{\tilde{a}}^T\,\tilde{a}$ $= 2\tilde{a}^T\,\dot{\tilde{a}}$. In order to reach the condition that $\dot{V}_1(s(t),\tilde{a}) \le 0$, given that the first term is always zero, using the following adaptive law and switching control law:

$$\dot{\tilde{a}} = -\eta_1 s(t)\xi \tag{20}$$

$$u_{vs}(s) = -E sgn(s(t)) \tag{21}$$

Then, substituting (21), (20) into (19), we get:

$$\begin{aligned}\dot{V}_1(s(t),\tilde{a}) &= -E\left|s(t)\right| - \varepsilon s(t) \le -E\left|s(t)\right| + |\varepsilon|\left|s(t)\right|\\ &= -\left(E - |\varepsilon|\right)\left|s(t)\right| \le 0\end{aligned} \tag{22}$$

In actual control, it is difficult to determine the switching gain $E(t)$, and the unsuitable $E(t)$ will have an adverse impact on the system, and even cause system unstable.

Replacing $E(t)$ with $\hat{E}(t)$, we get:

$$u_{vs}(s) = -\hat{E}(t)\mathrm{sgn}(s(t)) \tag{23}$$

where $\hat{E}(t)$ is estimated switching gain.

Define the estimated error as:

$$\tilde{E}(t) = \hat{E}(t) - E(t) \tag{24}$$

Consider the Lyapunov function candidate in the following form:

$$V\left(s(t), \tilde{a}, \tilde{E}(t)\right) = V_1\left(s(t), \tilde{a}\right) + \frac{1}{2\eta_2}\tilde{E}^2 = \frac{1}{2}s^2(t) + \frac{1}{2\eta_1}\tilde{a}^T\tilde{a} + \frac{1}{2\eta_2}\tilde{E}^2 \tag{25}$$

where η_2 is a positive real parameter.

By differentiating (25) with respect to time and using (20) and (24), we obtain:

$$\begin{aligned}\dot{V}\left(s(t), \tilde{a}, \tilde{E}(t)\right) &= \dot{V}_1\left(s(t), \tilde{a}\right) + \frac{1}{\eta_2}\tilde{E}\,\dot{\tilde{E}} = \tilde{a}^T\left(s(t)\xi + \frac{1}{\eta_1}\dot{\tilde{a}}\right) + s(t)\left(u_{vs}(s) - \varepsilon\right) + \frac{1}{\eta_2}\tilde{E}\,\dot{\tilde{E}} \\ &= -\hat{E}(t)\left|s(t)\right| - \varepsilon s(t) + \frac{1}{\eta_2}\left(\hat{E} - E\right)\dot{\tilde{E}} \\ &= -\hat{E}(t)\left(\left|s(t)\right| - \frac{1}{\eta_2}\dot{\tilde{E}}\right) - \varepsilon s(t) + \frac{1}{\eta_2}\dot{\tilde{E}}\,E\end{aligned} \tag{26}$$

In order to reach the condition that $\dot{V}(s(t),\ \tilde{a},\ \tilde{E}(t)) \leq 0$, given that the first term is always zero, we get:

$$\dot{\tilde{E}} = \eta_2\left|s(t)\right| \tag{27}$$

By differentiating (20) with respect to time, we get:

$$\dot{\tilde{E}} = \dot{\hat{E}} - \dot{E}(t) \tag{28}$$

The value of $E(t)$ is fixed, so $\dot{E}(t) = 0$.

Substituting (28) into (27), we obtain adaptive law as follows:

$$\dot{\hat{E}} = \eta_2\left|s(t)\right| \tag{29}$$

Substituting (29) into (26), we obtain:

$$\begin{aligned}\dot{V}\left(s(t), \tilde{a}, \tilde{E}(t)\right) &= -E\left|s(t)\right| - \varepsilon s(t) \leq \left|\varepsilon\right|\left|s(t)\right| - E\left|s(t)\right| \\ &= -\left(E - \left|\varepsilon\right|\right)\left|s(t)\right| \leq 0\end{aligned} \tag{30}$$

Since $\dot{V}(s(t), \tilde{a}, \tilde{E}(t)) \leq 0$, all parameters in Lyapunov function are bounded.

