한국마린엔지니어링학회지 제30권, 제2호, pp. 239~246, 2006. 3 (ISSN 1226-9549)
Journal of the Korean Society of Marine Engineering

Sliding Mode Control Scheme for an Induction Servomotor Drive

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(Manuscript : Received OCT 21, 2005 ; Revised JAN 20, 2006)

Abstract : This paper describes the scheme of sliding mode control (SMC) to adopt the conventional slip frequency vector drives. The purpose of sliding mode control is to achieve an accurate, robustness of response for ac servomotor speed control. A sliding mode control design method is proposed for a speed control of an induction servomotor. The control law is composed of the variable structure component and the suppressed coefficients to suppress load disturbance and variation of external parameters. The proposed control scheme is simulated by the computer which is installed in an ideal ac servomotor. The simulation results show that the proposed design method has robustness and accuracy in the speed response by adjusting the suppressed coefficients for load disturbance and the motor mechanical parameter variation.

Key words : Sliding mode control (SMC), Suppressed coefficients, Robustness.

Nomenclature

v_{1u}, v_{1v}, v_{1w} and i_{1u}, i_{1v}, i_{1w} : Stator voltage and current in each phase

v_{2u}, v_{2v}, v_{2w} and i_{2u}, i_{2v}, i_{2w} : Rotor voltage and current in each phase

i_{1d}, i_{1q} : Currents of d-q axis in synchronous reference frame.

θ_0, θ_r : Synchronous electrical and rotor shaft angle.

$\omega_0, \omega_r, \omega_s$: Synchronous angular frequency, rotor angular speed and slip angular frequency

M, L_1, L_2 : Magnetizing inductance, leakage inductance in stator and rotor.

R_1, R_2 : Stator, rotor resistance of motor.

* : Reference value.

1. Introduction

Due to advantages of induction motors such as ruggedness, high reliability, and low cost and minimum maintenance, induction motor drives are gradually replacing DC motor drives. However, in case of the implementation of the conventional vector control involves for the high performance induction motor drives, calculation work needed are more than the case of DC motor drives. Therefore a high-speed microcomputer or

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multiprocessor[1], [2] is usually required to fulfill the need of computation speed. Besides, the dynamic performance is also influenced very much due to motor's parameter change. Hence complicated control is required to achieve robustness.

Due to rapid improvements in power devices and microelectronics, the field-oriented vector control or feedback linear techniques have made the application of induction motor drives for high performance applications possible[3], [4].

In practical applications, the control performance of the induction motor is still influenced by the uncertainties of the plant, such as mechanical parameter uncertainty, external load disturbance, and unknown model dynamics. These uncertainties make the design and tuning of the controller difficult. There have been many intelligent techniques adopted to control the induction servomotor systems [5], [6].

The variable structure control (VSC) has been developed and applied to the control of a wide range of processes[7], [8]. When the sliding-mode control matches the sliding-mode condition, it has an invariance properties and robustness against uncertain system parameters and disturbances.

The sliding mode control(SMC) is one of the effective methods to overcome these problems, because it has many good features, such as robustness to parameter variations or load disturbance, fast dynamic response, and simplicity of design and implementation.

This paper describes the scheme of sliding mode control (SMC) to adopt the conventional slip frequency vector drives. The purpose of sliding mode control is to achieve an accurate, robustness of response for ac servomotor speed control. A sliding mode control design method is proposed for a speed control of an induction servomotor. The control law is composed of the variable structure component and the suppressed coefficients to suppress load disturbance and variation of external parameters.

The proposed control scheme is simulated by the computer which is installed in an ideal ac servomotor.

2. Design of Speed Control Scheme

2.1 Sliding Mode Control

To illustrate the basic design of SMC, the dynamic equation of mechanical part can be written as

$$\frac{d\omega}{dt} = \frac{1}{J}\left(T^{*} - B\omega \right) \qquad (1)$$

where, the T^{*} is torque command, J is inertia, B is friction coefficient.

