The Eighteenth International Symposium on Artificial Life and Robotics 2013 (AROB 18th '13),
Daejeon Convention Center, Daejeon, Korea, January 30-February 1, 2013

Drift Algorithm Second Order Sliding Mode Control for a Synchronous Reluctance Motor

Wen-Bin Lin[1,2], Huann-Keng Chiang[3], and Yi-Chang Chang[3]
[1] Graduate School of Engineering Science & Technology, National Yunlin University of Science & Technology, Yunlin 64002, Taiwan, R.O.C.
[2] Department of Optoelectronic Engineering, Far East University, Tainan 74448, Taiwan, R.O.C.
[3] Department of Electrical Engineering, National Yunlin University of Science & Technology, Yunlin 64002, Taiwan, R.O.C.
(Tel: 886-5- 5342601 ext: 4247, Fax :+886-5-5312065)

[3]chianghk@yuntech.edu.tw

Abstract: This paper shows the design of a drift 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 classical 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 drift algorithm second order sliding mode control. First, the SOSMC is obtained by mathematics. Finally, the presentation of the proposed method is verified by simulation. The proposed SOSMC shows the robustness for the motor parameters variation and the elimination of chattering effect.

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

1 INTRODUCTION

The motor control system with the high robustness is an important issue in research. Synchronous reluctance motors (SynRMs) 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]. 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. 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 has been applied to motor, and automatic docking [8-10].

The rest of this paper is organized as follows. SynRM modeling is discussed in Section 2. In Section 3, integral variable structure sliding mode controller is introduced. In Section 4, drift algorithm second-order sliding mode controller is described. In Section 5, simulation results show that the proposed algorithm controller provides high-performance dynamic characteristics and robustness under parameter variation and external load disturbances. Finally, conclusions are presented in Section 6.

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:

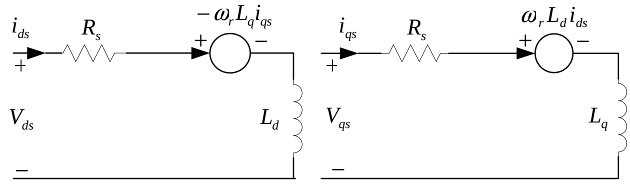

Fig.1. The d-q axis equivalent-circuit of SynRM

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

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

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 equation (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):

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

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]:

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

where $|f| \le K$ and $\eta > 0$.

4 DRIFT ALGORITHM SECOND-ORDER S LIDING MODE CONTROLLER

In conventional sliding mode control design, the control target is let the system states 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. Drift algorithm 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. The drift algorithm in the phase trajectories on the 2-sliding plane are characterized by loops with constant sign of the sliding variable y_1, furthermore it is characterized by the use of sampled values of the available signal y_1 with sampling period δ.

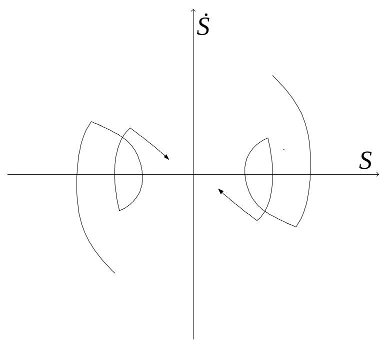

Fig.2. The phase plane trajectory of drift algorithm

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]：

$$v(t)=\begin{cases}-u, & if \quad |u|>U \\ -V_m \operatorname{sgn}(\Delta y_{1_i}), & if \quad y_1\Delta y_{1_i}\le 0;\ |u|\le U \\ -V_M \operatorname{sgn}(\Delta y_{1_i}), & if \quad y_1\Delta y_{1_i}>0;\ |u|\le U\end{cases} \quad (14)$$

