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Robust Speed Controller Design for Permanent Magnet Synchronous Motor Drives Based on Sliding Mode Control

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Abstract

This paper is concerned with the speed regulation of the permanent magnet synchronous motor (PMSM). The basic control algorithm is based on Field Oriented Control (FOC) with space vector pulse width modulation (SVPWM) technique. A novel integral sliding mode controller is designed in order to guarantee the robustness of the speed control under the load variation. Both conventional proportional-integral-derivative (PID) control system and the proposed sliding mode control (SMC) system are simulated, and the results validate the effectiveness of the proposed algorithm.

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Keyword: PMSM, FOC, SMC, robustness ;

Nomenclature

i_x	Stator current (x=d, q)
u_x	Stator voltage
L_x	Stator inductance
R_s	Stator resistance

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ω_r	Rotor mechanical angular speed
n_p	Number of pole pairs
ψ_f	Rotor flux linkage
T_L	Load torque
B	Viscous friction
J	Moment of inertia

1. Introduction

In recent years, progresses in magnetic materials, power electronic devices, and control theories have made permanent magnetic synchronous motor drive systems play a growingly important role in many industrial applications. Owing to their high torque/power density, high efficiency and low maintenance, PMSM drive systems are also widely employed in electric and hybrid electric vehicles [1, 2]. More and more researchers study to achieve higher control performance of PMSM, for example rapid response, small overshoot and strong anti-disturbance ability.

The conventional PID control algorithm based on the linearized model of PMSM has been widely applied due to its simple implementation. However, its control performance is affected by the unpredictable parameter variations, external load disturbances and nonlinear dynamics. It is difficult to achieve a satisfactory performance by only using linear control algorithm especially in complex working condition.

Various methods of nonlinear control algorithms have been proposed in order to enhance the control performance of PMSM, such as adaptive control, predictive control, sliding mode control [3-7], and intelligent control etc. Among them, sliding mode control is considered as an effective solution, for it has several distinctive advantages such as insensitivity to parameter variations, fast dynamic response and external disturbance rejection.

In this paper, by introducing an integral sliding mode control method, a novel robust controller is designed in the speed loop. The performance of the conventional PI controller and the proposed SMC speed controller is compared in simulation. The rest of the paper is organized as follows: Section 2 presents the model of PMSM system. In Section 3, a speed controller based on integral sliding mode is designed. Two control algorithms are simulated in Section 4. At last, the paper is concluded with a summary in Section 5.

2. Model of PMSM system

In the d-q synchronously rotating reference frame, the model of surface mounted permanent magnet synchronous motor (SPMSM) is represented as follows:

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{\omega}_r \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & n_p\omega_r & 0 \\ -n_p\omega & -\frac{R_s}{L_q} & -\frac{n_p\psi_f}{L_q} \\ 0 & \frac{1.5n_p\psi_f}{J} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega_r \end{bmatrix} + \begin{bmatrix} \frac{u_d}{L_d} \\ \frac{u_q}{L_q} \\ -\frac{T_L}{J} \end{bmatrix} \tag{1}$$

The phase current can be controlled in both magnitude and position angle by means of decoupling the d- and q-axis current components in the rotating reference frame aligned with the rotor flux. For a SPMSM, namely $L_d = L_q$, the electromagnetic torque is proportional to i_q^* and the representation is given by:

$$T_e = 1.5 n_p \psi_f i_q^* \tag{2}$$

The maximum torque per ampere can be achieved by setting $i_d^* = 0$. The ω_r can be obtained through the position sensor. Then, the speed error passes through the integral sliding mode controller which produces q-axis reference current. Two PI controllers are employed in the two current loops to minimize the d- and q-axis current errors respectively. The d- and q-axis stator voltage vectors are forecasted via these two current regulators. In this paper, we concentrate on the design of the controller in the speed loop. The FOC structure of the SPMSM system based on the proposed algorithm is shown in Fig.1.

