Discrete Sliding Mode Control of PMSM with Network Transmission

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Abstract. In this paper, a novel discrete full-order terminal sliding mode (FTSM) control approach is proposed for a permanent magnet synchronous motor (PMSM) working in network transmission environment. By utilizing the vector control technology, the decoupled model of PMSM with the structure of double closed loop can be deduced. The discretization influence of network transmission is specially investigated by comparing the control performances in continuous domain and discrete domain, following the guaranteed stability condition when working in network transmission environment. In order to simulate the network transmission environment, a test platform based on OPC technology is established. Simulations validate the proposed approach.

Keywords: Network transmission · Permanent magnet synchronous motor · Sliding mode control · OPC technology

1 Introduction

In recent years, the computer technology, network communication technology and control technology have been developed rapidly. Specially with the emergence and wide application of distributed control system, field bus control system and industrial Ethernet control system, which indicates that the network is becoming a new characteristic of control systems, including the permanent magnet synchronous motor (PMSM) [1]. The introduction of network transmission into the traditional control systems with peer to peer communication will bring benefits of structure networking and the intelligence of the controlled nodes [2]. Therefore, the research topic concerning the networked control systems (NCS) has become a hotspot. According to the 2010 market research report of Cisco Systems, the number of industrial Ethernet nodes throughout the world is about 300,000,000 [3].

Compared with the traditional PID and other conventional control approaches, sliding mode (SM) control has become a new control type due to its strong robustness, excellent dynamic and static control characteristics [4]. At present, there are two kinds approaches often used in the control of PMSM, i.e., linear sliding mode (LSM) and

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terminal sliding mode (TSM) which eliminate some undesired drawbacks such as high-frequency chattering and control singularity. Recently, a novel full-order TSM control approach is proposed due to its global control continuity [5]. Its idea is on the basis of high-order sliding mode (HOSM) to solve the chattering problem, while the control singularity can be avoided due to the introduction of special fractional power term [6].

At the same time, with the rapid development of digital technology and the increasing emergence of programmed microprocessor hardware applied in PMSM control systems, the discretization of SM controller has been given increasing amount of attention [7, 8]. In general, the discretization of SM controller includes two steps: designing an appropriate algorithm for the controlled systems in continuous-time domain on the basis of the expected dynamic and static performances; and further making an analog-to-digital (AD) transformation for the corresponding digital controller approximating to the original continuous-time counterpart [9, 10]. Although it is known that the smaller the sampling time is, the better the control performance of the discrete system will be, while it should be noted that although the sampling time is sufficiently small, the control performance of the digital controller is lower than the analog controller's. Therefore, how to select the sampling time and SM parameter is an important issue to be addressed for the control of PMSM systems.

In this paper, a novel full-order terminal SM approach is proposed for the network controlled PMSM system with consideration of the time-delay of communication characteristics. The structure of the paper is organized as follows. In Sect. 2, the modelling and controller design based on the full-order sliding mode control is given for PMSM control system in continuous domain, following its discretization and guaranteed stability in Sect. 3. And finally the simulation and conclusion are given in Sect. 4 and Sect. 5, respectively.

2 System Description in Continuous Domain

For the PMSM system in dq-axes, we assume the magnetic circuit is unsaturated, the space magnetic field is sine wave, eddy current and magnetic hysteresis loss can be excluded. Therefore, the equations of PMSM can be got as [11]

$$\begin{cases} \dot{i}_d = -\frac{R_s}{L} i_d + p\omega i_q + \frac{u_d}{L} \\ \dot{i}_q = -p\omega i_d - \frac{R_s}{L} i_q - \frac{p\psi_f}{L}\omega + \frac{u_q}{L} \\ \dot{\omega} = \frac{3p\psi_f}{2J} i_q - \frac{B}{J}\omega - \frac{T_L}{J} \end{cases} \tag{1}$$

where, i_d, i_q are dq-axes stator currents; u_d, u_q are dq-axes stator voltages; L is the equivalent inductance of winding; R_s is the stator resistance; p is number of motor pole pairs; ψ_f is magnetic potential generated by permanent magnet; ω is motor's mechanical angular velocity; T_L is load torque; J is total inertia of rotor and load; B is friction coefficient.