where V_m and V_M are suitable positive constants such that V_m < V_M and $\frac{V_M}{V_m}$ sufficiently large, and $\Delta y_{1_i}=y_1(t_i)-y_1(t_i-\delta)$, $t\in[t_i,t_{i+1})$. The corresponding sufficient conditions for the convergence to the sliding manifold are rather cumbersome [8] and are omitted here for the sake of simplicity. After substituting y_2 for Δy_{1_i} a first order sliding mode on $y_2 = 0$ would be achieved. This implies y_1 = *const.*, but, since an artificial switching time delay appears, we ensure a real sliding on y_2 with most of time spent in the set $y_1 y_2 < 0$, and therefore, $y_1 \to 0$. The accuracy of the real sliding on $y_2 = 0$ is proportional to the sampling time interval δ ; hence the duration of the transient process is proportional to δ^{-1}.This algorithm has no overshoot if parameters are chosen properly [8].

Equation (4) can be rewritten as equation (15):

$$\frac{d\omega_r}{dt}=\frac{1}{J_m}(T_e-T_L-B_m\omega_r) \quad (15)$$

We define state variable as shown in equation (16):

$$\begin{cases}x_1(t)=\int_{-\infty}^{t}x_2(\tau)d\tau \\ x_2(t)=e(t)=\omega_r^*-\omega_r\end{cases} \quad (16)$$

We define sliding function y_1 , and y_2 as

$$\begin{cases}y_1=x_2+cx_1 \\ y_2=\dot{y}_1\end{cases} \quad (17)$$

Then, the system equation can be expressed as

$$\begin{cases}\dot{y}_1(t)=y_2(t) \\ \dot{y}_2(t)=\ddot{\omega}_r^*+\frac{B_m}{J_m}\dot{\omega}_r^*+\left(-\frac{B_m}{J_m}+c\right)\dot{x}_2+\frac{1}{J_m}\dot{T}_L+v(t)\end{cases} \quad (18)$$

where

$$\begin{cases}\varphi(\cdot)=\ddot{\omega}_r^*+\frac{B_m}{J_m}\dot{\omega}_r^*+\left(-\frac{B_m}{J_m}+c\right)\dot{x}_2+\frac{1}{J_m}\dot{T}_L \\ \gamma(\cdot)=1 \\ v(t)=-\frac{1}{J_m}\dot{T}_e\end{cases} \quad (19)$$

According to (19) 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 drift algorithm second-order sliding mode controller speed control block diagram of the SynRM servo drive are shown in Fig. 3.

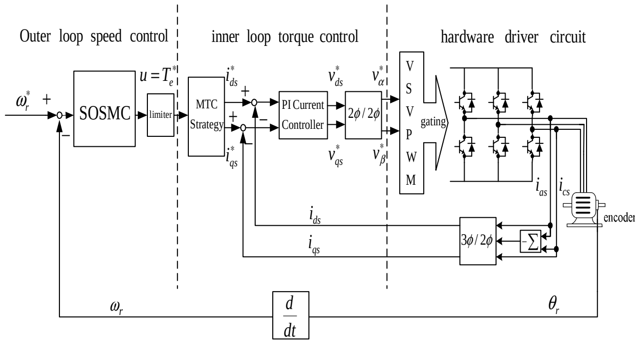

Fig.3. Drift algorithm SOSMC speed control block diagram of SynRM servo drive

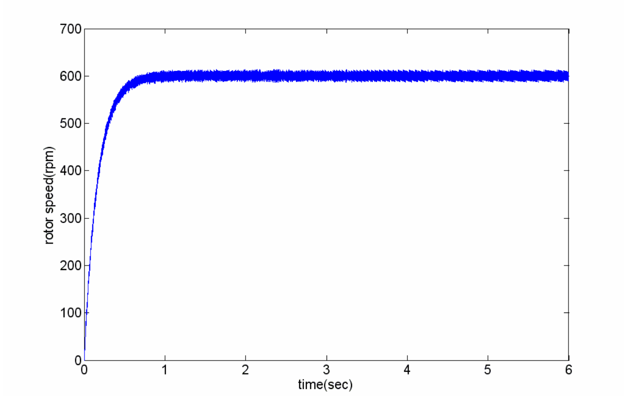

Fig.4. Simulation velocity response of the SMC due to $\omega_r^*=600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition

