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Twisting algorithm second order sliding mode control for a synchronous reluctance motor

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Abstract: This paper shows the design of a twisting algorithm second order sliding mode controller (SOSMC) for a synchronous reluctance motor. The second order sliding mode control is an effective tool for the control of uncertain nonlinear systems since it conquers the main shortcomings of the conventional sliding mode control, namely, the large control effort and the chattering effect. Its theory implies simple control laws and assures an improvement of the sliding accuracy with respect to conventional sliding mode control. This paper proposes a novel scheme that based on the technique of twisting second order sliding mode control. First, the SOSMC is obtained by mathematics. Finally, the proposed method is verified by simulation. The proposed SOSMC shows the robustness for the motor parameters variation and the development of chattering effect.

Keywords: Twisting Algorithm, Second Order Sliding Modes, Synchronous Reluctance Motor, Chattering Effect.

1 INTRODUCTION

Fast accurate dynamic response is of primary importance in control systems. The motor control system with the high robustness is an important issue in research. Synchronous reluctance motor (SynRM) have a mechanically simple and robust structure. They can be used in high speed and high temperature environments. The rotor circuit of the SynRM is open circuit such that the flux linkage of SynRM is directly proportional to the stator currents. The torque of SynRM can be controlled by adjusting the stator currents. Therefore, there has been renewed interest in SynRM [1-3].

Sliding mode control (SMC) has attracted increasing attention in recent years because it is an effective and robust technology for parameter variation and external disturbance rejection. It has been applied to robot and motor control [3,4-6]. SMC is a robust control for nonlinear systems. However, sliding mode is a mode of motions on the discontinuity set of a discontinuous dynamic system. Therefore, reducing the chattering is very important for SMC. The second-order sliding mode technique has the same properties of robustness to uncertainties of model and external disturbances. Second-order SMC (SOSMC) [7] improves the chattering phenomenon. Due to few literatures about SOSMC in SynRM control application, therefore, it has valuable on investigation in SynRM control application for SOSMC.

Distinct from the conventional first order SMC, the SOSMC is belonging to the region of higher-order sliding mode (HOSM). Levant [7] had discussed the theory of HOSM. HOSM control have been applied to motor, and automatic docking [8-10].

There is no paper choosing twisting algorithm SOSMC in SynRM speed control so far. Therefore, this paper proposes a novel scheme that based on the technique of twisting algorithm SOSMC. Finally, the presentation of the proposed method is verified by simulation.

2 MODELING OF THE SYNRM

The d-q equivalent voltage equations of ideal SynRM model with a synchronously rotating rotor reference frame are shown in Fig. 1.

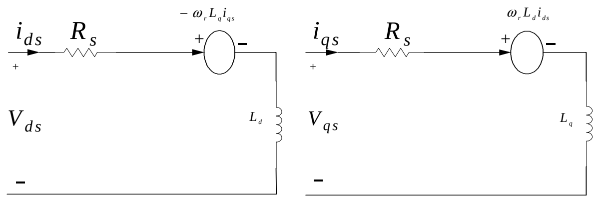

Fig.1. The d-q axis equivalent-circuit of SynRM

$$V_{ds} = R_s i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_r L_q i_{qs} \tag{1}$$

$$V_{qs} = R_s i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_r L_d i_{ds} \tag{2}$$

The corresponding electromagnetic torque T_e is:

$$T_e = \frac{3}{4} P_{ole} \left(L_d - L_q\right) i_{ds} i_{qs} \tag{3}$$

The corresponding motor dynamic equation is:

$$T_e - T_L = J_m \frac{d\omega_r}{dt} + B_m \omega_r \tag{4}$$

where V_{ds} and V_{qs} are direct and quadrature axis terminal voltages, respectively; i_{ds} and i_{qs} are, respectively, direct axis and quadrature axis terminal currents or the torque producing current; L_d and L_q are the direct and quadrature axis magnetizing inductances, respectively; R_s is the stator resistance; and ω_r is the speed of the rotor. P_{ole}, T_L, J_m, and B_m are the poles, the torque load, the inertia moment of the rotor, and the viscous friction coefficient, respectively. In this paper, the maximum torque control (MTC) strategy [3,4] is adopted. The torque current commands are shown in equations (5) and (6) [3]:

$$i_{ds}^{*} = \sqrt{\frac{|T_e|}{\frac{3}{8}P_{ole}\left(L_d - L_q\right)}}\cos\left(\frac{\pi}{4}\right) \tag{5}$$

$$i_{qs}^{*} = \mathrm{sgn}\left(T_e\right)\sqrt{\frac{|T_e|}{\frac{3}{8}P_{ole}\left(L_d - L_q\right)}}\sin\left(\frac{\pi}{4}\right) \tag{6}$$

