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PAPER

Model-free control of permanent magnet synchronous motor based on terminal second-order sliding mode

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SUMMARY Considering the problem that the vector speed control system of permanent magnet synchronous motor (PMSM) is susceptible to uncertainties such as load disturbances, a model-free control strategy based on terminal second-order sliding mode (TSOSM-MFC) is proposed. First, the mathematical model of PMSM is analysed and processed, and the corresponding ultra-local model of the system is summarised; then, the model-free terminal sliding mode speed controller is designed according to the ultra-local model of the system, and the chattering phenomenon in the system is suppressed by designing the second-order sliding mode reaching law (SOSMRL). Then, the sliding mode disturbance observer (SMDO) is designed to estimate the unknown part of the ultra-local model and compensate the speed loop to improve the robust performance of the system. Finally, the feasibility and effectiveness of the proposed control method are verified by simulation.

key words: *PMSM; Chattering; Sliding Mode; Model-Free Control.*

1. Introduction

PMSMs are commonly utilised in various fields such as robotics, industrial production, and wind power generation due to their superior torque, power density, and energy conversion efficiency. However, PMSMs are complex systems that are strongly coupled and multivariable, making them susceptible to parameter and load disturbances [1-3]. Therefore, control algorithms that can improve the robustness of the speed control system have become a popular topic in motor speed control research.

PMSM speed control systems typically employ proportional-integral controllers (PI). These controllers are easy to implement but require an accurate system model. They are highly sensitive to uncertainties in the actual system and do not provide high control accuracy under complex operating conditions [4]. To address these issues, scholars worldwide utilise modern control theories, including sliding mode control [5-6], model predictive control [7-8], model-free control (MFC) [9], and intelligent control [10-11]. MFC, proposed by Michel Fliess, is a robust control method for systems with unknown parameters and complex coupling structures [12]. Literature [13] proposes an adaptive model-free control approach by analysing the ultra-local model in model-free control. This approach adopts an adaptive law for online parameter tuning, which reduces the workload of related parameter tuning. The model-free control method applies to the PMSM speed control system by designing a model-free current controller to overcome the effects of parameter variations. Literature [14] utilised a sliding mode controller to substitute the PI controller in the model-free algorithm for achieving robust fault-tolerant control of the motor under degaussing faults. However, the analysis of the impact of external disturbances on the system was not conducted. In the literature [15], an extended state observer is used to estimate the unknown part of the ultra-local model, which is fed back into the speed loop control to improve the robustness of the system, but the design process of the observer is complex and cumbersome.

Therefore, for the PMSM vector control system, this paper combines the terminal sliding mode control with the model-free control, and proposes a model-free speed controller based on the terminal second-order sliding mode to improve the robustness and speed of the system. Firstly, an ultra-local model of the speed loop is established based on the mathematical model of the motor. Then the non-singular fast terminal sliding mode surface is constructed according to the system error to ensure the system converges in finite time, and the second-order sliding mode reaching law is introduced to achieve the purpose of weakening the sliding mode chattering. Secondly, a sliding mode disturbance observer is constructed to estimate the unknown part of the ultra-local model, which is fed back into the speed loop, thus improving the robust performance of the system. Finally, the proposed control strategy is verified by simulation. The effectiveness of the proposed control strategy is verified by system simulation.

2. Model of System

In this paper, the mathematical model of surface-mounted PMSM ($L_d = L_q = L_s$) is the object of research:

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$$\begin{cases} L_s\dfrac{\mathrm{d}i_d}{dt} = -Ri_d + \omega_e L_s i_q + u_d \\ L_s\dfrac{\mathrm{d}i_q}{dt} = -Ri_q - \omega_e L_s i_d - \varphi_f \omega_e + u_q \end{cases} \tag{1}$$

Where i_d, i_q, u_d, u_q, L_d, L_q represents for the stator current as well as stator voltage and stator inductance in d-q coordinate system, separately, R is the stator resistance, ω_e represents the electrical motor angular speed; ψ_f represents magnetic flux.