3. Speed controller design

From Eq.1 and Eq.2, the PMSM dynamic equation can be rewritten

$$\dot{\omega}_r = a\omega_r + b i_q^* + cT_L \tag{3}$$

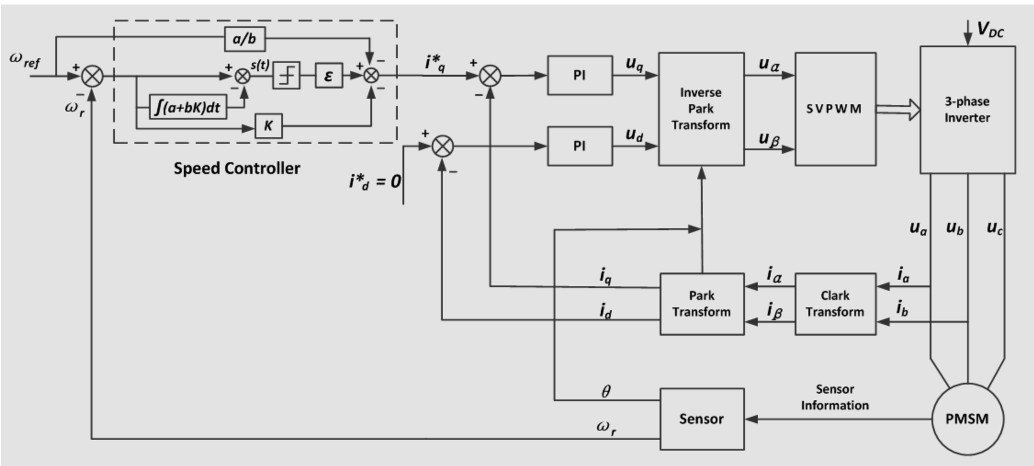

Fig. 1. Block diagram of SMC for SPMSM based on FOC

where $a=-B/J$, $b=1.5n_p\psi_f/J$, and $c=-1/J$. If parameter's uncertainties are considered, the equation above can be transformed as follow

$$\dot{\omega}_r=(a+\Delta a)\omega_r(t)+(b+\Delta b)i_q^*(t)+cT_L \tag{4}$$

where Δa and Δb are defined as the uncertainties introduced by system parameters J, B and ψ_f . The state variables of the speed error are defined as

$$x(t)=\omega_r(t)-\omega_{ref} \tag{5}$$

$$\dot{x}(t)=-\dot{\omega}_r(t) \tag{6}$$

where ω_{ref} is the reference speed. Substituting Eq.4 and Eq.5 into Eq.6 yields

$$\dot{x}(t)=ax(t)+b\left[\bar{i}_q(t)+e(t)\right] \tag{7}$$

where $e(t)=-\frac{\Delta a}{b}\omega_r(t)-\frac{\Delta b}{b}i_q^*(t)-\frac{c}{b}T_L$, which can be regarded as lumped disturbances, and

$$\bar{i}_q(t)=-i_q^*(t)-\frac{a}{b}\omega_{ref} \tag{8}$$

3.1. Design of switching surface

In order to achieve fast convergence and strong robustness, the switching surface of integral sliding mode is designed as

$$s(t)=x(t)-\int_0^t(a+bK)x(\tau)d\tau \tag{9}$$

where K is a linear feedback gain. When the state trajectory of system Eq.7 is trapped on the switching surface, namely $s(t)=\dot{s}(t)=0$, the equivalent dynamics of system is governed by:

$$\dot{x}(t)=(a+bK)x(t) \tag{10}$$

Obviously, the state $x(t)$ approaches zero exponentially, and the time constant is $1/(a+bK)$.

3.2. Selection of control law

Based on the switching surface above, a switching control law that guarantees the existence of the sliding mode is designed as

$$\bar{i}_q(t)=Kx(t)-\varepsilon\,\mathrm{sgn}(s(t)) \tag{11}$$

where ε is switching gain and sgn(.) is a signum function:

$$\mathrm{sgn}(s(t))=\begin{cases}+1, s(t)>0\\-1, s(t)<0\end{cases} \tag{12}$$

So the speed controller can be designed as

$$i_q^*(t) = -Kx(t) + \varepsilon \operatorname{sgn}(s(t)) - \frac{a}{b}\omega_{ref} \tag{13}$$

Choose Lyapunov Function $V = \frac{1}{2}s^2$, and its derivative is $\dot{V} = s\dot{s}$. Substituting Eq.7 and Eq.9 into it, the stability condition can be derived as

$$\dot{V} = s\dot{s} \le -b|s(t)|\left[\varepsilon - |e(t)|\right] \tag{14}$$

Assume that the lumped disturbance $e(t)$ is bounded [3]. The asymptotical stability can be guaranteed by selecting the switching gain that satisfies $\varepsilon > e(t)$. Therefore, the former control law Eq.13 guarantees the existence of the sliding mode. When the state $x(t)$ reaches the sliding manifold, it will slide toward the origin.

4. Simulation and comparison

In this section, two different schemes of FOC, namely the conventional PI controller and the proposed sliding mode controller, are built in MATLAB. The parameters of SPMSM used in the simulation are presented in Table 1.

Table 1. Parameters of SPMSM

Parameter	Value	Unit
Voltage supply	300	V
Flux linkage	0.175	Wb
Number of pole pairs	4	
Stator resistance	0.875	Ω
q-axis inductance	0.0085	H
d-axis inductance	0.0085	H
Inertia moment	0.002	kg • m^2
Viscous friction coefficient	0.0001	N • m • s /rad