In (1), for T^{*} control law is given by

$$T^{*} = \Psi_1 x + \Psi_2 \dot{x} \qquad (2)$$

where, the state variables are $x = \omega^{*} - \omega$, $\dot{x}$ and ω^{*} represents speed command. Ψ_1, Ψ_2 are the feedback gains defined as

$$\Psi_1 = \begin{cases} \alpha & sx > 0 \\ -\alpha & sx < 0 \end{cases} \quad \Psi_2 = \begin{cases} \beta & s\dot{x} > 0 \\ -\beta & s\dot{x} < 0 \end{cases} \qquad (3)$$

The switching function is (4) and when the condition, $\lim_{s \to 0} s \cdot \dot{s} < 0$ is satisfied state variable x goes to the origin after minimal vibration in switching surface. It is a sliding mode. The switching function defined as

$$s(x) = cx + \dot{x} \tag{4}$$

In sliding mode condition (4) is transformed to (5)

$$s \cdot \dot{s} = (c - a - b\Psi_2)s\dot{x} - b\Psi_1 sx \tag{5}$$

where $a = B/J$ and $b = 1/J$.

In (5), the feedback gains α, β can be expressed as (6) because sliding mode condition, $\lim_{s \to 0} s \cdot \dot{s} < 0$ should be satisfied.

$$\begin{cases} \alpha > 0 \\ \beta > \left| \frac{c-a}{b} \right| \end{cases} \tag{6}$$

In design specification, when rise up time is 1[sec], $c \fallingdotseq 3$, $\alpha = 0.06$ and $\beta = 0.006$.

When the disturbance torque T_L, inertia J and friction coefficient B are changed to $T' = T^* + T_L$ $B' = B + B_1$ $J' = J + J_1$, the sliding mode condition, $\lim_{s \to 0} s \cdot \dot{s} < 0$ can not be satisfied. Therefore, the control law is proposed (8) with a compensation coefficient of disturbance torque,

$$T^* = \psi_1 x + \psi_2 \dot{x} - \psi_{sgn}\gamma \tag{7}$$

where, $\gamma = \max|T_L|$ is compensation coefficient to suppressed external load disturbance torque and Ψ_{sgn} is sign function. The Ψ_1, Ψ_2, Ψ_{sng} are defined as

$$\Psi_1 = \begin{cases} \alpha & \text{if } sx > 0 \\ -\alpha & \text{if } sx < 0 \end{cases} \quad \Psi_2 = \begin{cases} \beta & \text{if } s\dot{x} > 0 \\ -\beta & \text{if } s\dot{x} < 0 \end{cases}$$

$$\Psi_{sng} = \begin{cases} 1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases} \tag{8}$$

The sliding line for the speed limit is adopted as (9) to prevent the overspeed of motor.

$$s = \pm|\dot{x}_{\max}| - \dot{x} \tag{9}$$

The limit condition of the torque command is given by

$$|T^*| = |T_{\max}| \quad \text{if} \quad |T^*| > |T_{\max}| \tag{10}$$

The sliding mode control is to calculate the torque command T^* from position displacement and speed. Therefor, an information of a maximum disturbance load torque, $|T_L|$ is required.

2.2 Vector control algorithm

Denoting d-q axis components, state equations of induction motor are expressed by (11).

$$\frac{d}{dt}\begin{pmatrix} i_{1u} \\ i_{1v} \\ i_{1w} \\ i_{2u} \\ i_{2v} \\ i_{2w} \end{pmatrix} = \frac{1}{3\sigma}\left(\begin{pmatrix} -2L_2 & L_2 & L_2 & 2M & -M & -M \\ L_2 & -2L_2 & L_2 & -M & 2M & -M \\ L_2 & L_2 & -2L_2 & -M & -M & 2M \\ 2M & -M & -M & -2L_1 & L_1 & L_1 \\ -M & 2M & -M & L_1 & -2L_1 & L_1 \\ -M & -M & 2M & L_1 & L_1 & -2L_1 \end{pmatrix}\begin{pmatrix} v_{1u} \\ v_{1v} \\ v_{1w} \\ 0 \\ 0 \\ 0 \end{pmatrix}\right.$$