Integrating the above equation, we get

$$\int_0^t \dot{V}(\tau)d(\tau) = V(t) - V(0) \leq -\int_0^t \left(E - \left|\varepsilon\right|\right)\left|s(\tau)\right| d\tau \tag{31}$$

Then:

$$V(t) + \int_0^t \left(E - \left|\varepsilon\right|\right)\left|s(\tau)\right| d\tau \leq V(0) \tag{32}$$

Because $V(0)$ is bounded and $V(t)$ is non-increasing and bounded, the following result can be obtained:

$$\lim_{t\to\infty} \int_0^t \left(E - \left|\varepsilon\right|\right)\left|s(\tau)\right| d\tau < \infty \tag{33}$$

According to Barbalat's lemma, it can be shown that $\lim_{t\to\infty}\left(E - \left|\varepsilon\right|\right)\left|s(t)\right| = 0$, and this implies that $\lim_{t\to\infty}\left|s(t)\right| = 0$. Then $\lim_{t\to\infty} e(t) = 0$.

4. **Simulation Study.** In order to explore the validity of the adaptive fuzzy sliding mode control and to verify the superiority of AFSMC compared with PI controller, AFSMC and PI controller are respectively used for position loops. We establish the simulation model of the PMSM control system in MATLAB/Simulink environment according to the PMSM mathematical model and AFSMC strategy, and then implement related simulation experiments to analyze the performances of control system. The parameters of PMSM model are listed as in Table 1.

Parameters of position loop's for PI controller are: $K_P = 11.7$, $K_i = 140$. Three fuzzy membership functions are selected: $\mu_{NM}(s) = \exp[-((s+\pi/23)/(\pi/24))^2]$, $\mu_{NS}(s) = \exp[-((s+\pi/46)/(\pi/24))^2]$, $\mu_{ZO}(s) = \exp[-(s/(\pi/24))^2]$.

We choose the suitable number $k_1 = k_2 = 200$, $\eta_1 = 210$, $\eta_2 = 30$.

The simulation results of the PMSM position and velocity using AFSMC and their comparisons with PI controller without load disturbance are shown in Figures 3 and 4. Comparison results of the position between AFSMC and PI controller in Figure 3 indicate that the system is stable and the control result is satisfactory. The position curve of the system using AFSMC can reach the reference value in a short time of 0.11s smoothly without shock and overshoot, while the traditional PI control reaches the reference value in 0.48. Simulation results indicate that the PMSM system based on AFSMC is effective.

To verify robustness against external disturbance for PMSM system using AFSMC, keep the system's parameters unchanged, and add a load disturbance of (2N/m) at the 0.2s, then the PMSM position, velocity, current and their comparisons are shown in Figures 5-7. The comparison of the position between AFSMC and PI controller under load disturbance in Figure 5 shows that AFSMC system has better performance compared with traditional PI control system in the presence of load disturbance.

The simulation result of the sliding surface is described in Figure 8, indicating that the sliding surface can converge to zero asymptotically. The input of control u in Figure 9 indicates that when E is estimated adaptively, it can automatically adjust the size of E, and greatly decrease chattering. Adaptive estimation of $\hat{E}(t)$ in Figure 10 shows that

Table 1. Parameters of PMSM model

Mark	value		Mark	value		Mark	value
R_s	2.875Ω		P	1		K_{Pc}	10.7
L_d	0.0085mH		U	31.7415V		K_{ic}	80
L_q	0.0085mH		J	$0.0008\text{Kg}\cdot\text{m}^2$		P_m	2
ψ_f	0.175Wb		K_{Ps}	11.7		t	0.6
B	0		K_{is}	140			