In order to remove the couplings in (1), the vector control method [12] is introduced in this paper. The double closed-loop controller of PMSM is designed on the basics of full-order TSM approach, and the system diagram is given in Fig. 1, where the outer loop is a speed loop, and the inner current loop is decoupled into two independent controllers based on $i_d = 0$.

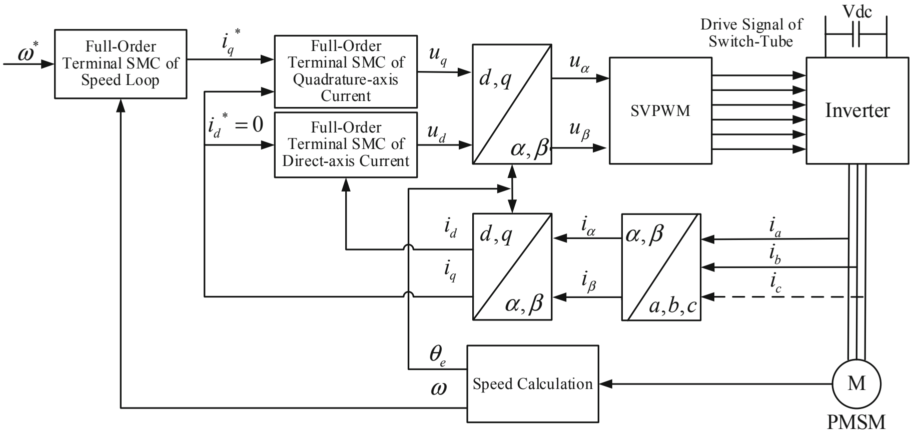


Fig. 1. System control scheme with double closed-loop structure

2.1 Design of Speed Controller

Here we define the speed tracking error $e_\omega = \omega^* - \omega$, where ω^* is the desired speed. And from (1), the first derivatives of e_ω can be obtained as

$$\dot{e}_\omega = \dot{\omega}^* - \frac{3p\psi_f}{2J} i_q^* + \frac{B}{J}\omega + \frac{T_L}{J} \tag{2}$$

The control objective is to make the speed error e_ω converge to zero. And the design process of full-order TSM controller is described as follows.

Step 1: A TSM sliding surface is designed as

$$s_\omega = \dot{e}_\omega + c_1 e_\omega^{p_1/q_1} \tag{3}$$

where the design parameter $c_1 > 0$, p_1 and q_1 are integers with $0 < p_1/q_1 < 1$.

Step 2: Based on the equivalent control of SM [13], here we design the control low i_q^* as

$$\begin{cases} i_q^* = \frac{2J}{3p\psi_f}\left(i_{qeq}^* + i_{qn}^*\right) \\ i_{qn}^* = k_1 \int \text{sgn}(s_\omega) \\ i_{qeq}^* = \dot{\omega}^* + \frac{B}{J}\omega + \frac{T_L}{J} + c_1 e_\omega^{p_1/q_1} \end{cases} \tag{4}$$

Where i_{qeq}^* is the equivalent control term to drive the system to reach and stay on the sliding surface; i_{qn}^* is the switching control term to overcome the influence of external disturbance and internal parameter disturbance; $k_1 > 0$.

Step 3: Ignoring the influence of system parameters disturbance and external disturbance temporarily, and substituting (2) into (3), it yields

$$s_{\omega} = \dot{\omega}^{*} - \frac{3p\psi_f}{2J} i_q^{*} + \frac{B}{J}\omega + \frac{T_L}{J} + c_1 e_{\omega}^{p_1/q_1} \tag{5}$$