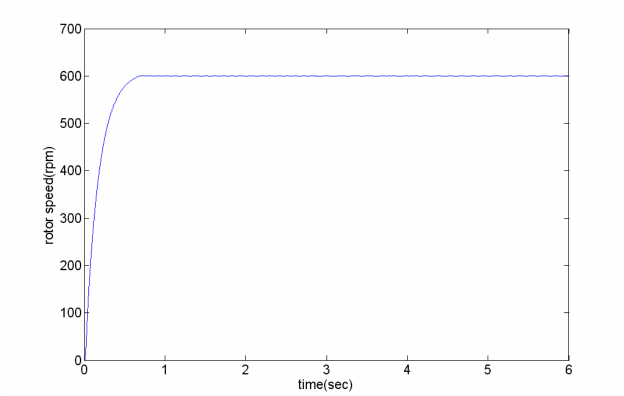

Fig.5. Simulation velocity response of the drift algorithm SOSMC due to $\omega_r^*=600$ rev/min without machine load in the nominal motor inertia and friction coefficient condition

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. 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 proposed 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.

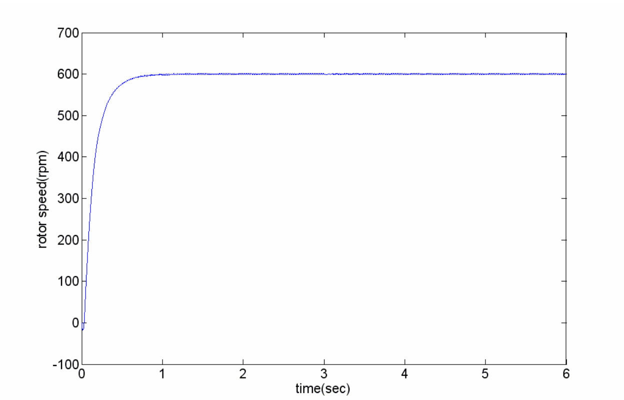

Fig.6. Simulation velocity response of the drift algorithm SOSMC due to $\omega_r^* = 600$ rev/min under an 0.3 Nt-m machine load at the beginning and an 0.9Nt-m machine load at 3 seconds in the 2 times nominal case of the motor inertia and friction coefficient condition

Table 1. Parameters of SynRM (0.37kW)

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

6 CONCLUSION

In this paper, a drift 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.

ACKNOWLEDGMENT

This work is supported by the National Science Council in Taiwan, Republic of China, through grant NSC100-2221-E-224-002.

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] Lin W. B., Chen C. A., and Chiang H. K. (2011), Design and implementation of a sliding mode controller using a Gaussian radial basis function neural network estimator for a synchronous reluctance motor speed drive. Electric Power Components and Systems 39(6): 548- 562.

[4] 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

[5] 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

[6] Bartolini G., Ferrara A., Levant F., and Usai E. (1999), Variable Structure Systems, Sliding Mode and Nonlinear Control. Springer-Verlag

[7] Levant A. (1993), Sliding order and sliding accuracy in sliding mode control. International Journal of Control 58(6):1247-1263

[8] Bartolini G., Ferrara A., Levant F., and Usai E. (1999), On second order sliding mode controllers, in Variable Structure Systems, Sliding Mode and Nonlinear Control, Lecture Notes in Control and Information Sciences K. D. Young and U. Ozguner, Eds., Springer-Verlag, London Ltd: 329-350

[9] Tournes C., and Shtessel Y. (2007), Automatic docking using second order sliding mode control. 2007 American Control Conference, New York City, USA, July 11-13, 2007 , pp.3455-3460

[10] Mohamadian M., Pedram M. M., and Ashrafzadeh F. (2004), Digital second order sliding mode control for a synchronous reluctance motor. Proceeding of 2004 IEEE Industry Applications Conference, Seattle, U.S., Oct 3-7, 2004, pp.1899-1902