The equation of motion for SPMSM can be expressed as:

$$\frac{\mathrm{d}\omega_m}{dt} = \frac{1.5 p i_q \varphi_f}{J} - \frac{T_L}{J} - \frac{B\omega_m}{J} \tag{2}$$

Where T_e, T_L, p, ω_m, B and J are the electromagnetic torque, load torque, number of pole pairs, mechanical angular speed, damping coefficient and rotational inertia respectively. When internal and external disturbances are considered, Eq. (2) is rewritten as:

$$\frac{\mathrm{d}\omega_m}{dt} = (a+\Delta a)i_q - (b+\Delta b)\omega_m - (c+\Delta c) \tag{3}$$

Where $a = 1.5p\psi_f/J$; $b = B/J$; $c = T_L/J$; $\Delta a = 1.5p\Delta\psi_f/\Delta J$, $\Delta b = \Delta B/\Delta J$, $\Delta c = \Delta T_L/\Delta J$ represents the uptake of the motor parameters.

3. Design of TSOSM-MFC

3.1 Speed loop ultra-local model

For single-input-output nonlinear control systems, no matter how complex their mathematical models are, these can be represented by traditional ultra-local models as:

$$\begin{cases} y^{(v)} = g(x) + \alpha u \\ y = x \end{cases} \tag{4}$$

Where $y^{(v)}$ is a v-order derivative of y, $v = 1$; $g(x)$ is the unknown of the system; α is a constant. Based on the principle of the new ultra-local model, the $g(x)$ part is further decomposition [13]:

$$g(x) = \beta x + F \tag{5}$$

Where β is a constant; F is the system disturbance. Substituting Eq. (5) into Eq. (4) gives:

$$\dot{x} = \alpha u + \beta x + F \tag{6}$$

Combining Eq. (3) extends the equations of motion of the PMSM to a new ultra-local model:

$$\frac{\mathrm{d}\omega_m}{dt} = F + \alpha i_q + \beta\omega_m \tag{7}$$

Where $\alpha = 1.5p\psi_f/J$, $\beta = -B/J$, $F = \Delta a i_q - \Delta b\omega_m - c - \Delta c$.

3.2 Design of TSOSM-MFC

Based on Eq. (7), Eq. (8) is designed:

$$i_q = \frac{-\beta\omega_m - F + u_s}{\alpha} \tag{8}$$

Where u_s is the control law. Define system state error:

$$e = \omega^*_m - \omega_m \tag{9}$$

Where ω^*_m is the reference mechanical angular speed. Combined Eq. (7), Eq. (8) and Eq. (9) gives:

$$\dot{e} = -u_s \tag{10}$$

To ensure that the system state error converges to 0 in finite time, the design of the non-singular fast terminal sliding mode surface for:

$$s = \int edt + \lambda_1\left(\int edt\right)^{\frac{g}{c}} + \lambda_2 e^{\frac{k}{d}} \tag{11}$$

Where λ_1 and λ_2 are constant; g, c, k, d are odd integers; $\frac{g}{c} > \frac{k}{d}$, $1 < \frac{k}{d} < 2$. The derivation of Eq. (11) is obtained:

$$\dot{s} = e + \frac{g}{c}e\lambda_1\left(\int edt\right)^{\frac{g}{c}-1} + \frac{k}{d}\lambda_2 e^{\frac{k}{d}-1}\dot{e} \tag{12}$$

In order to allow the state variables of the control system to enter the sliding mode, the second-order sliding mode reaching control law is designed as [16]:

$$\dot{s} = -\vartheta_1|s|^{\frac{1}{2}} sign(s) - \int \vartheta_2 sign(s)dt + F \tag{13}$$

Where ϑ_1, ϑ_2 are constant.