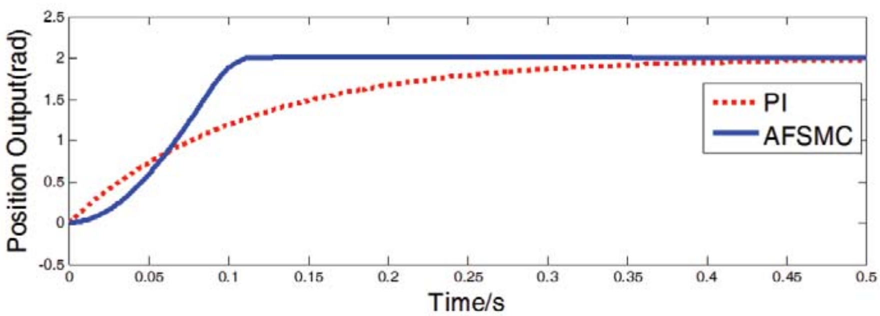

Figure 3. Comparison results of the position between AFSMC and PI controller

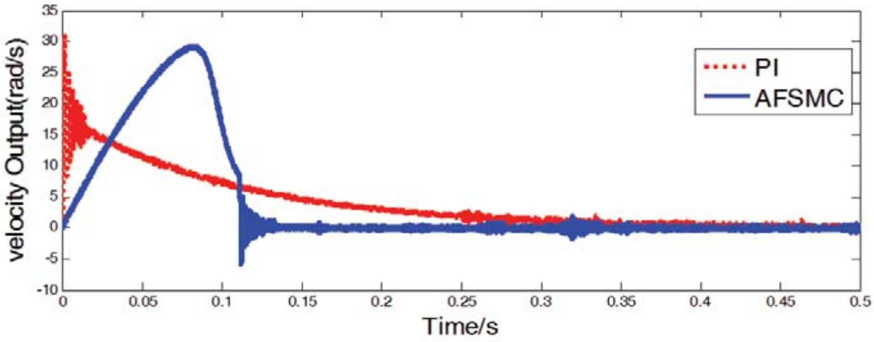

Figure 4. Comparison results of the velocity between AFSMC and PI controller

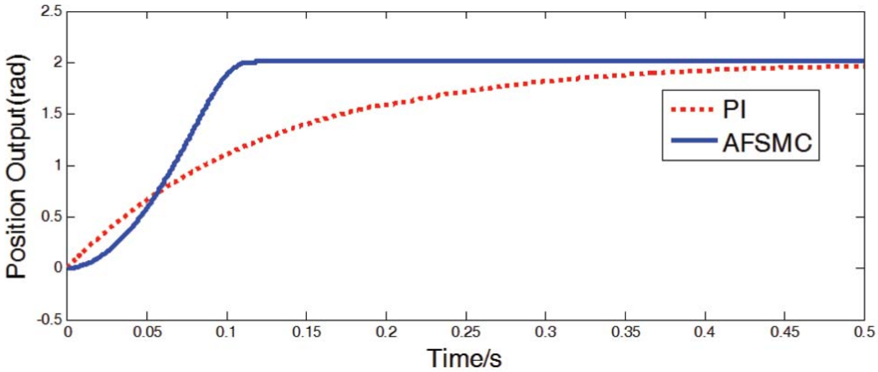

Figure 5. Comparison results of the position between AFSMC and PI controller under load disturbance

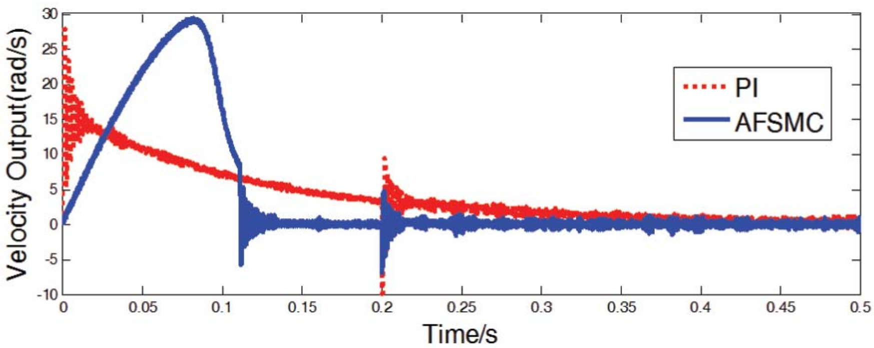

Figure 6. Comparison results of the velocity between AFSMC and PI controller under load disturbance

adaptive curve tends to final stable constant value. Simulation results demonstrate that PMSM control based on AFSMC has better robustness against load disturbance.

5. **Conclusions.** In this paper, a new AFSMC approach has been proposed for PMSM position system. To perform the AFSC, the dynamic model of the PMSM control system is transferred to a simplified form under the condition $(L_d = L_q = L)$ $(i_d = 0)$, where modeling error is considered. The main contribution here is to design two adaptive controllers, the switching controller is used to ensure the stability and fastness of the control system, and the adaptive fuzzy controller is used to adjust the switching controller's parameters, estimate and compensate the uncertainties of the PMSM control systems. In addition,

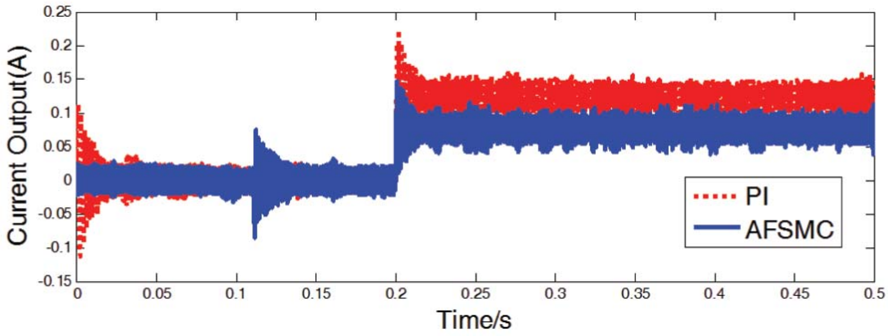

FIGURE 7. Comparison results of the current between AFSMC and PI controller under load disturbance