Then we continuously substitute the first and third term in (4) into (5), it has

$$s_{\omega} = -i_{qn} \tag{6}$$

Based on the existence condition of SM, i.e., $s_w \dot{s}_w < 0$, here we choose a Lyapunov function $V = 0.5{S_{\omega}}^2$, and its derivative can be got as

$$\begin{aligned} &= s_{\omega}\dot{s}_{\omega} = s_{\omega}(-\dot{i}_{qn}^{*}) \\ \dot{V} &= -k_1 s_{\omega}\text{sgn}(s_{\omega}) \\ &= -k|s_{\omega}| < 0 \end{aligned} \tag{7}$$

Which means the Lyapunov stability condition is satisfied and the system states e_{ω} and $\dot{e}_{\omega}$ will converge to zero in a finite time. And after that, the dynamic characteristics of the PMSM system can be described as

$$s_{\omega} = \dot{e}_{\omega} + c_1 e_{\omega}^{p_1/q_1} = 0 \tag{8}$$

Here we assume $e_{\omega}(0) \neq 0$ is the initial value of the variable e_{ω}. Therefore from (8), the convergence time from $e_{\omega}(0)$ to $e_{\omega}(t_s) = 0$ can be calculated as

$$t_s = -\frac{1}{c_1}\int_{e_{\omega}(0)}^{0} \frac{de_{\omega}}{e_{\omega}^{p_1/q_1}} = \frac{|e_{\omega}(0)|}{c_1(1 - p_1/q_1)} \tag{9}$$

2.2 Design of Current Controller

For the current loop in Fig. 1, it includes two independent controllers. As the full-order TSM controller design of the speed loop, we define current error variable $e_d = {i_d}^{*} - i_d$. From (1), the corresponding error system of the d-axis current can be described as

$$\dot{e}_d = -p\omega i_q + \frac{R_s}{L} i_d - \frac{u_d}{L} \tag{10}$$

And the controller can be designed as

$$\begin{cases} s_d = \dot{e}_d + c_2 e_d^{p_2/q_2} \\ u_d = L(u_{deq} + u_{dn}) \\ u_{deq} = -p\omega i_q + \frac{R_s}{L} i_d + c_2 e_d^{p_2/q_2} \\ u_{dn} = k_2 \int \text{sgn}(s_d) \end{cases} \tag{11}$$

where s_d is the designed sliding surface; $c_2 > 0$, p_2 and q_2 are integers with $0 < p_2/q_2 < 1$; u_{deq} and u_{dn} are the equivalent control and switching control of u_d respectively, $k_2 > 0$.

For the q-axis current, we define its current error variable $e_q = i_q^* - i_q$. From (1), the direct axis current error system can be deduced as

$$\dot{e}_q = \dot{i}_q^* + p\omega i_d + \frac{R_s}{L} i_q + \frac{p\psi_f}{L}\omega - \frac{u_q}{L} \tag{12}$$

And based on the full-order TSM approach, the corresponding controller can be designed as

$$\begin{cases} s_q = \dot{e}_q + c_3 e_q^{p_3/q_3} \\ u_q = L(u_{qeq} + u_{qn}) \\ u_{qeq} = \dot{i}_q^* + p\omega i_d + \frac{R_s}{L} i_q + \frac{p\psi_f}{L}\omega + c_3 e_q^{p_3/q_3} \\ u_{qn} = k_3 \int \mathrm{sgn}(s_q) \end{cases} \tag{13}$$

where, $c_3 > 0$; p_3 and q_3 are integers, and $0 < p_3/q_3 < 1$; u_{qeq} and u_{qn} are the equivalent control and switching control of u_q respectively, $k_3 > 0$.

3 System Discretization Based on Zero-Order Holder

In order to test the influence of network transmission, the zero-order holder is adopted to simulate the system discretization. Here we take the speed loop as an example to illustrate the process. In order to simplify the explanation, we define variables

$$\begin{cases} \alpha = \frac{-3p\psi_f}{2J} \\ b = \frac{B}{J} \\ p = \dot{\omega}^* + \frac{T_L}{J} \end{cases} \tag{14}$$

