Adaptive Sliding Mode For Indirect Field Oriented Controlled of Induction Motor

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Abstract—**In this paper, an adaptive Sliding Mode Control (SMC) for indirect field oriented control of three-phase induction motor is proposed. First, a sliding mode controller with integral sliding surface is designed. Then, an adaptive function of sliding gain is introduce to reduce the control effort of the SMC, so that there is no need to calculate the upper bound of the system uncertainties, as in traditional SMC. Finally the smooth function is applied to reduce chattering problem across the sliding surface. The speed control for the induction motor using the proposed control scheme is illustrated and the theoretical analysis for the adaptive SMC are described in detail. The results show that the proposed controller provides high performance characteristics and robust with regard to parameter variation and load disturbances. The effectiveness of the proposed scheme is verifying using MATLAB/SIMULINK.**

Keywords-adaptive Sliding Mode Control, field oriented control, induction motor

I. INTRODUCTION

Induction motors are widely used in industrial application due to their relatively low cost, high reliability and almost free maintenance. To regulate these induction motor in high performance application, one of the most popular technique is indirect field oriented control method [1-3]. It allows, by means a co-ordinate transformation, to decouple the electromagnetic torque control from the rotor flux, and hence manage induction motor as DC motor. From this technique, the motor equations are transformed into a reference frame in which the dynamic behave like dc quantities. The decoupling control between the flux and torque allows induction motor to achieve fast transient response. However, the control performance of induction motor still influenced by uncertainties which usually are composed from parameter variation and load disturbance. Therefore, several studies has been made to preserve the performance under parameter variation and external load disturbance[4, 5] .

Variable structure control strategy that used sliding mode control has received much attention for controlling AC machine because it has many good features, such as robustness to parameter variations or load disturbances, fast dynamic response, and simplicity of design and implementation [6-10]. In Sliding mode strategy, the drive response is forced to slide along predefined trajectory in a phase plane by switching algorithm. The strategy is obtained by breaking the design procedures of SMC into two schemes. First, design the sliding surface, and second, choose a control law so that the system trajectory of the closed loop motion direct towards the surface. The performance of the sliding mode control is guaranteed by respecting Lyapunov stability analysis [8,11]. In order to meet these conditions, a sliding gain that represents the upper bound of uncertainties should be determined precisely. However, in real application, the knowledge of the upper bound of uncertainties is difficult to obtain. To overcome this problem, this paper investigates an adaptive sliding mode control to estimate the upper bound of uncertainties of the motor drives system so that the upper bound of uncertainties need not be known in advance.

The discontinuous nature of the control law of sliding mode control can cause chattering in the control system [11-13]. The smooth function is also applied to reduce chattering problem that occur on the sliding surface. The complete field oriented control of induction motor incorporating the adaptive sliding mode controller has been successfully implemented in simulation using MATLAB/SIMULINK. The performances of the proposed controller are compared with those obtained from traditional sliding mode controller. The results show that the proposed adaptive sliding mode controller gives better result in external load rejection as well as maintains the rest characteristics of sliding mode control. This report is organized as follows. The field oriented control of induction motor is presented in section 2, and then the adaptive sliding mode controlled is introduced in section 3. The comparison performance of the system is presented in simulation result in section 4 and finally some concluding remarks are stated in the last section.

II. FIELD ORIENTED CONTROL OF INDUCTION MOTOR

Three phase squirrel cage induction motor in synchronously rotating reference frame are represented in mathematical form [1] as (1) –(8):

$$V_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_e \varphi_{ds} \tag{1}$$

$$V_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} + \omega_e \varphi_{qs} \tag{2}$$

$$V_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_e - \omega_r)\varphi_{dr} \tag{3}$$

$$V_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_e - \omega_r)\varphi_{qr} \tag{4}$$

Where V_{qr}, $V_{dr}=0$, and the flux equation are:

$$\varphi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \quad (5)$$

$$\varphi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \quad (6)$$

$$\varphi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \quad (7)$$

$$\varphi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \quad (8)$$

Where V_{qs}, V_{ds} are the applied voltages to the stator, i_{ds}, i_{qs}, i_{dr}, i_{qr} are the corresponding d and q axis stator current and rotor currents. φ_{qs}, φ_{qr}, φ_{ds}, φ_{dr} are the stator and rotor flux component, R_s, R_r are the stator and rotor resistances, L_{ls}, L_{lr} denotes stator and rotor inductances, whereas L_m is the mutual inductance. The electromagnetic torque equation is:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) \quad (9)$$

where P, denote the pole number of the motor. If the vector control is fulfilled, the q component of the rotor field φ_{qr}, would be zero. Then the electromagnetic torque is controlled only by q-axis stator current and becomes:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\varphi_{dr} i_{qs}) \quad (10)$$