3 INTEGRAL VARIABLE STRUCTURE SLIDING MODE CONTROLLER

We can rewrite the equation (4) as

$$\begin{aligned}\frac{d\omega_r}{dt} &= \left(-\frac{B_m}{J_m}\right)\omega_r + \frac{1}{J_m}\left(T_e - T_L\right)\\ &= a\omega_r + b\left(T_e - T_L\right)\\ &= \left(a_0 + \Delta a\right)\omega_r + \left(b_0 + \Delta b\right)\left(T_e - T_L\right)\\ &= a_0\omega_r + b_0\left(u(t) + f\right)\end{aligned} \tag{7}$$

where

$$a \equiv -\frac{B_m}{J_m} = a_0 + \Delta a$$

$$b \equiv \frac{1}{J_m} = b_0 + \Delta b$$

$$u \equiv T_e$$

$$f \equiv \frac{1}{b_0}\left(\Delta a\omega_r + \Delta b u(t) - bT_L\right)$$

$$J_m \equiv J_0 + \Delta J$$

$$B_m \equiv B_0 + \Delta B$$

The subscript index "o" indicates the nominal system value; "Δ" represents uncertainty, and f represents the lumped uncertainties.

Define the velocity error as $e(t) = \omega_r^* - \omega_r$, where ω_r^* is the velocity command. The velocity error differential equation of SynRM can be expressed as equation (8):

$$\frac{de(t)}{dt} = \dot{\omega}_r^* - a_0\omega - b_0\left[u(t) + f\right] \tag{8}$$

Let

$$S = e(t) + c\int_{-\infty}^{t} e(t)d\tau, \quad c > 0 \tag{9}$$

The input control $u(t)$ (the electromagnetic torque T_e) of (8) can be defined as equation (10).

$$u(t) = u_{eq}(t) + u_n(t) \tag{10}$$

where $u_{eq}(t)$ is used to control the overall behavior of the system and $u_n(t)$ is used to suppress parameter uncertainties and to reject disturbances. By making mathematical calculation, we get the overall control $u(t)$ as equation (10) [3].

$$u(t) = \frac{1}{b_0}\left[\dot{\omega}_r^* - a_0\omega_r + ce(t)\right] + (K + \frac{\eta}{b_o})\mathrm{sgn}(S) \tag{11}$$

where $|f| \le K$.

4 TWISTING SECOND-ORDER SLIDING MODE CONTROLLER

In conventional SMC design, the control target is let the system state move into sliding surfaces $S = 0$. But a second-order sliding mode controller aims for $S = \dot{S} = 0$. The system states converge to zero intersection of S and $\dot{S}$ in state space.

Twisting method mainly develops relative one order system for reducing chattering event [7]. The state trajectory of S and $\dot{S}$ phase plane is shown in Fig. 2. It converges to the origin of phase plane in finite time.

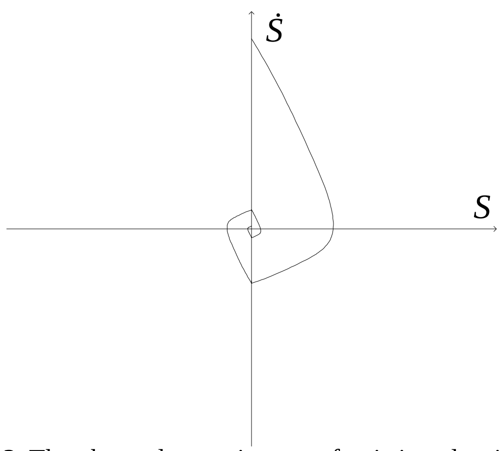

Fig.2. The phase plane trajectory of twisting algorithm

Now consider the following uncertain second order system:

$$\begin{cases}\dot{y}_1(t) = y_2(t)) \\ \dot{y}_2(t) = \varphi\left(\mathbf{x}(t), \mathbf{y}(t), t\right) + \gamma\left(\mathbf{x}(t), \mathbf{y}(t), t\right)\nu(t)\end{cases} \tag{12}$$

in which $\varphi(\cdots)$ and $\gamma(\cdots)$ are uncertain functions with the upper and lower bounds of equation (13).