By substituting (14) into (2), the speed error system can be changed as

$$\dot{e}_\omega = \alpha i_q^* + b\omega + p \tag{15}$$

By adopting zero-order holder, the discretization of the system (15) can be expressed as

$$e_\omega(k+1) = \Phi\omega(k) + \Gamma i_q^*(k) + p\int_0^h e^{\alpha\tau} d\tau \tag{16}$$

where h is the sampling period, and the variables

$$\begin{cases} \Phi = e^{\alpha T} \\ \Gamma = b\int_0^h e^{\alpha\tau}\mathrm{d}\tau \end{cases}$$

with

$$\begin{cases} e^{\alpha h} = I + \alpha h + \frac{\alpha^2 h^2}{2!} + O(h^3) \\ \int_0^h e^{\alpha\tau} d\tau = hI + \frac{h^2\alpha}{2!} + O(h^3) \end{cases} \tag{17}$$

Correspondingly, the sliding surface in (3) and the full-order TSM controller in (4) can be discretized respectively as

$$s_\omega(k) = \frac{e_\omega(k) - e_\omega(k-1)}{h} + C_1 e_\omega(k)^{\frac{p_1}{q_1}} \tag{18}$$

$$\begin{cases} i_q^*(k) = \frac{2J}{3p\psi_f}\left(i_{qeq}^*(k) + i_{qn}^*(k)\right) \\ i_{qn}^*(k) = i_{qn}^*(k-1) + hk_1\mathrm{sgn}(s_w(k)) \\ i_{qeq}^*(k) = \frac{w^*(k) - w^*(k-1)}{h} + \frac{B}{J}w(k) + \frac{T_L}{J} + C_1 e_w(k)^{\frac{p_1}{q_1}} \end{cases} \tag{19}$$

In order to guarantee the system stability after discretization, the discrete SMC stability condition $s_w^2(k+1) < s_w^2(k)$ should be satisfied. Therefore, it has

$$\begin{aligned} &\left| \frac{e^{\alpha h}\omega(k) + b\int_0^h e^{\alpha\tau}\mathrm{d}\tau\left(\frac{-1}{\alpha}\left(i_{qn}^*(k-1) + hk_1\mathrm{sgn}(s_\omega(k)) + C_1 e_\omega(k)^{\frac{p_1}{q_1}} + p(k) + b\omega(k)\right)\right) + p\int_0^h e^{\alpha\tau}\mathrm{d}\tau - e_\omega(k)}{h} \right. \\ &\left. + C_1\left(b\int_0^h e^{\alpha\tau}\mathrm{d}\tau\left(\frac{-1}{\alpha}\left(i_{qn}^*(k-1) + hk_1\mathrm{sgn}(s_\omega(k)) + C_1 e_\omega(k)^{\frac{p_1}{q_1}} + p(k) + b\omega(k)\right)\right) + p\int_0^h e^{\alpha\tau}\mathrm{d}\tau\right)^{\frac{p_1}{q_1}} \right| \\ &< \left| \frac{e_\omega(k) - e_\omega(k-1)}{h} + C_1 e_\omega(k)^{\frac{p_1}{q_1}} \right| \end{aligned} \tag{20}$$

Similarly, for the d-axis current controller in (11) and q-axis current controller in (13), their discretization can be deduced respectively as

$$\begin{cases} s_d(k) = \frac{e_d(k) - e_d(k-1)}{h} + c_2 e_d(k)^{p_2/q_2} \\ u_d(k) = L(u_{deq}(k) + u_{dn}(k)) \\ u_{deq}(k) = -p\omega i_q(k) + \frac{R_s}{L} i_d(k) + c_2 e_d(k)^{p_2/q_2} \\ u_{dn}(k) = u_{dn}(k-1) + hk_2\mathrm{sgn}(s_d(k)) \end{cases} \tag{21}$$

