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# Permanent Magnet Synchronous Motor Speed Control Using Chattering Free Sliding Mode Control and RBF Neural Network

Tae Hyong Ri*

*Institute of Robotic Technology, Kim Chaek University of Technology, Pyongyang, Democratic, People's Republic of Korea*

***Abstract*: This paper proposes a full order terminal sliding mode (FOTSM) control scheme for the speed loop in the permanent magnet synchronous motor (PMSM) servo system. Firstly, to overcome the chattering problem of the sliding mode control, the full order sliding mode control scheme is proposed for speed control of PMSM system. Then, novel adaptive FOTSM control scheme is designed based on the RBF neural network. The radial based function (RBF) neural network is used to estimate the disturbances. The proposed controller requires no prior knowledge about the dynamics of the PMSM servo system and no off-line learning phase. Lyapunov stability analysis and MATLAB simulation results indicate the superiority of the proposed method.**

***Keywords*: Permanent magnet synchronous motor (PMSM), Speed control, RBF neural network, Chattering problem.**

## 1. Introduction

The permanent magnet synchronous motor (PMSM) is widely used in the robotics and motion control systems due to its compact structure, low noise, high torque to inertia ratio. PMSM is also a typical system which is multivariable, nonlinear, with strong coupling and uncertain model parameters. The working environment of the PMSM system is much rough and the external disturbances will seriously affect the control precision. The disturbance torque of the system will become extremely complex by the friction between mechanism parts. Even an ambient temperature change will also make a big variation on the motor parameters such as the resistance of motor, the permanent magnet flux and the viscous friction coefficient. Because, it is difficult to achieve a high performance for PMSM system by using conventional linear control methods, such as proportional-integral-differential (PID) control method. Traditionally, the PID controller is widely adopted to control the PMSM systems in industrial applications owing to its simplicity, clear functionality, and effectiveness. However, a big problem of the PID controller is its sensitivity to the system uncertainties. Hence, many advanced nonlinear control methods have been used for PMSM system, e.g., adaptive control, nonlinear optimal control, fuzzy logic control, neural network control.

The adaptive control is also an interesting method for the PMSM drives because it can deal with the motor parameter and load torque variations [1], [2]. But, the adaptive control algorithm does not guarantee the convergence condition of the system dynamic error. The nonlinear predictive control is successfully applied on the PMSM drives [3]. Unfortunately, this control method requires full knowledge of the motor parameters with a sufficient accuracy and the results under serious variations of the mechanical parameters are not shown. The fuzzy logic control [4] is a preferred research topic due to its fuzzy reasoning capacity. However, as the number of the fuzzy rules increases, the control accuracy can get better but the control algorithm can be complex.

Meanwhile, the neural network control technique has been presented as a substitutive design method to control the speed of the PMSM system [5]. The most valuable property of this technique is its ability to approximate the linear or nonlinear mapping through learning. However, the high computational burden increases the complexity in the control algorithm, which limits the implementation of this strategy in the practical applications. Besides the above mentioned methods, sliding mode control (SMC) is one of the most widely and successfully applied nonlinear control methods in PMSM system [6-9]. The sliding mode control systems has excellent features that they are very simple to implement and have sliding mode control (SMC) has gained a wide range of applications due to its fast global convergence, simplicity of implementation, high robustness to external disturbances and parameter variations. But sliding mode control must solve the problems of high frequency chattering, finite time convergence and singularity. Many control schemes have been studied to solve these challenges. A number of methods for eliminating chattering have been proposed, such as boundary layer method [10], disturbance estimation method [11] and dynamic sliding mode control [12]. The boundary layer methods use saturation function to replace the sign function to eliminate the chattering, but the disturbance rejection ability of system is sacrificed to some extent. The disturbance observer-based methods reduce the chattering by selecting a smaller switching gain. This method can reduce the chattering of system, but the control law is still discontinuous. Dynamic sliding mode can solve the chattering problem more effectively, but it is difficult to meet

