Super-Twisting Second Order Sliding Mode Control for a Synchronous Reluctance Motor

Huann-Keng Chiang[1], Wen-Bin Lin[2], Chang-Yi Chang[1], and Chien-An Chen[3]

[1] Department of Electrical Engineering, National Yunlin University of Science & Technology, Taiwan, R.O.C.

[2] Graduate School of Engineering Science & Technology, National Yunlin University of Science & Technology, Taiwan, R.O.C.

[3] Electronic Vehicle and System Verification Group R & D Division, Automotive Research and Testing Center, Taiwan, R.O.C.

Fax :+886-5-5312065
E-mail: chianghk@yuntech.edu.tw

Abstract: This paper presents design and implementation of a super-twisting 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 overcomes the main drawbacks of the classical sliding mode control, i.e., the large control effort and the chattering phenomenon. Its real implementation 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 super-twisting second order sliding mode control. First, the SOSMC is derived by mathematics. Finally, the performance of the proposed method is verified by simulation and experiment. The proposed SOSMC shows the robustness for the motor parameters variation and the improvement of chattering phenomenon.

Keywords: Super-Twisting Algorithm, Second Order Sliding Modes, Synchronous Reluctance Motor, Chattering Phenomenon.

I. 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 [1-4].

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 [3,5-7]. Sliding mode control (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. Hence, 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) [8] improves the chattering phenomenon. Due to few literatures about SOSMC in SynRM control application, therefore, it has valuable on research in SynRM control application for SOSMC.

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

motor, FEM fuel cells and automatic docking [9-12].

There is no paper adopting super-twisting SOSMC in SynRM speed control so far. Therefore, this paper proposes a novel scheme that based on the technique of super-twisting SOSMC. Finally, the performance of the proposed method is verified by simulations.

II. 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:
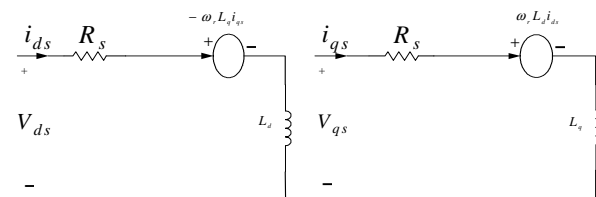

Fig.1. The d-q axis equivalent-circuit of SynRM

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

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

The corresponding electromagnetic torque T_e is:

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

The corresponding motor dynamic equation is:

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

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 equation (5) and (6) [3]:

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

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

III. INTEGRAL VARIABLE STRUCTURE SLIDING MODE CONTROLLER

We can rewrite the equation (4) as

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

where

$$a \equiv -\frac{B}{J} = a_0 + \Delta a$$

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

$$u \equiv T_e$$

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

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

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

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):

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

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]:

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

where $|f| \leq K$.

IV. SUPER-TWISTING SECOND-ORDER SLIDING MODE CONTROLLER

In conventional sliding mode control 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.

Super-twisting method mainly develops relative one order system for reducing chattering phenomenon [7]. The state trajectory of S and $\dot{S}$ phase plane is shown in Fig.2. It twists together and approaches in state space. Finally, it converges to the origin of phase plane.
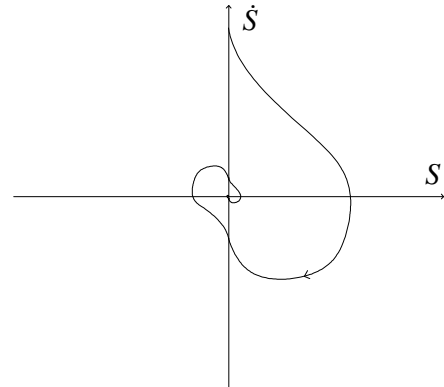

Fig.2. The phase plane trajectory of Super-twisting

Consider sliding variable dynamics given by a system with a relative degree two:

$$\dot{y}_1(t) = \varphi_{ST}(y_1, t) + \gamma_{ST}(y_1, t)u_{ST}(t) \tag{12}$$

where $y_1(t)$ means the sliding variable S, in which φ_{ST} and γ_{ST} are uncertain functions with the upper and lower bounds of equation (13), and $u_{ST}(t)$ is the scalar control input.

$$\begin{cases} |\varphi_{ST}| \leq \Phi_{ST} \\ 0 < \Gamma_{mST} \leq \gamma_{ST} \leq \Gamma_{MST} \end{cases} \tag{13}$$