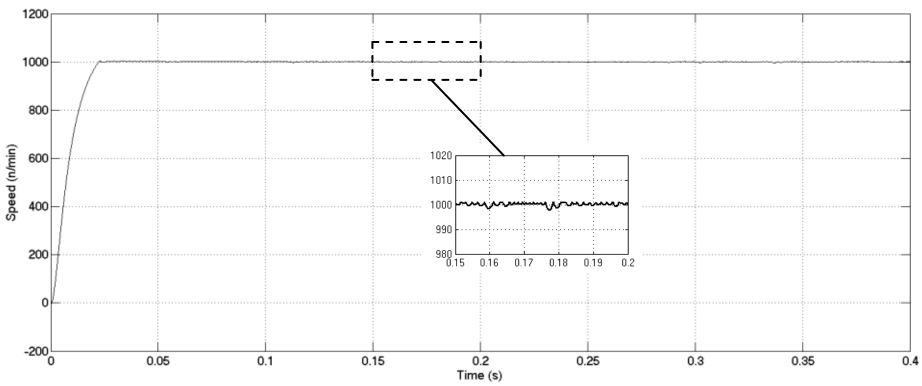

Fig. 2. Speed response of SMC controller

4.1. Speed response

The speed response from 0 to 1000r/min under the SMC algorithm presented above is illustrated in Fig.2 and the load torque is 2N·m. It can be seen that the SMC scheme has small overshoots and a rapid regulation that takes 0.023s.

4.2. Load variation

In this set of simulation, a sudden load variation is added when the motor is under the speed control, and the operating speed is 1000rpm. At t=0.2s, the load torque is changed from 2N·m to 4N·m. The speed regulation of each algorithm is shown in Fig. 3 and Fig. 4. The conventional PI algorithm suffers from the obvious speed drop and variation, and the speed drop is nearly 16rpm. At the same time, the SMC controller shows better disturbance rejection ability and the speed fluctuation is only 2rpm. Thus, it can be considered that the proposed controller is robust under load variation.

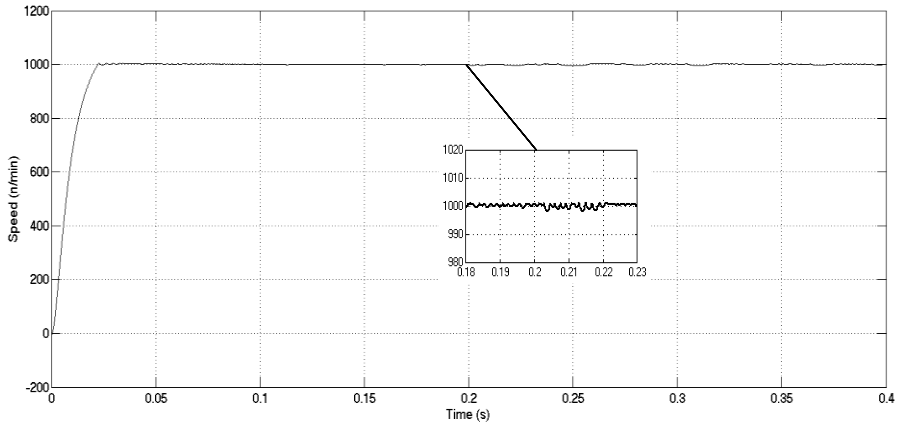

Fig. 3. Speed regulation of SMC under load variation

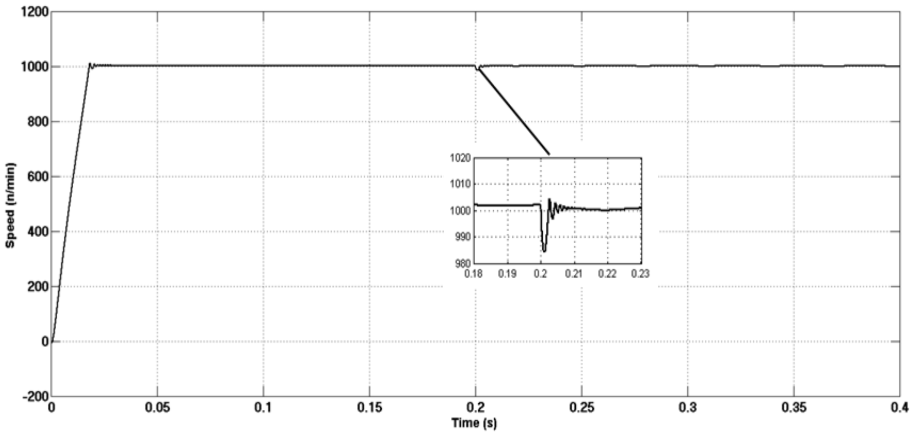

Fig. 4. Speed regulation of PI controller under load variation

5. Conclusion

In this paper, the integral SMC algorithm based on FOC with SVPWM is adopted for PMSM speed regulation system. The performance of the conventional PI controller and the proposed SMC speed controller is compared in simulation. Under the load variation, SMC speed control system shows better robustness than PI control system. A related further study is testing the algorithm in experiment.

6. Copyright

Acknowledgements

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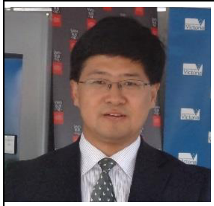

Biography

From 2004 to now, Dr. Song worked as a lecture and then an associate professor in Beijing Institute of Technology. He focuses his research work on the technology of design, control, optimization, and test experiment of electric vehicle’s driving motor and powertrain system.