Theorem 1 When $\vartheta_1 > 0$ and $\vartheta_2 > 0$, the second order sliding mode reaching law can converge in finite time to 0 [16]. Therefore, when $|\dot{F}| \leq \gamma$, then:

$$\begin{cases} \vartheta_1 > 2 \\ \vartheta_2 > \dfrac{\vartheta^3{}_1 + (4\vartheta_1 - 8)\gamma^2}{4\vartheta^2{}_1 - 8\vartheta_1} \end{cases} \tag{14}$$

When the state of the system enters the sliding mode, i.e: $s = \dot{s} = 0$, Combined Eq. (12), Eq. (13) and Eq. (3) lead to:

$$\begin{aligned} i^*_q = \frac{1}{\alpha}\Bigg(&\frac{d}{k\lambda_2}e^{2-\frac{k}{d}}\left(1 + \frac{g}{c}\lambda_1\left(\int edt\right)^{\frac{g}{c}-1}\right) - \beta\omega_m - F \\ &+ \vartheta_1|s|^{\frac{1}{2}} sign(s) + \int \vartheta_2 sign(s)dt\Bigg) \end{aligned} \tag{15}$$

Where i^*_q is the reference q axis current. To prove the stability of the Eq. (15), the Lyapunov function is used as:

$$V=\frac{1}{2}s^2 \tag{16}$$

The derivation of Eq. (16) is obtained:

$$\begin{aligned}\dot{V}&=s\cdot\dot{s}\\ &=s\left[e+\frac{g}{c}\lambda_1\left(\int edt\right)^{\frac{g}{c}-1}e+\frac{k}{d}\lambda_2 e^{\frac{k}{d}-1}\dot{e}\right]\\ &=s\frac{k}{d}\lambda_2 e^{\frac{k}{d}-1}\left[-\vartheta_1|s|^{\frac{1}{2}}sign(s)-\int\vartheta_2 sign(s)dt\right]\\ &\le\frac{k}{d}\lambda_2 e^{\frac{k}{d}-1}\left[-\vartheta_1|s|^{\frac{3}{2}}-\vartheta_2|s|\right]\end{aligned} \tag{17}$$

Due to $1<\frac{k}{d}<2$, then $0<\frac{k}{d}-1<1$; Due to k and d are positively odd, then $e^{\frac{k}{d}-1}>0$, Then Eq. (17) is rewritten as:

$$\dot{V}\le-\vartheta_1|s|^{\frac{3}{2}}-\vartheta_2|s| \tag{18}$$

According to Eq. (18), when ϑ_1,ϑ_2 satisfy Eq. (14), the non-singular fast terminal sliding mode control based on second order sliding mode reaching law converges to 0 in finite time.

To prove that ϑ_1 and ϑ_2 satisfy Eq. (14), the class of quadratic Liapunov functions is chosen as [17]:

$$V(s,\kappa)=\mathrm{H}^T\mathrm{ZH} \tag{19}$$

Where:

$$\begin{cases}\kappa=-\int\vartheta_2 sign(s)dt+F\\ H^T=\left[\sqrt{|s|}sign(s),\kappa\right]\\ Z=\frac{1}{2}\begin{bmatrix}4\vartheta_2+\vartheta_1^2 & -\vartheta_1\\ -\vartheta_1 & 2\end{bmatrix}\end{cases} \tag{20}$$

Where Z is the positive definite symmetric matrix. The derivation of Eq. (19) is obtained:

$$\begin{aligned}\dot{V}(s,\kappa)&=2\dot{H}^{\mathrm{T}}ZH\\ &=\frac{1}{\sqrt{|s|}}\left(2\dot{H}^{\mathrm{T}}D^T+2\tilde{\dot{F}}E^T\right)ZH\\ &\le\frac{1}{\sqrt{|s|}}\left[2H^{\mathrm{T}}D^TZH+2\tilde{\dot{F}}E^TZH+\gamma^2|s|-\tilde{\dot{F}}^2\right]\\ &=\frac{1}{\sqrt{|s|}}\left[2H^{\mathrm{T}}D^TZH+2\tilde{\dot{F}}E^TZH+\gamma^2H^{\mathrm{T}}P^TPH-\tilde{\dot{F}}^2\right]\\ &\le\frac{1}{\sqrt{|s|}}H^{\mathrm{T}}\left[D^TZ+ZD+\gamma^2P^TP+ZEE^TZ\right]H\end{aligned} \tag{21}$$