$$\begin{cases}\left|\varphi\left(\mathbf{x}(t), \mathbf{y}(t), t\right)\right| \le \Phi \\ 0 < \Gamma_m \le \gamma\left(\mathbf{x}(t), \mathbf{y}(t), t\right) \le \Gamma_M\end{cases} \tag{13}$$

By the control rule of equation (14), we can define this control method [8,9]：

$$v(t)=\begin{cases}-u, & if \quad |u|>U\\ -V_m \operatorname{sgn}(y_1), & if \quad y_1y_2\le 0; |u|\le U\\ -V_M \operatorname{sgn}(y_1), & if \quad y_1y_2>0; |u|\le U\end{cases} \tag{14}$$

where U is control value boundary, and the sufficient condition of finite time converges to sliding situation as equation (15) [8].

$$\begin{cases}V_M>V_m\\ V_m>\dfrac{4\Gamma_M}{S_0}\\ V_m>\dfrac{\Phi}{\Gamma_m}\\ \Gamma_m V_M-\Phi>\Gamma_M V_m+\Phi\end{cases} \tag{15}$$

where S_0 is a boundary layer around the sliding surface S. Equation (4) can be rewritten as equation (16):

$$\frac{d\omega_r}{dt}=\frac{1}{J_m}(T_e-T_L-B_m\omega_r) \tag{16}$$

We define state variable as shown in equation (17):

$$\begin{cases}x_1(t)=\int_{-\infty}^{t}x_2(\tau)d\tau\\ x_2(t)=e(t)=\omega_r^*-\omega_r\end{cases} \tag{17}$$

We define sliding function y_1, and y_2 as

$$\begin{cases}y_1=x_2+cx_1\\ y_2=\dot{y}_1\end{cases} \tag{18}$$

Then, the system equation can be expressed as

$$\begin{cases}\dot{y}_1(t)=y_2(t)\\ \dot{y}_2(t)=\ddot{\omega}_r^*+\dfrac{B_m}{J_m}\dot{\omega}_r^*+\left(-\dfrac{B_m}{J_m}+c\right)\dot{x}_2+\dfrac{1}{J_m}\dot{T}_L+v(t)\end{cases} \tag{19}$$

where

$$\begin{cases}\varphi(\cdot)=\ddot{\omega}_r^*+\dfrac{B_m}{J_m}\dot{\omega}_r^*+\left(-\dfrac{B_m}{J_m}+c\right)\dot{x}_2+\dfrac{1}{J_m}\dot{T}_L\\ \gamma(\cdot)=1\\ v(t)=-\dfrac{1}{J_m}\dot{T}_e\end{cases} \tag{20}$$

According to (20), T_e is calculated from the integration of $v(t)$ which is a switching signal defined in (14), so improving the chattering problem in SOSMC control of SynRM.

5 SIMULATION RESULTS

A block diagram of the experimental SynRM drive and the super-twisting second-order sliding mode controller speed control block diagram of the SynRM servo drive are shown in Fig. 3. The synchronous reluctance motor modeled in this paper is a 0.37 kW, 2 pole, 230V, 4.7A, 60Hz, 3600rpm machine. The machine parameters are as follows: (1).Stator resistance Rs =4.2Ω, (2).Direct axis magnetizing inductance L_{dS} =328mH, (3).Quadrature axis magnetizing inductance L_{qS}=181mH, (4).Rotor inertia J_m = 0.00076Kg.m^2, and (5). Friction coefficient B_m =0.00012 Nt-m/rad/sec.