*Corresponding author: rth8295@star-co.net.kp

the requirements of modern control due to its slow convergence. In [13]-[15], a terminal sliding mode (TSM) control is proposed. Terminal sliding mode improves the convergence character of the system by including nonlinear terms in the sliding surface, making the system state converge to the desired trajectory in a finite time. However, the terminal sliding mode has the singular problem. In order to solve these problems, a non-singular terminal sliding mode (NTSM) control is presented for a class of nonlinear dynamical systems [16], [17]. The NTSM control overcame the singularity problem and guaranteed to be finite time. However, this method is still the chattering problem. In [18], [19], a full order sliding mode control method is presented to solve the above mentioned problems. In this method, the control is smooth and no chattering phenomenon exists in the system response. Nevertheless, the information about the upper bound of perturbations is needed in order to achieve asymptotic stability.

In this paper, a full-order terminal-sliding-mode (FOTSM) control scheme with RBF neural network is proposed to solve the speed tracking problem for PMSM system. The proposed control method is more efficient in eliminating the chattering and can handle the unknown disturbance. The finite time convergence is also guaranteed. This method utilizes the neural network to approximate the load disturbance so that their effect can be overcome without requiring prior knowledge of their bounds. Simulation results are provided to show the effectiveness of the proposed method. The rest of this paper is organized as follows. The mathematical model of PMSM is described in Section 2. In section 3, FOSTM controller is developed for the speed control loop of PMSM system. In section 4, an adaptive FOSTM controller is developed based on RBF neural network. In section 5, illustrative examples are presented to validate the effectiveness of the proposed control schemes. Finally, some conclusions are given in Section 6.

## 2. Mathematical Model of the PMSM

In this Paper, a surface-mounted permanent magnet synchronous motor is considered. For modeling of PMSM, we assume as follows. Assumption 1: Assume that the stator core is not saturated, hysteresis and vortex losses are ignored and the current of the three phases are symmetric sine wave. Under this assumption, the mathematical model of the PMSM in rotor reference frame is depicted by Eq. (1).

$$\begin{aligned} \frac{d\omega}{dt} &= \frac{K_t}{J} i_q - \frac{B}{J}\omega - \frac{T_L}{J} \\ \frac{di_d}{dt} &= -\frac{R_S}{L_d} i_d + n_p \omega i_q + \frac{1}{L_d} u_d \\ \frac{di_q}{dt} &= -\frac{R_S}{L_q} i_q - n_p \omega i_d - \frac{n_p \phi_v}{L_q} u_q + \frac{1}{L_q} u_q \end{aligned} \tag{1}$$

where $\omega$ the rotor speed, $i_d$ and $i_q$ the d-axis and q-axis stator currents, $u_d$ and $u_q$ the d-axis and q-axis stator voltages, $R_S, L_d$ and $L_q$ the stator resistance, d-axis and q-axis inductances, $n_p$ the number of pole pairs, $\phi_v$ the rotor flux, $J$ the moment of inertia, **B** the viscous friction coefficient, and $K_t = 3n_p\phi_v / 2$.

Assuming $i_d = 0$ based on maximum torque per ampere (MTPA) method, the motion dynamic equation of PMSM can be rewritten as,

$$\dot{\omega} = bi_q - \omega + d(t) \tag{2}$$

where $b = K_t / J, a = B / J, d(t) = -T_L / J$ can be considered as the system disturbances.

Assumption 2: The disturbance of the PMSM system is bounded, i.e., $\dot{d}(t) \le k_d$,

where $k_d > 0$ is a constant.

Note that this assumption is realistic in practical applications. For example, when a cutting tool or an end mill of a CNC machine tool cuts a work-piece, the load torque may change as the cutting thickness changes, but the change rate of the load torque is always limited.