Where:

$$\begin{cases}D=\begin{bmatrix}-\frac{1}{2}\vartheta_1 & \frac{1}{2}\\ -\vartheta_2 & 0\end{bmatrix}\\ E=\begin{bmatrix}0 & 1\end{bmatrix}^T\\ P=\begin{bmatrix}1 & 0\end{bmatrix}\\ \tilde{\dot{F}}=\sqrt{|s|}\dot{F}\\ \dot{H}=\frac{1}{\sqrt{|s|}}\left(DH+E\tilde{\dot{F}}\right)\end{cases} \tag{22}$$

Let be $G=-(D^TZ+ZD+\gamma^2P^TP+ZEE^TZ)$, then $\dot{V}(s,\kappa)\le-\frac{1}{\sqrt{|s|}}H^TGH$, at which point it is obtained:

$$G=\begin{bmatrix}\vartheta_1\vartheta_2+\frac{\vartheta^3{}_1}{2}-\gamma^2-\frac{\vartheta^2{}_1}{4} & \frac{\vartheta_1-\vartheta^2{}_1}{2}\\ \frac{\vartheta_1-\vartheta^2{}_1}{2} & \frac{\vartheta_1-2}{2}\end{bmatrix} \tag{23}$$

If $G>0$, then $\dot{V}(s,\kappa)<0$. From the Shur complementary property, we get that G is a positive definite symmetric matrix when ϑ_1 and ϑ_2 satisfy Eq. (14). The use of **Theorem 1** it is known that the second order sliding mode reaching law can converge to 0 in finite time.

3.3 Design of an SMDO

For Eq. (7) construct SMDO as:

$$\begin{cases}\frac{\mathrm{d}\hat{\omega}_m}{dt}=\hat{F}+\alpha i_q+\beta\hat{\omega}_m+u_{smo}\\ \frac{\mathrm{d}\hat{F}}{dt}=ku_{smo}\end{cases} \tag{24}$$

Where $\hat{\omega}_m$, $\hat{F}$ are the estimates of the corresponding values, respectively. k is constant and u_{smo} is the SMDO output value. Combining Eqs. (7) and (24), the error dynamic equation of the observer can be obtained as:

$$\begin{cases}\dot{e}_{\omega m}=\tilde{F}+\beta e_{\omega m}+u_{smo}\\ \dot{\tilde{F}}=ku_{smo}-f(t)\end{cases} \tag{25}$$

Where $f(t)$ as the rate of change of F. $\tilde{F}=\hat{F}-F$, $e_{\omega m}=\widehat{\omega_m}-\omega_m$.

The sliding mode surface is selected as:

$$s_1=e_{\omega m} \tag{26}$$

The derivation of Eq. (26) is obtained:

$$\dot{s}_1=\dot{e}_{\omega m}=\tilde{F}+\beta s_1+u_{smo} \tag{27}$$

To effectively suppress the chattering and reduce the convergence time, the constant reaching law is chosen as:

$$\dot{s}_1 = -l\,sign(s_1) \tag{28}$$

Where l is sliding mode gain. Combined Eq. (27) and Eq. (28), and consider $\tilde{F}$ as a disturbance of u_{smo} is obtained:

$$u_{smo} = -\beta s_1 - l\,sign(s_1) \tag{29}$$

The Lyapunov function is chosen:

$$V_1 = \frac{1}{2}s_1^2 \tag{30}$$

The derivation of Eq. (30) is obtained:

$$\begin{aligned}\dot{V}_1 &= s_1 \cdot \dot{s}_1 \\ &= s_1\left[\tilde{F} + \beta e_{\omega_m} + u_{smo}\right] \\ &= s_1\left[\tilde{F} - l\,sign(s_1)\right] \\ &\le \left|\tilde{F}\right|\left|s_1\right| - l\left|s_1\right|\end{aligned} \tag{31}$$