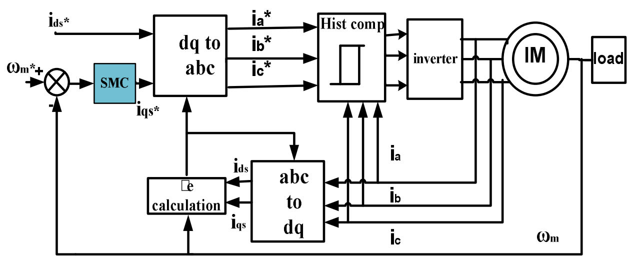


Figure 1. Indirect field oriented control of induction motor

Fig. 1 shows the basic structure of field oriented control for three-phase induction motor. The flux command i^*_{ds} indicates the right rotor flux command for every speed reference within the nominal value. The rotor speed ω_m is compared to rotor speed command ω^*_m and the resulting error is process in the sliding mode controller. The controller generates the q axis reference current i^*_{qs}. Both d-axis and q-axis stator currents generate three phase reference currents i^*_a, i^*_b and i^*_c through Park's Transformation which compared with sensed winding currents i_a, i_b and i_c of the induction motor. The current errors are fed to hysteresis current controllers which generate switching signals for the voltage source inverter.

III. Adaptive Sliding Mode Control

Under the complete field oriented control, the mechanical equation is equivalently described as:

$$T_e = K_T i_{qs} \quad (11)$$

where, K_T is the torque constant and defined as follows:

$$K_T = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\varphi_{dr}) \quad (12)$$

The mechanical equation of an induction motor can be written as:

$$T_e = J\dot{\omega}_m + B\omega_m + T_L \quad (13)$$

using (11) into (13), the equation is obtained as:

$$b i_{qs} = \dot{\omega}_m + a\omega_m + f \quad (14)$$

Where $a=B/J$, $B=K_T/J$ and $f=T_L/J$. Equation (14) is represented with uncertainties Δa , Δb and Δf in term a, b and f respectively, as follows:

$$\dot{\omega}_m = -(a+\Delta a)\omega - (f+\Delta f) + (b+\Delta b) i_{qs} \quad (15)$$

The tracking speed error is defined as:

$$e(t) = \omega_m(t) - \omega^*_m(t) \quad (16)$$

Where ω^*_m is a rotor speed reference. Taking derivative of (16) with respect to time yields:

$$\dot{e}(t) = \dot{\omega}_m(t) - \dot{\omega}^*_m(t) = -ae(t) + u(t) + d(t) \quad (17)$$

Where:

$$u(t) = b i_{qs} - a\omega^*_m(t) - f(t) - \dot{\omega}^*_m \quad (18)$$

and the uncertainties $d(t)$ are:

$$d(t) = -\Delta a\omega_m(t) - \Delta f(t) + \Delta b i_{qs} \quad (19)$$

A. Sliding Mode Controller Design

Here the sliding variable S(t) for speed controller is defined with integral component as:

$$S(t) = e(t) - \int_0^t (k-a)e(\tau)d\tau \quad (20)$$

where k is a constant gain, defines as $k<0$. When the sliding mode occurs on the sliding surface, then $S(t) = \dot{S}(t) = 0$ and therefore, the dynamical behaviour of the controlled system is expressed as:

$$\dot{e}(t) - (k-a)e(t) = 0 \quad (21)$$

The variable structure controller is designed as:

$$u(t) = ke(t) - \beta\,\mathrm{sgn}(S) \quad (22)$$

where β is the switching gain that defines as $\beta \geq |d(t)|$, S is the sliding variable and $sgn(.)$ is the sign function defined as:

$$\mathrm{sgn}(S(t)) = \begin{cases} 1 & \mathrm{if} S(t) > 0 \\ -1 & \mathrm{if} S(t) < 0 \end{cases} \quad (23)$$