## 3. FOTSM Controller Design

The input of PMSM speed control system is $i_q$, $\omega_r$ denote the reference speed signal. Substituting tracking error $e = \omega - \omega_r$ and control input $u = i_q$ into Eq. (2), the following error equation can be obtained.

$$\dot{e} = -\dot{\omega}_r + bu - a\omega + d(t) \tag{3}$$

The full order terminal sliding surface is designed as:

$$s = \dot{e} + \beta \operatorname{sgn}(e)|e|^{\alpha} \tag{4}$$

Where $\beta$ is designed to fulfil the condition that the corresponding polynomial $p + \alpha$ is Hurwitz, $\alpha \in (0,1)$. Based on Eq. (4), the speed controller is designed as [18]:

$$u = b^{-1}(u_1 + u_2) \tag{5}$$

$$u_1 = \dot{\omega}_r + a\omega - \beta \operatorname{sgn}(e)|e|^{\alpha} \tag{6}$$

$$\dot{u}_2 + Tu_2 = v \tag{7}$$

$$v = -(k_d + k_T + \eta)\operatorname{sgn}(s) \tag{8}$$

Where $u_2(0)=0, \beta>0, T>0, k_T \le Tu_2, \eta>0$, sgn( ) is the signum function.

Theorem 1: Consider the dynamic equation (1) of PMSM under Assumption 2. If the full order terminal sliding surface is chosen as Eq. (4), and the control law is designed as Eq. (5), then the speed tracking error $e, \dot{e}$ will converge to zero in finite time. Proof: Considered the following Lyapunov function candidate:

$$V=\frac{1}{2}s^T s \tag{9}$$

According to Eq. (3) and Eq. (5) ~ (8), Eq. (4) can be rewritten as follows:

$$s=-\dot{\omega}_r+bu-a\omega+d(t)+\beta\operatorname{sgn}(e)|e|^{\alpha}=d(t)-u_2 \tag{10}$$

Taking the derivative of sliding surface along error system yields:

$$\dot{s}=\dot{d}(t)-v+Tu_2 \tag{11}$$

Differentiating $V$ with respect to time yields:

$$\begin{aligned}\dot{V}&=s\dot{s}=\dot{d}(t)s-v+Tu_2\\&=(\dot{d}(t)s-k_d|s|)+(Tu_2 s-k_T|s|)-\eta|s|\end{aligned} \tag{12}$$

According to Assumption 2 and $\dot{d}(t)s-k_d|s|\le 0, \quad u_2 s-k_T|s|\le 0, \quad \eta|s|>0$, the above equation can be rewritten as follows:

$$\dot{V}\le-\eta|s|<0 \tag{13}$$

The above inequality means that the speed error will arrive at the sliding surface $s=0$ in finite time and the speed error will converge to zero along the sliding surface $s=0$. This completes the proof.

Remark 1: The sliding mode variable $s$ in control law (8) is not available because the acceleration signal $\dot{\omega}$ in $s$ could not be measured directly. For calculating the sign of sliding mode variable $s$ in (8), a function g(t) is defined as follows,

$$\dot{d}(t)=W^{*T}\phi(y)+\varepsilon \tag{14}$$

$\operatorname{sgn}(s)$ can be obtained by the following equation,

$$\operatorname{sgn}(s)=\operatorname{sgn}(g(t)-g(t-\tau)) \tag{15}$$

where $\tau$ is a time delay.

$$s(t)=\lim_{\tau\to 0}\left[(g(t)-g(t-\tau))/\tau\right].$$

Remark 2: In Theorem 1, the control signal (7) is equivalent to a low-pass filter.

Where $v(t)$ is the input and $u_2(t)$ is the output of the filter.

The Laplace transfer function of the filter (7) is:

$$\frac{u_2(s)}{v(s)}=\frac{1}{s+T} \tag{16}$$

Although $v(t)$ in (8) is non-smooth because of the switch function, $u_2(t)$ in (5) is the output of the low-pass filter (7) and is softened to be a smooth signal by (7).