To ensure that $\dot{V}_1 \le 0$, l should be satisfied:

$$l \ge \left|\tilde{F}\right| \tag{32}$$

From Eq. (32), s_1 is converging asymptotically to 0, i.e., $\dot{e}_{\omega m} = e_{\omega m} = 0$. At this point, Eq. (25) is rewritten as follows:

$$\begin{cases} \tilde{F} = -u_{smo} \\ \dot{\tilde{F}} = ku_{smo} - f(t) \end{cases} \tag{33}$$

The Eq. (33) is rewritten as:

$$\dot{\tilde{F}} + k\tilde{F} + f(t) = 0 \tag{34}$$

The solution to Eq. (34) is:

$$\tilde{F} = \mathrm{e}^{-kt}\left(C + \int f(t)\mathrm{e}^{kt}\mathrm{d}t\right) \tag{35}$$

Where C is a constant. When $k>0$, $\tilde{F}$ converges to 0. By taking $\hat{F}$ into Eq. (15), the expression of i^*_q is rewritten as:

$$\begin{aligned} i^*_q = \frac{1}{\alpha}&\left(\frac{d}{k\lambda_2}e^{2-\frac{k}{d}}\left(1+\frac{g}{c}\lambda_1\left(\int edt\right)^{\frac{g}{c}-1}\right) - \beta\omega_m - \hat{F}\right. \\ &\left. +\vartheta_1|s|^{\frac{1}{2}}sign(s) + \int \vartheta_2 sign(s)dt\right) \end{aligned} \tag{36}$$

4. Simulation

The simulation model of the SPMSM-driven motor is built in the MATLAB2022a/Simulink environment, the system parameters are: $R = 1.124\ \Omega$, $\psi_f = 0.36\ Wb$, $L_s = 0.00219$ H, $p = 10$, $J = 0.0246 kg \cdot m^2$, $B = 0.001\ N \cdot m^2$. In this paper, PI, Terminal Sliding Mode Model-Free Control (TSM-MFC) and TSOSM-MFC are simulated and compared to verify the effectiveness of the proposed strategy, and each control parameter is respectively: PI: $K_p = 0.15$, $K_i = 10$; TSM-MFC: $\lambda_1 = 0.01$, $\lambda_2 = 5000$, $g = 7$, $c = 3$, $k = 5$, $d = 3$, $l = 5000$, $k = 100$, $\varepsilon = 0.002$, $q = 300$; TSOSM-MFC: $\lambda_1 = 0.01$, $\lambda_2 = 15000$, $g = 7$, $c = 3$, $k = 5$, $d = 3$, $l = 5000$, $k = 1000$, $\vartheta_1 = 2.1$, $\vartheta_2 = 3000$.

The system is started with no load, the initial given speed is 400 Rpm, at 0.1s the load increases abruptly from 0 N·m to 30 N·m, at 0.2s the speed rises to 600 Rpm, at 0.3s the load becomes 0 N·m, at 0.4s the speed becomes 300 Rpm and the results are shown in Figs. 1, 2 and 3. Based on Fig. 1 and Fig. 2, it is clear that the speed waveform of the PI controller has a large amount of overshoot in both the system start-up, speed change and disturbance change phases, which are 72 Rpm, 33 Rpm and 27.5 Rpm, respectively. Compared with the PI, the TSM-MFC has basically no starting overshoot, and due to the combination of the SMC and the MFC, the amount of disturbance is feed-forward compensated, which makes it better able to cope with disturbance changes, and its overshoot in the disturbance change phase is 12 Rpm. Compared with the TSM-MFC, the TSOSM-MFC has the smallest overshoot of 4.7 Rpm in response to the disturbance change and the smallest time to recover to the steady state phase, thus it can be seen that it not only has the strongest anti-disturbance capability but also has the fastest response speed.