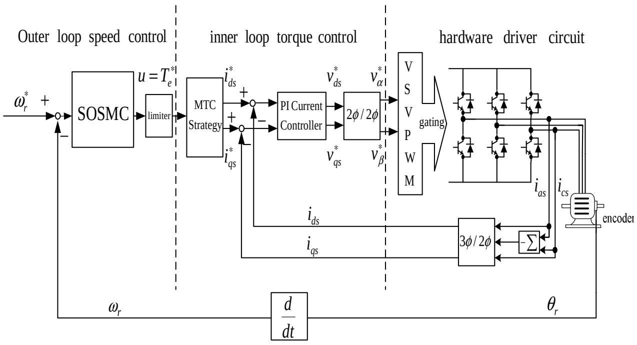

Fig.3. Twisting algorithm SOSMC speed control block diagram of SynRM servo drive

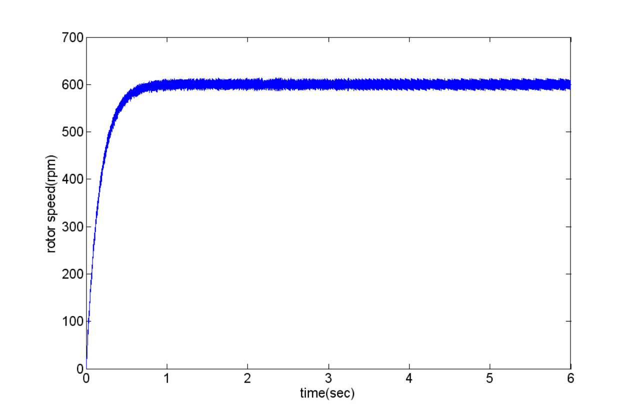

Fig.4. Simulation velocity response of the SMC due to $\omega_r^*=600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition

In Fig.4, the simulation velocity response of the SMC due to $\omega_r^*=600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition is depicted. In Fig.5, the simulation velocity response of the SOSMC due to $\omega_r^*=600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition is depicted. The velocity response of SOSMC is smoother than the convention SMC.

In Fig.6, the simulation velocity response of the SOSMC due to $\omega_r^*=600$ rev/min under an 0.3 Nt-m machine load at the beginning and an 0.9 Nt-m machine load at 3seconds is added for the 2 times nominal case of the motor inertia and friction coefficient condition is presented. Hence, the SOSMC is a robust controller and improve the chattering phenomenon when the system has external disturbances and parameter variations.

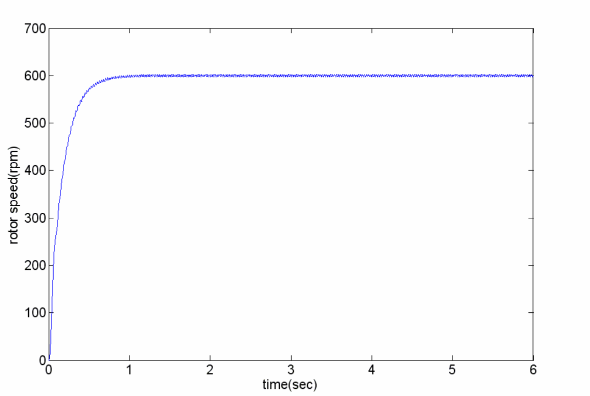

Fig.5. Simulation velocity response of the twisting algorithm SOSMC due to $\omega_r^* = 600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition

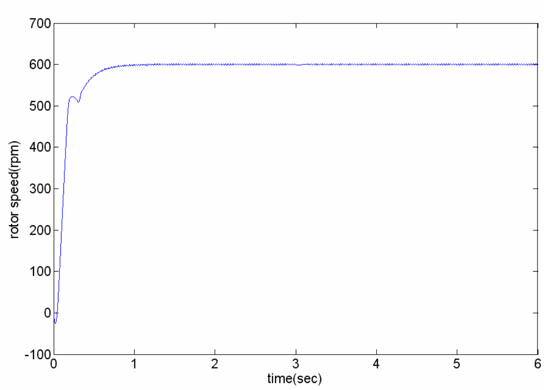

Fig.6. Simulation velocity response of the twisting algorithm SOSMC due to $\omega_r^* = 600$ rev/min under a 0.3 Nt-m machine load at the beginning and a 0.9Nt-m machine load at 3 seconds in the 2 times nominal case of the motor inertia and friction coefficient condition

6 CONCLUSION

In this paper, a twisting algorithm second-order sliding mode speed control design for robust stabilization and disturbance rejection of SynRM is presented. The simulation results show good performance of SOSMC under uncertain load subject to variaitons in inertia and system frcition. Also with SOSMC, there is no need for acceleration feedback. The proposed SOSMC law shows the advantage of continuous control signal which eliminates the chattering effect apparently and is more acceptable in application.

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