In the special case, $T=0$, (7) and (8) become

$$\dot{u}_2=v \tag{17}$$

$$v=-(k_d+\eta)\operatorname{sgn}(s) \tag{18}$$

If (7) and (8) are replaced with (17) and (18), Theorem 1 holds also and the control $u$ in (5) is continuous as well. But (17) is a pure integrator and more difficult for hardware implementation in practical applications than the low-pass filter (7).

Remark 3. We prevent differentiating terms $\beta\operatorname{sgn}(e)|e|^{\alpha}$ in the TSM manifold (4) from deriving the control laws. So, singularity can be avoided, and the ideal TSM, $s=0$, is nonsingular.

## 4. FOSTM Controller Design Based on Neural Network

In this section, we study the FOTSM control for PMSM system when the bounds of the system disturbance' derivative cannot be obtained and a novel adaptive FOTSM control scheme is designed based on the RBF neural network. This scheme can guarantee the finite time convergence of the error without prior knowledge of the bounds of system disturbance's derivative. Since $\dot{d}(t)$ is unknown, we utilize the RBF neural network to approximate it. Assume there is an ideal weight matrix $W^*$ so that $\dot{d}(t)$ can be approximated as:

$$\dot{d}(t)=W^{*T}\phi(y)+\varepsilon \tag{19}$$

where, $W^*=\left[w_1, w_2, \cdots, w_p\right]$, $\varepsilon$ denotes the inputs, $\varepsilon$ denotes the approximation error and satisfies $|\varepsilon|\le\varepsilon_N$, $\phi(y)=\left[\phi_1(y), \phi_2(y), \cdots, \phi_p(y),\right]^T$ is the Gaussian function given by:

$$\phi(y) = \exp\left[\frac{-(y-v_i)^T (y-v_i)}{2\sigma_i^2}\right], \qquad i = 1,2,\ldots,p \tag{20}$$

Where $v_i = [\mu_{i1}, \mu_{i2}, \cdots, \mu_{in}]^T$ denotes the center of the receptive field, $\sigma_i$ denotes the width of the Gaussian function.

The FOTSM based on RBF neural network is designed as follows:

$$u = b^{-1}(u_1 + u_2) \tag{21}$$

$$u_1 = \dot{\omega}_r + a\omega - \beta\,\mathrm{sgn}(e)|e|^{\alpha} \tag{22}$$

$$\dot{u}_2 = \hat{W}^T \phi(y) - (k_\varepsilon + \eta)\,\mathrm{sgn}(s) \tag{23}$$

where $\hat{W}$ is the estimate of $W^*$

$$k_\varepsilon > \varepsilon_N, \eta > 0, u_2(0) = 0$$

Since $W^*$ is constant, the adaptive law is adopted as:

$$\hat{W} = -\dot{\hat{W}} = -\frac{1}{\lambda}\phi(y)s^T \tag{24}$$

Where $\hat{W} = W^* - \hat{W}, \lambda > 0$

Theorem 2: Consider the dynamic equation (1) of PMSM under Assumption 2. If the full order terminal sliding surface is chosen as (4), and the control law is designed as Eq. (21) to Eq. (23) and the adaptive law is adopted as Eq. (24), then the speed tracking error $e, \dot{e}$ will converge to zero in finite time.

Proof: Considered the following Lyapunov function candidate:

$$V = \frac{1}{2}s^T s \tag{25}$$

Differentiating $V$ with respect to time yields:

$$\dot{V} = s\dot{s} \tag{26}$$

Substituting Eq. (19) and Eq. (21) ~ (24) into Eq. (10) yields:

$$\begin{aligned} \dot{s} &= d(t) - u_2 \\ &= \hat{W}^T\phi(y) - (k_\varepsilon + \eta)\,\mathrm{sgn}(s) - W^{*^T}\phi(y) + \varepsilon \\ &= -\hat{W}^T\phi(y) - (k_\varepsilon + \eta)\,\mathrm{sgn}(s) \end{aligned} \tag{27}$$