$$-\left(\begin{matrix} -2R_1L_2 & R_sL_2 + \sqrt{3}\omega_r M^2 & R_1L_2 - \sqrt{3}\omega_r M^2 \\ R_1L_2 - \sqrt{3}\omega_r M^2 & -2R_1L_r & R_1L_2 + \sqrt{3}\omega_r M^2 \\ R_1L_2 + \sqrt{3}\omega_r M^2 & R_1L_2 - \sqrt{3}\omega_r M^2 & -2R_1L_2 \\ 2R_1M & -R_1M - \sqrt{3}\omega_r L_1M & -R_1M + \sqrt{3}\omega_r L_1M \\ -R_1M + \sqrt{3}\omega_r L_1M & 2R_1M & -R_1M - \sqrt{3}\omega_r L_1M \\ -R_1M - \sqrt{3}\omega_r L_1M & -R_1M + \sqrt{3}\omega_r L_1M & 2R_1M \end{matrix}\right.$$

$$\left.\left.\begin{matrix} 2R_2M & -R_2M + \sqrt{3}\omega_r L_2M & -R_2M - \sqrt{3}\omega_r L_2M \\ -R_2M - \sqrt{3}\omega_r L_2M & 2R_2M & -R_2M + \sqrt{3}\omega_r L_2M \\ -R_2M + \sqrt{3}\omega_r L_2M & -R_2M - \sqrt{3}\omega_r L_2M & 2R_2M \\ -2R_2L_1 & R_2L_s - \sqrt{3}\omega_r L_1L_2 & R_2L_1 + \sqrt{3}\omega_r L_1L_2 \\ R_2L_1 + \sqrt{3}\omega_r L_1L_2 & -2R_2L_1 & R_2L_1 - \sqrt{3}\omega_r L_1L_2 \\ R_2L_1 - \sqrt{3}\omega_r L_1L_2 & R_2L_1 + \sqrt{3}\omega_r L_1L_2 & -2R_2L_1 \end{matrix}\right)\begin{pmatrix} i_{1u} \\ i_{1v} \\ i_{1w} \\ i_{2u} \\ i_{2v} \\ i_{2w} \end{pmatrix}\right) \tag{11}$$

where $\sigma = M^2 - L_1L_2$. The torque is given by (12).

$$T = -\frac{M}{\sqrt{3}}\left[i_{1u}(i_{2v} - i_{2w}) + i_{1v}(i_{2w} - i_{2u}) + i_{1w}(i_{2u} - i_{2v})\right] \tag{12}$$

where, all subscript $_{1}$, $_{2}$ stand for a variables and parameters of stator, rotor of induction motor, and u, v, w stand for three phase.

If the output of VSS controller is T^* d-q axis amplitudes of the stator current are given by

$$i_{1d}^{\ *} = K_0 \qquad i_{1q}^{\ *} = \frac{L_2}{M^2 K_0} T^* \tag{13}$$

where, K_0 is determined by flux-speed characteristics of motor and a subscript * stands for a command value.

The slip frequency can be written as

$$\omega_s^{\ *} = \frac{R_2}{L_2 K_0} i_{1q}^{\ *} \tag{14}$$

The current commands are as follows

$$\begin{cases} i_{1u}^* = \sqrt{\frac{2}{3}} |I_1| \cos(\Theta_0 + \Theta_T) \\ i_{1v}^* = \sqrt{\frac{2}{3}} |I_1| \cos(\Theta_0 + \Theta_T - \frac{2}{3}\pi) \\ i_{1w}^* = \sqrt{\frac{2}{3}} |I_1| \cos(\Theta_0 + \Theta_T + \frac{2}{3}\pi) \end{cases} \tag{15}$$