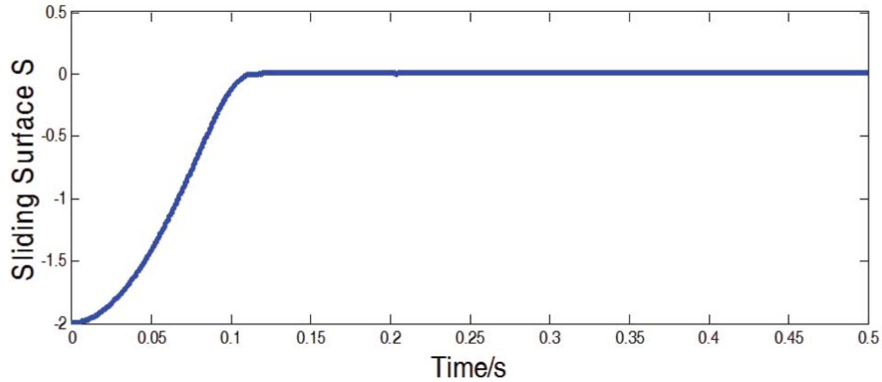

FIGURE 8. The simulation result of the sliding surface s

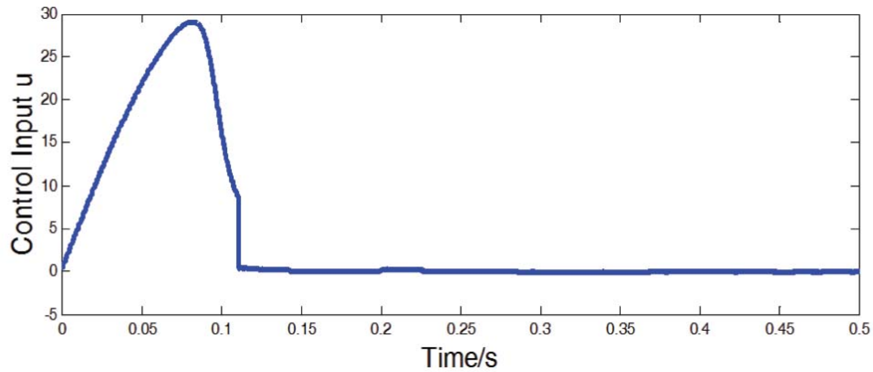

FIGURE 9. The simulation result of the control output u

the stability of the two proposed adaptive controllers and PMSM control system can be guaranteed by the Lyapunov theorem. Compared to the conventional PI, simulation results illustrate the superiority of the proposed AFSMC in the aspects of computation feasibility and robustness performance.

Acknowledgment. This work is partially supported by National Science Foundation of China under Grant No. 61374100; Natural Science Foundation of Jiangsu Province under Grant No. BK20131136; The Fundamental Research Funds for the Central Universities under Grant No. 2013B19314, 2014B04014.

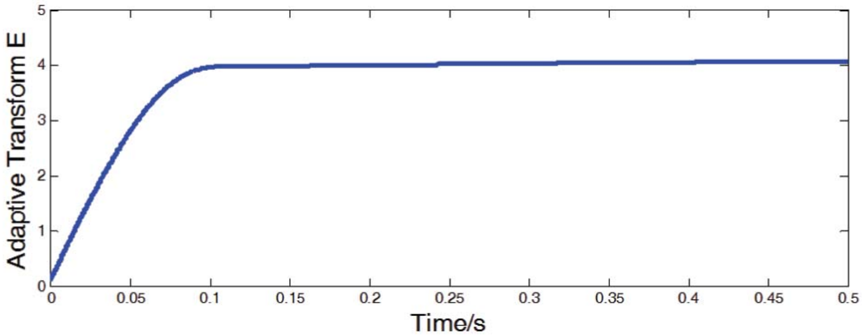

FIGURE 10. The simulation result of the adaptive transform $\hat{E}(t)$

REFERENCES

[1] Y. Mohamed, Design and implementation of a robust current-control scheme for a PMSM vector drive with a simple adaptive disturbance observer, *IEEE Trans. Ind. Electron.*, vol.54, no.4, pp.1981-1988, 2007.

[2] S. Li and Z. Liu, Adaptive speed control for permanent-magnet synchronous motor system with variations of load inertia, *IEEE Trans. Ind. Electron.*, vol.56, no.8, pp.3050-3059, 2009.