From Eq. (25), (26), (27), we can obtain as follows:

$$\begin{aligned} \dot{V} &= s^T\left[-\hat{W}^T\phi(y) - (k_\varepsilon + \eta)\mathrm{sgn}(s) - \varepsilon\right] + trace\left[\hat{W}^T(\lambda\dot{\hat{W}} - \phi(y)s^T)\right] \\ &= s^T(k_\varepsilon + \eta)\mathrm{sgn}(s) - s^T\varepsilon \\ &= -|s|(k_\varepsilon + \eta) + |s|\cdot|\varepsilon| \end{aligned} \tag{28}$$

Since, $k_\varepsilon > \varepsilon_N, \eta > 0$ it can be obtained that:

$$\dot{V} \le -\eta|s| \tag{29}$$

Therefore, $s$ and $\widetilde{W}$ are bounded according to the Lyapunov stability theorem. The boundedness of $e, \dot{e}$ can then be ensured from Eq. (4). Thus, all the signals of the closed-loop system are bounded. However, inequality (29) is not sufficient to guarantee the finite-time convergence of the system states to zero. We will address this problem in the following part [17]. Since the Gaussian function $0 < \phi_i(y) < 1, i = 1,2\ldots,p$, it follows:

$$\|\phi(y)\| \le \sqrt{p}$$

From the property of Frobenius norm, the following inequality holds [19].

$$\left\|\widetilde{W}^T\phi(y)\right\|_F \le \left\|\widetilde{W}^T\right\|_F \cdot \|\phi(y)\| \tag{30}$$

According to Eq. (30), we can obtain that $\left\|\widetilde{W}^T\phi(y)\right\|_F$ is bounded.

Since $k_F \ge \left\|\widetilde{W}^T\phi(y)\right\|_F$, it can be obtained that:

$$\dot{V} \le -\eta|s| < 0 \tag{31}$$

Therefore, $V$ will converge to zero in finite time and the full order TSM $s = 0$ will be established identically. According to Theorem 2, $e, \dot{e}$ will converge to zero in finite time. The proof is completed.

### 5. Simulation Results

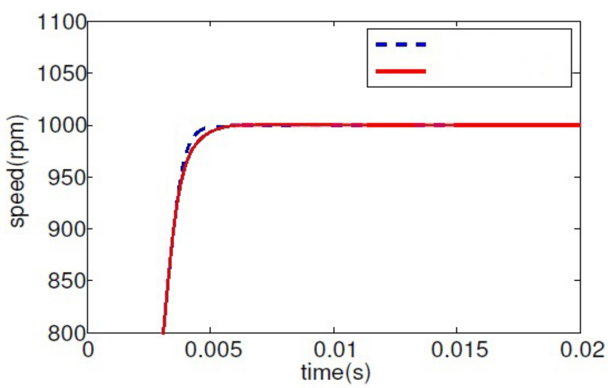
To validate the effectiveness of the proposed control schemes, simulations have been performed on a PMSM servo system. The proposed control methods, FOTSM and FOTSM based on RBFNN are applied to the PMSM servo system respectively. The parameters of a PMSM used in the simulation and experiment are given as: rated power $P = 750W$, rated voltage $U = 220V$, number of poles $n_p = 4$, armature resistance $R_S = 1.74\Omega$, stator inductances, $L_d = L_q = 0.004H$, viscous damping, $B = 7.403\times10^{-5} N\cdot ms/rad$, moment of inertia $J = 1.74\times10^{-4} kg\cdot m^2$, rate speed $n = 3000rpm$, torque constant $K_T = 1.58 N \cdot m / A$ and rated torque. $T_L = 2.4 N \cdot m$

The parameters of FOTSM controller are $\beta = 4, \gamma = 5/3$.