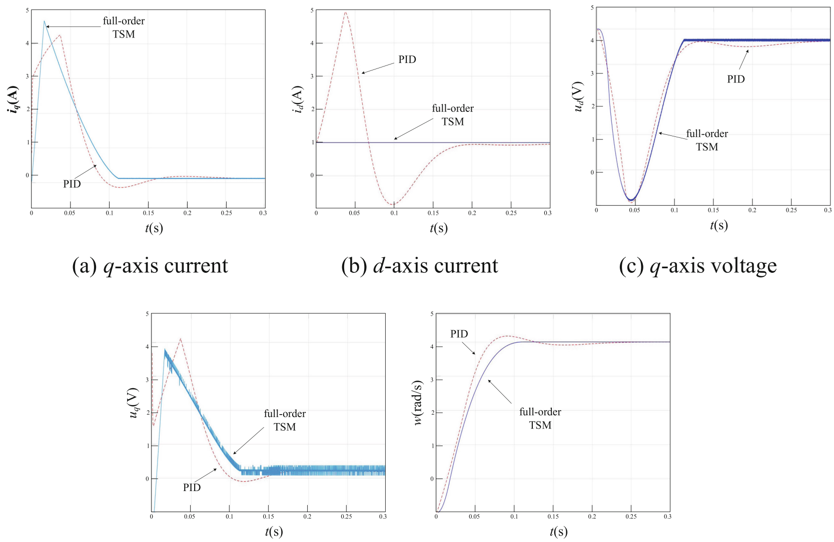
$$\begin{cases} s_q(k) = \frac{e_q(k) - e_q(k-1)}{h} + c_3 e_q(k)^{p_3/q_3} \\ u_q(k) = L(u_{qeq}(k) + u_{qn}(k)) \\ u_{qeq}(k) = \frac{i_q^*(k) - i_q^*(k-1)}{h} + p\omega i_d(k) + \frac{R_s}{L} i_q(k) + \frac{p\psi_f}{L}\omega(k) + c_3 e_q(k)^{p_3/q_3} \\ u_{dn}(k) = u_{dn}(k-1) + hk_3\mathrm{sgn}(s_q(k)) \end{cases} \tag{22}$$

4 Simulation and Experiment

In order to validate the proposed the double closed-loop full-order TSM control approach and the discretization influence of of network transmission on the system, the PMSM parameters are chosen as: the rated speed $n_e = 3000$ r/min, phase resistance $R_s = 2.26\ \Omega$, polar logarithm $p_n = 4$, permanent magnet flux $\psi_f = 0.0103$ Wb, winding equivalent inductance $L = 1.31$ mH, moment of inertia $J = 0.00009$ kg m^2, friction coefficient $B = 0.00005$ N m s, load torque is 0, given the rotating speed $\omega^* = 100$ rad/s, the current limit is 6 A. In the following, the simulation and experiment are given respectively.

4.1 Simulation Results

In order to validate the proposed full-order TSM approach applied in PMSM with double closed-loop structure in Fig. 1, the parameters of speed controller in (3) and (4) are chosen as: $p_1 = 3$, $q_1 = 5$, $c_1 = 100$, $k_1 = 200000$; the parameters of d-axis current controller in (11) are chosen as $p_2 = 3$, $q_2 = 5$, $c_2 = 10$, $k_2 = 10$; and the parameters of d-axis current controller in (13) are chosen as $p_3 = 3$, $q_3 = 5$, $c_3 = 10$, $k_3 = 10$. In continuous domain, we compare the proposed full-order TSM control approach with the traditional PID control, and the comparative simulations are given in Fig. 2(a)–(e).