[3] J. Zhou and Y. Wang, Adaptive back stepping speed controller design for a permanent magnet synchronous motor, *IEE Proc. of Electric Power Appl.*, vol.149, no.2, pp.165-172, 2002.

[4] Y. Kung and M. Tsai, FPGA-based speed control IC for PMSM drive with adaptive fuzzy control, *IEEE Trans. Power Electron.*, vol.22, no.6, pp.2476-2486, 2007.

[5] Y. Su, C. Zheng and B. Duan, Automatic disturbances rejection controller for precise motion control of permanent-magnet synchronous motors, *IEEE Trans. Ind. Electron.*, vol.52, no.3, pp.814-823, 2005.

[6] S. Li and H. Liu, A speed control for a PMSM using finite-time feedback and disturbance compensation, *Trans. Inst. Meas. Contr.*, vol.32, no.2, pp.170-187, 2010.

[7] S. Li, K. Zong and H. Liu, A composite speed controller based on a second-order model of PMSM system, *Trans. Inst. Meas. Contr.*, vol.33, no.5, pp.522-541, 2011.

[8] R.-M. Jan, C.-S. Tseng and R.-J. Liu, Robust PID control design for permanent-magnet synchronous motor: A genetic approach, *Electric Power Syst. Res.*, vol.78, no.7, pp.1161-1168, 2008.

[9] F. El-Sousy, Hybrid H-infinity-based wavelet-neural-network tracking control for permanent-magnet synchronous motor servo drives, *IEEE Trans. Ind. Electron.*, vol.57, no.9, pp.3157-3166, 2010.

[10] P. Cortes, M. P. Kazmierkowski, R. M. Kennel, D. E. Quevedo and J. Rodriguez, Predictive control in power electronics and drives, *IEEE Trans. Ind. Electron.*, vol.55, no.12, pp.4312-4324, 2008.

[11] R. Errouissi, M. Ouhrouche, W.-H. Chen and A. M. Trzynadlowski, Robust nonlinear predictive controller for a PMSM with optimized cost function, *IEEE Trans. Ind. Electron.*, vol.59, no.7, pp.2849-2858, 2012.

[12] H. Liu and S. Li, Speed control for PMSM servo system using predictive functional control and extended state observer, *IEEE Trans. Ind. Electron.*, vol.59, no.2, pp.1171-1183, 2012.

[13] Y. Luo, Y. Chen, H.-S. Ahn and Y. Pi, Fractional order robust control for cogging effect compensation in PMSM position servo systems: Stability analysis and experiments, *Contr. Eng. Practice*, vol.18, no.9, pp.1022-1036, 2010.

[14] G. Taylor, Nonlinear control of electric machines: An interview, *IEEE Control System Mag.*, vol.14, no.4, pp.41-51, 1994.

[15] H. K. Bini and J. Ghaboussi, Nonlinear structural control using neural networks, *Journal of Engineering Mechanics*, vol.124, no.3, pp.319-327, 1998.

[16] F. Casciati, L. Faravelli and T. Yao, Control of nonlinear structures using the fuzzy control approach, *Nonlinear Dynamics*, pp.171-187, 1996.

[17] J. Wang, A. B. Rad and P. T. Chan, Indirect adaptive fuzzy sliding mode control, part fuzzy switching, *Fuzzy Set and System*, vol.122, pp.21-30, 2001.

[18] B. Wang, P. Shi and H. Karimi, Fuzzy sliding mode control design for a class of disturbed systems, *J. of Franklin Institute*, vol.351, no.7, pp.3593-3609, 2014.

[19] L. Wu, X. Su and P. Shi, Sliding mode control with bounded L_2 gain performance of Markovian jump singular time-delay systems, *Automatic*, vol.48, no.8, pp.1929-1933, 2012.
[20] M. Liu, P. Shi, L. Zhang and X. Zhao, Fault tolerant control for nonlinear Markovian jump systems via proportional and derivative sliding mode observer, *IEEE Trans. Circuits and Systems, I: Regular Papers*, vol.58, no.11, pp.2755-2764, 2011.
[21] P. Shi, Y. Xia, G. Liu and D. Rees, On designing of sliding mode control for stochastic jump systems, *IEEE Trans. Automatic Control*, vol.51, no.1, pp.97-103, 2006.
[22] P. Guan, X. J. Liu and J. Z. Liu, Adaptive fuzzy sliding mode control for flexible satellite, *Engineering Applications of Artificial Intelligence*, vol.18, pp.451-459, 2005.
[23] J. Y. Chen, Rule regulation of fuzzy sliding mode controller design: Direct adaptive approach, *Fuzzy Set and System*, vol.120, pp.159-168, 2001.