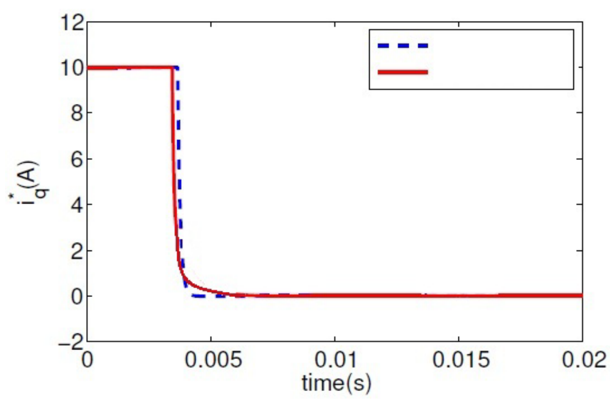
The parameters of FOTSM controller based on RBF neural network are $\beta = 4, \gamma = 7/5, \sigma = 3, p = 5$. The centre of the receptive field is given by:

$$v = \begin{vmatrix} -2 & -1 & 0 & 1 & 2 \\ -2 & -1 & 0 & 1 & 2 \\ -2 & -1 & 0 & 1 & 2 \end{vmatrix}$$

The step responses of PMSM speed control system are shown in Figure 1.

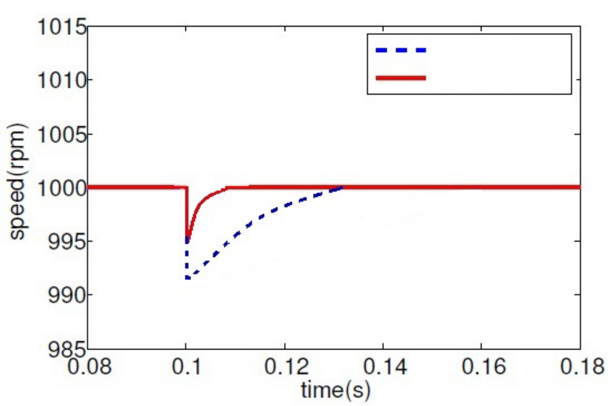



(a)

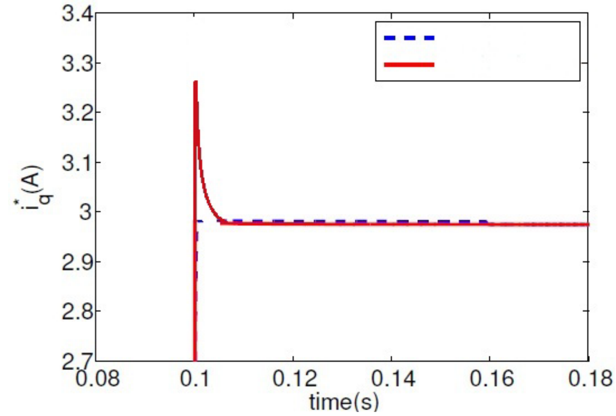



(b)

Fig. 1. Response of the PMSM speed control system
(a) speed, (b) q-axis current




(a)




(b)

Fig. 2. Response of the PMSM speed control system with load disturbance
(a) speed, (b) q-axis current

## 6. Discussion

From this result, we can see that the control scheme guarantees the finite time convergence of tracking errors to zero. Also unlike conventional TSM the proposed scheme overcame singularity and chattering problems. Figure 2 shows that when a load torque $T_L = 4.5 N \cdot m$ is applied at t = 0.1s, the speed response under our method recovers faster from the load torque disturbance. From this figure, we can see that the disturbances can be eliminated in the proposed two control methods. However, the FOTSM control based on RBF neural network doesn't require the load disturbances' bound, which verifies the advantage of this scheme.

## 7. Conclusions

In this paper, the design and implementation of a FOTSM speed controller based on neural network for the PMSM system has been investigated. Firstly, in order to eliminate the chattering phenomenon in conventional SMC, a continuous FOTSM technique has been introduced. Then, a FOTSM speed controller based on RBF neural network has been designed. In the presence of the external disturbance, the proposed scheme can ensure the finite time convergence of the tracking error to zero and avoid chattering problem. Meanwhile, the stability of PMSM system under the proposed method has been guaranteed by means of Lyapunov stability criteria. Finally, the simulation and experimental results show that the system under the proposed method has a more satisfying performance.

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