where, $|I_1| = \sqrt{i_{1d}^2 + i_{1q}^2}$, $\Theta_T = \tan^{-1}\frac{i_{1q}}{i_{1d}}$

$$\Theta_0 = \int_0^t (\omega + \omega_s) dt$$

3. Simulations and Results

3.1 Schematic of the Control System

Fig. 1 shows the schematic diagram of the proposed sliding mode of speed control system for induction motor drive using slip frequency vector control. It is composed of a sliding mode controller, a current controller, a current controlled current source inverter (CSI), a current detector and a pulse encoder. SMC and constant flux vector are controlled by the microcomputer. A primary reference current i_1^* is output and reference current estimate an actual current by comparator.

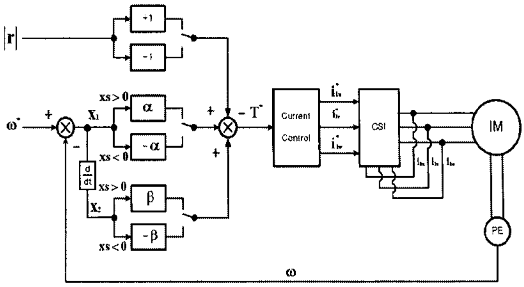

Fig. 1 Proposed adaptive sliding mode speed control scheme of ac servomotor

3.2 Simulation Program

Fig. 2 shows the flow chart of simulation program. The simulation program is divided by analog blocks which are composed of comparison part, motor part and mechanical part, and digital blocks which are composed of a sliding mode control part and vector control part.

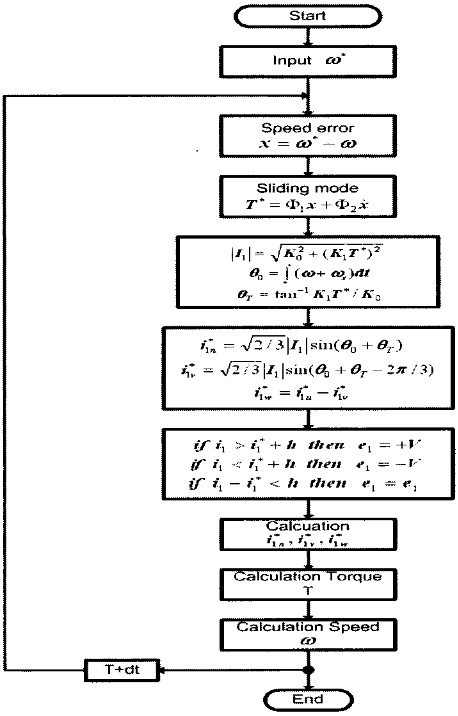

Fig. 2 The flowchart of the speed control for induction motor

The sampling time of analog block is 0.00001[sec] and digital block is 0.001[sec]. The i_{1d}^{*} is sets to 1.5 and hysteresis band h is 0.1. Table 1 shows the load and motor parameters.

Table 1 The system parameters

J	3.234×10^{-4} $[Nms^2]$	R_1	5.86 Ω
B	3.745×10^{-4} $[Nms]$	R_2	5.3 Ω
Rated speed	50[rps]	L_1, L_2	164 mH
Limited current	10[A]	M	143 mH

3.3 Simulation Results and Discussion

In the simulation, step up torque command of 2.5 [Nm] and seed command of 3000[rpm] are applied to drive system.

Fig. 3 shows a switching curve, a torque and a speed response for step input, at the compensation coefficient, $\gamma=0$, load disturbance torque, $T_L=0$, respectively.

The speed response reaches to the reference speed but has a small steady state error and there is not overshoot, and this error is considered to be caused by the calculation error for motor model.

The torque response reaches asymptotically to zero in steady state, and switching curve shows to be matched with sliding mode control by design control law.

Fig. 4 shows switching curve and a torque, speed response for step input, in $\gamma=0.1$ and $T_L=0$. Speed response reaches asymptotically to reference command without error in steady stat, but torque response has more steady state error than in case of Fig. 3.