(a) q-axis current (b) d-axis current (c) q-axis voltage

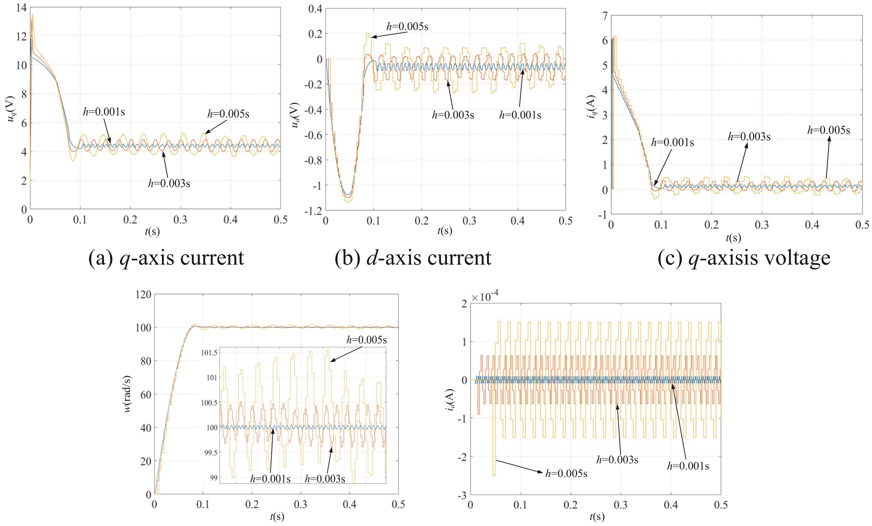
(d) d-axis voltage (e) PMSM speed

Fig. 2. Simulation comparisons of full-order TSM and PID

From the comparative simulations in Fig. 2, we can see that, the control performance of PMSM under the control of full-order TSM approach is better than the traditional PID control at fast speed and high accuracy. Furthermore, we test the discretization influence of network transmission. And the sampling period h are chosen as 0.001 s, 0.003 s and 0.005 s for comparison. The simulations are given in Fig. 3(a)–(e) and Table 1.

Table 1. Output results of speed with different sampling period h

Sampling period h (s)	Rise time (ms)	Maximum speed ω (rad/s)	Relative steady state error
0.001	54	100.56	0.04%
0.003	51	101.06	0.41%
0.005	50	101.64	1.33%



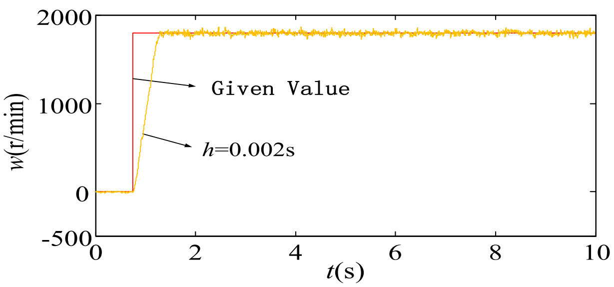
(a) q-axis current (b) d-axis current (c) q-axisis voltage

(d) d-axis voltage (e) PMSM speed

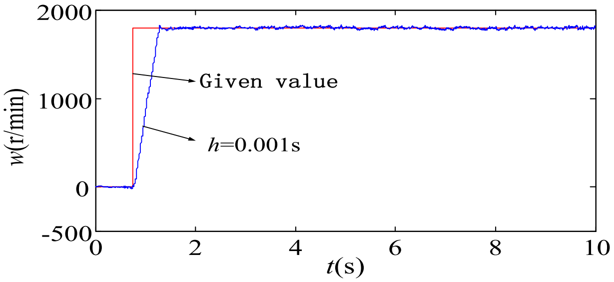
Fig. 3. Influence of sampling time on PMSM control system

4.2 Experimental Results

In the following, we continue to validate the proposed full-order TSM approach in PMSM control system by dSPACE platform. And the step size is set as 0.0001 s, PWM wave frequency as 2500 Hz and the given speed $n^* = 2000$ r/min. In order to test the influence of sampling time h, we choose 0.001 s and 0.002 s for comparisons. And the experimental results are shown in Fig. 4(a)–(b) and Table 2.



(a) Sampling period h = 0.001s



(b) Sampling period h = 0.002s

Fig. 4. Comparisons of motor speed with different sampling times

Table 2. Comparison of motor speed with different sampling periods

Sampling period h (s)	Rise time (ms)	Maximum speed ω (rad/s)	Relative steady state error
0.001	0.46	46	2.32%
0.002	0.47	88	4.39%

5 Conclusion

In this paper, a novel full-order TSM approach is proposed for the control of PMSM working in network transmission environment. In order to remove the model coupling, the vector control approach is utilized and correspondingly, the system is decomposed into two closed loops. Specially, the discretization influence of network transmission is investigated by comparing the control performances in continuous domain and discrete domain. And the guaranteed stability condition after the system discretization is deduced. The comparative simulations and experiment results validate the proposed approach.

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