Adaptive Fuzzy Sliding Mode Control for PMSM System

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***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 overcome 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 the 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.**

Keywords-adaptive control; permanent magnet synchronous motor; position regulation; adaptive fuzzy sliding mode Control

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) plays a crucial part in many applications which have a high demand on fast 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 can not 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, thus the vector control of PMSM can not 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] and intelligent control [4]. These nonlinear control methods improve the performance of permanent magnet synchronous motor system.

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 and adaptive fuzzy control, and overcome their shortcomings, 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.

II. 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 is no damper windings on the rotor; excluding 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; T_1 is load torque.

According to field oriented vector control ($i_d = 0$) and Clark /Park transformation, a control configuration of the PMSM system is illustrated in Fig.1,we mainly design a controller for position loop;

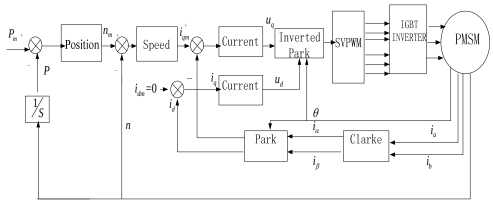

FIGURE I. CONTROL CONFIGURATION OF THE PMSM SYSTEM.

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 Fig.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. From equation (1) and (2)

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

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

Then $\ddot{p} = f + gu + d$ (4)

Where u denotes the input control parameter.

III. ADAPTIVE FUZZY SLIDING CONTROL SYSTEM

Thus, an adaptive fuzzy sliding control system , as shown in Fig.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 :

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

Where k_1, k_2 is non-zero positive constant.

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

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

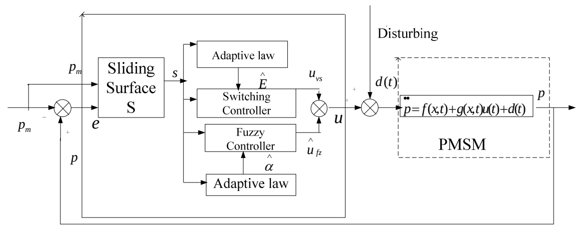

FIGURE II. BLOCK DIAGRAM OF ADAPTIVE FUZZY SLIDING MODE CONTROL SYSTEM.

It can easily be seen that, By determined the suitable k_1, k_2 , a tracking error will exponentially approach zero . Substituting eqn (7) to eqn (5), the equivalent control law can be obtain as:

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

Because f , g and d are unknown, it is difficult to use $\overset{*}{u}(t)$ in some practical needs , 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 $\xi_1 = \frac{w_i}{\sum_{i=1}^m w_i}$ (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 meet to the condition: $|\varepsilon| < E$.

Using 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:

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

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

Substituting eqn (14) into eqn (5) yields:

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

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

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

According to eqn (12) , we obtain

$$\tilde{u}_{fz} = \hat{u}_{fz} - u^{*} = \hat{u}_{fz} - u_{fz}^{*} - \varepsilon \qquad (16)$$

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

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

Consider a Lyapunov function candidate as:

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

Where η_1 is a positive real parameter.

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

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

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 :

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

$$u_{vs}(s) = -E\,\mathrm{sgn}(s(t)) \qquad (21)$$

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

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

According to Barbalat's Lemma, it can be shown that $\lim_{t\to\infty} e(t) = 0$

IV. 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. Parameters of position loop's for PI controller are: $K_P = 11.7$, $K_i = 140$.

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

The simulation results of the PMSM position and velocity using AFSMC and their comparisons with PI controller without load disturbance are shown in Figs.3-4. Comparison results of the position between AFSMC and PI controller in Fig.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.

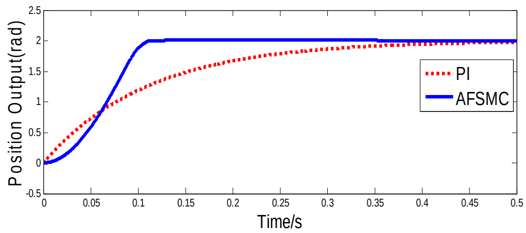

FIGURE III. COMPARISON OF THE POSITION BETWEEN AFSMC AND PI CONTROLLER

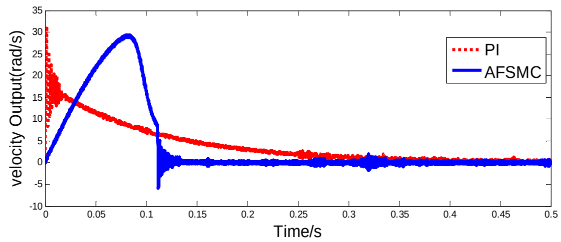

FIGURE IV. COMPARISON OF THE VELOCITY BETWEEN AFSMC AND PI CONTROLLER

V. Conclusion

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, 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, the stability of the two proposed adaptive controller 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.

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