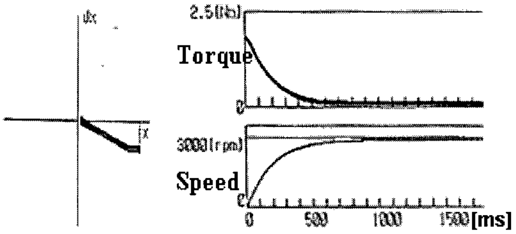

Fig. 3 Switching curve and dynamic response, in case of $T_L=0, \gamma=0$

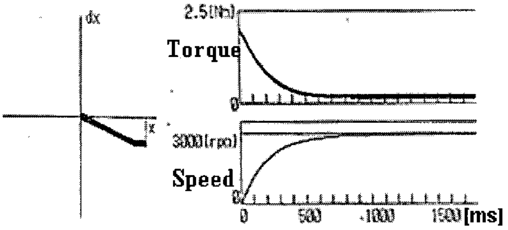

Fig. 4 Switching curve and dynamic response, in case of $T_L=0$, $\gamma=0.1$

Fig. 5, 6 and 7 show the responses in case of $\gamma=0.1$, $\gamma=0.2$ and $\gamma=0.3$ when the $T_L=0.1[Nm]$ is applied to the drive system.

In this case, the speed response reaches to the speed command with a small steady state error.

The results in the switching curves indicate that motor drive operates to be sliding mode control in three case, dynamic responses is improved by adjusting γ and the disturbance torque is suppressed.

The results also show that the speed responses converge to speed command with the robustness in steady state, compared with the larger γ of the small γ.

In the torque responses, chattering phenomenon occurs without relation to value of the compensation coefficient, hence it is considered to be caused by the oscillation of real output torque to input torque command. It also notes that the increase of γ decreases the error in steady state while increases the chattering.

The increase of chattering becomes loss by switching delay of a switching device and weak robustness. Therefore, the results implies that γ is parameter to improve a response characteristics of system by choosing a fitting value between robustness of response and allowable chattering, and the proper γ is 0.2.

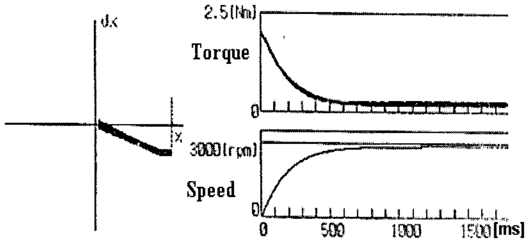

Fig. 5 Switching curve and dynamic response in case of $T_L=0.1$, $\gamma=0.1$

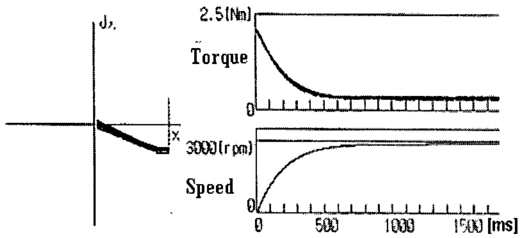

Fig. 6 Switching curve and dynamic response in case of $T_L=0.1$, $\gamma=0.2$

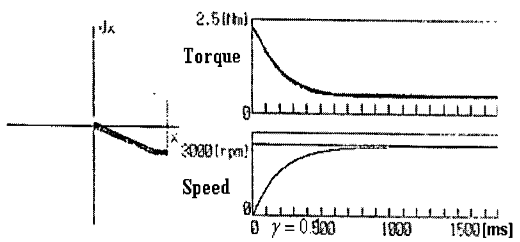

Fig. 7 Switching curve and dynamic response in case of $T_L=0.1$, $\gamma=0.3$

Fig. 8 and 9 show the responses when it is applied to the drive system during sliding mode from t= 500[ms] to 1000[ms] and t= 1000[ms] to 1500[ms] respectively. In this case compensation coefficient and input of disturbance torque set to $\gamma=0.1$ and, $T_L=0.1$ respectively.