The control $u_{ST}(t)$ can be given as a sum of two components as shown in equation (14) [6,7] :

$$u_{ST}(t) = u_1(t) + u_2(t) \tag{14}$$

where

$$\dot{u}_1(t) = \begin{cases} -u_{ST}, & if \quad |u_{ST}| > U \\ -W\,\mathrm{sgn}(y_1), & if \quad |u_{ST}| \le U \end{cases} \tag{15}$$

$$u_2(t) = \begin{cases} -\lambda |S_0|^\rho \,\mathrm{sgn}(y_1), & if \quad |y_1| > S_0 \\ -\lambda |y_1|^\rho \,\mathrm{sgn}(y_1), & if \quad |y_1| \le S_0 \end{cases} \tag{16}$$

where U is control value boundary, and S_0 is a boundary layer around the sliding surface S ∘

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 as

$$y_1 = x_2 + cx_1 \tag{18}$$

Then, the system equation can be expressed as

$$\dot{y}_1 = \dot{\omega}_r^* + \left(-\frac{B_m}{J_m} + c\right)x_2 + \frac{1}{J_m}T_L + \frac{B_m}{J_m}\omega_r^* + u_{ST}(t) \tag{19}$$

where

$$\begin{cases} \varphi(\cdot) = \dot{\omega}_r^* + \left(-\frac{B_m}{J_m} + c\right)x_2 + \frac{1}{J_m}T_L + \frac{B_m}{J_m}\omega_r^* \\ \gamma(\cdot) = 1 \\ u_{ST}(t) = -\frac{1}{J_m}T_e \end{cases} \tag{20}$$

According to equation (20), the practical controllable signal T_e of SynRM is a continuous controllable signal. Different from the discontinuous controllable signal of conventional SMC, it can improve the chattering problem in SOSMC of SynRM apparently.

V. 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 proposed controller was applied to a 0.37 kw three-phase SynRM whose nominal parameters and proposed controller parameters are shown in Table 1. The detail specifics of SynRM are shown in Appendix 2.
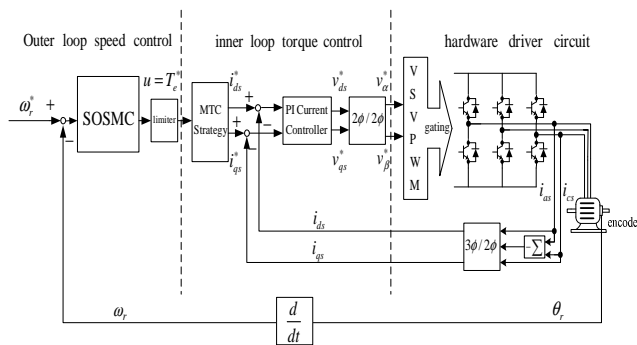

Fig.3. Super-Twisting SOSMC speed control block diagram of SynRM servo drive

Table 1. Parameters of SynRM (0.37kW)

$R_s = 4.2\,\Omega$	$P_{ole} = 2$
$L_{ds} = 0.328$ H ($f = 60\,\mathrm{Hz}$)	$L_{qs} = 0.181$ H ($f = 60\,\mathrm{Hz}$)
$J_m = 0.00076$ Kg-m^2	$B_m = 0.00012$ Nt-m/rad/sec

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.
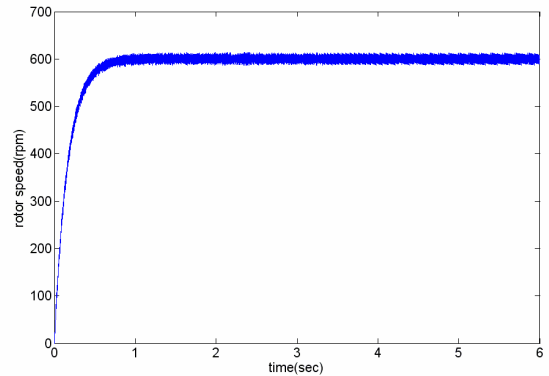

Fig.4. Simulation velocity response of the SMC due to $\omega_r^* = 600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition
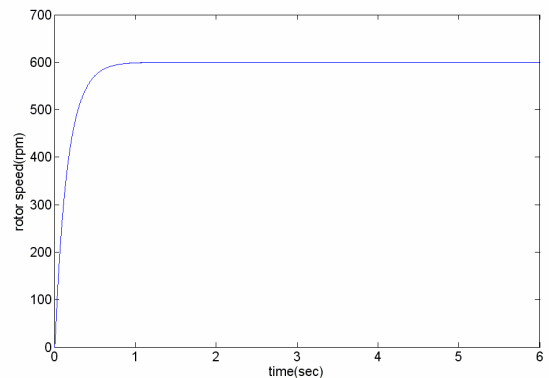