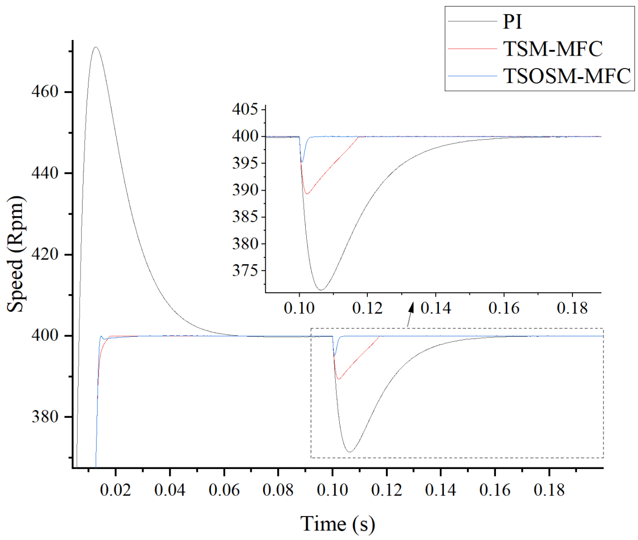

Fig. 1 Speed response at 400 Rpm.

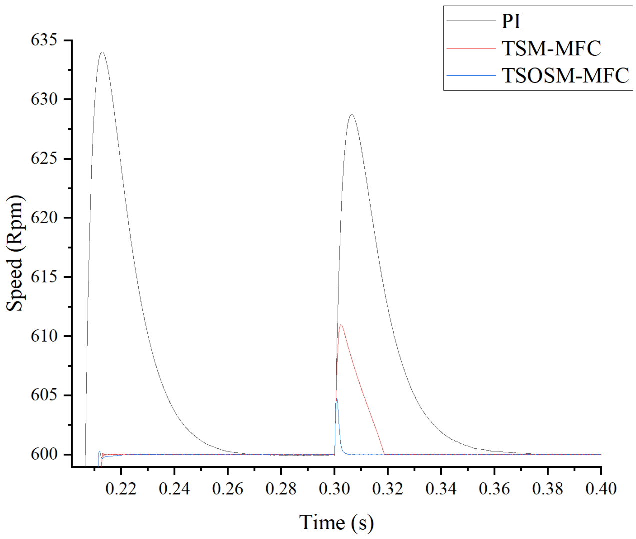

Fig. 2 Speed response at 600 Rpm.

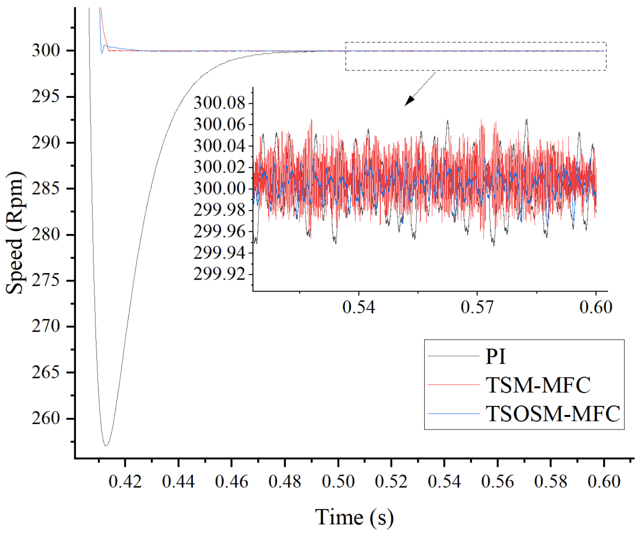

Fig. 3 Speed response at 300 Rpm.

According to Fig. 3, when the system speed is reduced to 300 Rpm and the system is running to a stable state, the speed fluctuations of PI and TSM-MFC are basically the same, compared with the previous two control strategies, TSOSM-MFC greatly weakened the sliding mode chattering due to the introduction of the second-order sliding mode control law, which makes its speed fluctuation the smallest, that is to say, its control accuracy is the highest.

5. Conclusions

For the SPMSM speed control system, a TSOSM-MFC is proposed in this paper, which ensures the finite time convergence of the system state. And the simulation comparison with PI, TSM-MFC proves that the method is not only robust and fast response speed, but also can significantly reduce chattering and improve of the operational quality of the system.

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