The results indicate dynamics of response in which chattering occurs in the neighborhood of the sliding line at step input of disturbance torque and sliding mode control is operated, but speed response is steady state error for speed command. After step disturbance torque disappear, in steady state speed responses obtain to good result to be estimated speed command.

Fig. 10 and 11 shows sliding cover, torque and speed response when inertia of $3J$ friction coefficients of $3B$ is applied to the drive system respectively. Where γ and T_L set to 0 and 0, respectively.

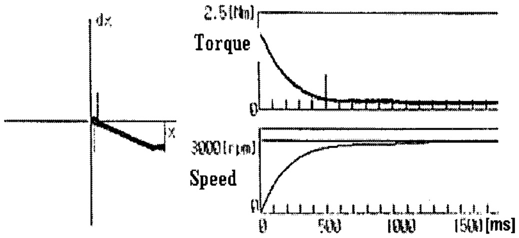

Fig. 8 The dynamic response, $T_L=0.1$ input from 500[ms] to 1000[ms]

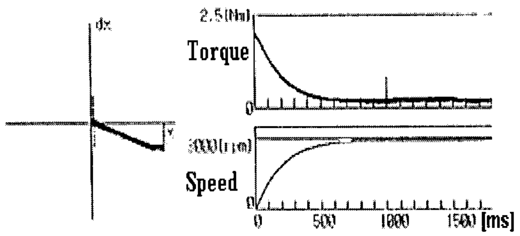

Fig. 9 The dynamic response, $T_L=0.1$ input from 1000[ms] to 1500[ms]

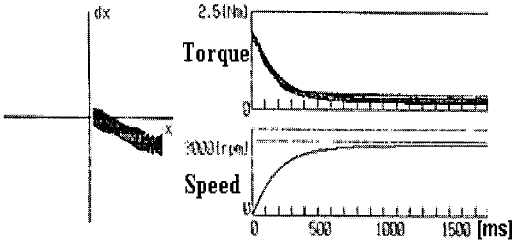

Fig. 10 The dynamic response in case of $3J$

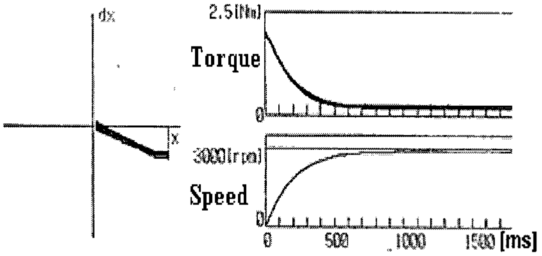

Fig. 11 The dynamic response in case of $3B$

The results indicate dynamics of response that speed response has steady state error for speed command but sliding mode control is applied. This steady state error may be solved if the compensation coefficient is applied. It also shows that torque responses occur a large chattering because of inertia moment of change. However, It is considered not to be problem because J and B is not change in real system.

From this result, though the change of an inertia moment and friction coefficient happen in the range of three times of their normal value, the dynamic response does not almost affect the performance characteristics.

This means the dynamic behavior of the proposed control system is robust with regard to uncertainties such as the induction motor mechanical parameters variation and external load disturbance.

4. Conclusions

This paper describes scheme of sliding mode control (SMC) to adopt the conventional slip frequency vector drives.

An adaptive sliding mode control design method is proposed for induction servomotor drive of high performance. The control law consists the variable structure component and a compensation component to suppress load disturbance and variation of external parameters.

The proposed control scheme has been implemented the sliding mode controller (SMC), current controlled a voltage source inverter, speed detected encoder and simulated in ideal ac servomotor by computer.

This simulation results has successfully demonstrated the effectiveness of the proposed sliding mode controller (SMC) for the speed control of induction servo motor.

The proposed control methode is robust to the motor mechanical parameter variation and the load disturbance.

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