Fig.5. Simulation velocity response of the super-twisting SOSMC due to $\omega_r^* = 600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition

The Sixteenth International Symposium on Artificial Life and Robotics 2011 (AROB 16th '11),
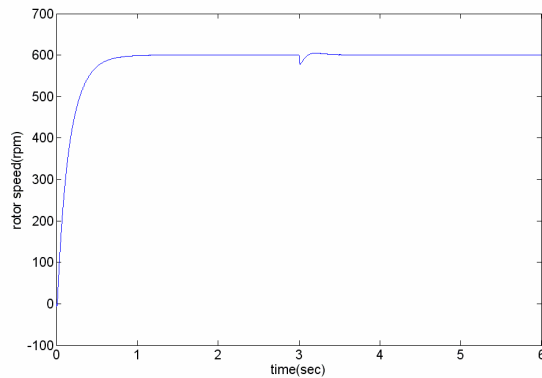B-Con Plaza, Beppu,Oita, Japan, January 27-29, 2011

Fig.6. Simulation velocity response of the super-twisting 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

VI. CONCLUSION

In this paper, a super-twisting second-order sliding mode (SOSMC) speed control design for robust stabilization and disturbance rejection of SynRM drive. 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. An experimental setup has been prepared to assess the perfromance of the proposed controller. Employing the experiments, this controller provides a fast and good response for the parameter variations and external disturbances. Apart from the robustness feature, the proposed second-order SMC laws have the advantage of being continuous, thus eliminating the chattering effect apparently and being more acceptable in application.

ACKNOWLEDGMENT

APPENDIX
Table 2. Rated parameters of SynRM

Specifics	Value
Rated voltage	230/400 V
Rated current	4.7/2.7 V
Rated speed	3600 rpm
Rated power	0.37 kW
Power factor	0.37
Insulation class	F
Waterproof and dust-proof class	IP 20

REFERENCES

[1] Bianchi N., Bolognani S., Bon D., and Pre M. D. (2009), Rotor flux-barrier design for torque ripple reduction in synchronous reluctance and PM-assisted synchronous reluctance motors. IEEE Transactions on Industry Applications 45(3):921-928
[2] Kim W. H., Kim K. S., Kim S. J., Kang D. W., Go S. C., Chun Y. D., and Lee J. (2009), Optimal PM design of PMA-SynRM for wide constant-power operation and torque ripple reduction. IEEE Transactions on Magnetics 45(10):4660-4663
[3] Chen C. A., Lin W. B., and Chiang H. K. (2009), Design and implementation sliding mode controller based on radial basis function neural network for synchronous reluctance motor. ICIEA 2009, 4th IEEE Conference on Industrial Electronics and Applications: 281-286.
[4] Betz R. E., Lagerquist R., Miller T. J. E., and Middleton R. H. (1993), Control of synchronous relutance machines. IEEE Transactions on Industry Applications 29(6):1110-1122
[5] Shyu K. K., and Lai C. K. (2002), Incremental motion control of synchronous reluctance motor via multisegment sliding mode control method. IEEE Transactions on Control Systems Technology 10(2): 169-176
[6] Huang Y. S., and Sung C. C. (2010), Implementation of sliding mode controller for linear synchronous motors based on direct thrust control theory. IET Proceedings on Control Theory & Applications 4(3):326-338
[7] Bartolini G., Ferrara A., Levant F., and Usai E. (1999), Variable Structure Systems, Sliding Mode and Nonlinear Control. Springer-Verlag
[8] Levant A. (1993), Sliding order and sliding accuracy in sliding mode control. International Journal of Control Automation and Systems 58(6):1247-1263
[9] Rashed M., Goh K. B., Dunnigan M. W., MacConnell P. F. A., Stronach A. F., and Williams B. W. (2005), Sensorless second-order sliding-mode speed control of a voltage-fed induction-motor drive using nonlinear state feedback., IEE Proceedings on Electric Power Applications 152(5):1127-1136
[10] Kunusch C., Puleston P. F., Mayosky M. A., and Riera J. (2009), Sliding mode strategy for PEM fuel cells stacks breathing control using a super-twisting algorithm. IEEE Transactions on Control Systems Technology 17(1):167-174
[11] Tournes C., and Shtessel Y. (2007), Automatic docking using second order sliding mode control. 2007 American Control Conference:3455-3460
[12] Mohamadian M., Pedram M. M., and Ashrafzadeh F. (2004), Digital second order sliding mode control for a synchronous reluctance motor. 2004 IEEE Industry Applications Conference:1899-1902