From (18) and (22), the current command i^*_{qs} is obtained as:

$$i^*_{qs} = \frac{1}{b}[ke - \beta\,\mathrm{sgn}(S) + a\omega^*_m(t) + \dot{\omega}^*_m(t) + f] \quad (24)$$

B. Adaptive Sliding Mode Control

The application of (22) for sliding mode controller requires the knowledge of upper bound of uncertainties, so that $\beta \geq |d(t)|$ all the time. By choosing the large value of β the system can reach the sliding surface in a short time, but it will result chattering phenomenon. Whereas, the small value of β cause the system reach the sliding surface in a long time. Therefore an adaptive sliding mode controller is proposed to estimate the upper bound of uncertainties for the system. Now the variable structure controller incorporating with adaptive sliding gain is design as:

$$u(t) = ke(t) - \hat{\beta}\gamma \operatorname{sgn}(S) \tag{25}$$

where β is the adaptive switching gain, *S, sgn(.)* and *k* is define earlier. The proposed adaptive sliding mode control is expressed as:

$$\dot{\hat{\beta}} = \gamma|S| \text{ with } \beta(0) = 0 \tag{26}$$

where the gain γ is a positive constant, when sliding mode occurs on the sliding surface, then $S(t) = \dot{S}(t) = 0$ and the tracking error converges to zero exponentially. From (18) and (25), the current command i^*_{qs} is obtained as:

$$i^*_{qs} = \frac{1}{b}[ke - \hat{\beta}\gamma \operatorname{sgn}(S) + a\omega^*_m(t) + \dot{\omega}^*_m(t) + f] \tag{27}$$

C. Smooth Function

One of the drawbacks of sliding mode controller is the discontinuous control signal that cause chattering of the system. Different approaches are suggested in the literature: [14] has proposed a variable band filter to reduce the effect, [15] proposed a thin boundary layer using fuzzy logic and [13, 16, 17] proposed saturation function to replace the sign function. In this section, the saturation function is applied by using a boundary layer around the switching surface. For this reason, a constant factor ξ , represent the thickness of boundary layer and *sat(.)* represent the saturation function is introduce, so that its becomes:

$$u(t) = ke(t) - \hat{\beta}(t)\gamma sat(\frac{S}{\xi}) \tag{28}$$

Where

$$sat\left(\frac{S}{\xi}\right) = \begin{cases} \operatorname{sgn}(S) & if|S| > \xi \\ \frac{S}{\xi} & if|S| \leq \xi \end{cases} \tag{29}$$

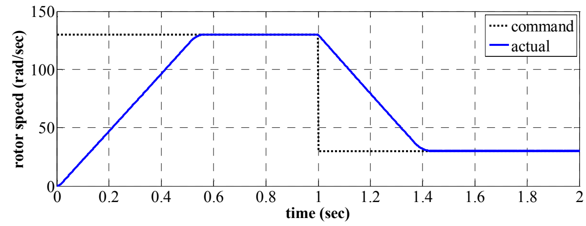
By using (18), (28) and (29) the current command i^*_{qs} is obtained as: ξ

$$i^*_{qs} = \frac{1}{b}[ke - \hat{\beta}\gamma sat(\frac{S}{\xi}) + a\omega^*_m(t) + \dot{\omega}^*_m(t) + f] \tag{30}$$

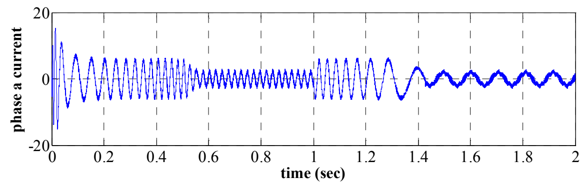
Therefore, the above sliding mode speed controller resolves the speed tracking problem under parameter variation and load disturbances and reduce the chattering problems of common sliding mode controller.

IV. Result

The performance of the proposed control law was investigated using MATLAB/SIMULINK. The specification of the induction motor is given as in Appendix 1. For simulation of adaptive sliding mode controller, the value of *k* and γ is set to be -30 and 1.5. The thickness of the boundary layer ξ is set to 0.1. Figure 2(a) to (i) show the results of speed respond, phase current and associate control effort (torque current command i^*_{qs}), of sliding mode control, adaptive sliding mode control and adaptive sliding mode control with smooth function respectively, in no load condition. For Fig. 2(a), (d) and (g), it may be observed, good tracking responses are obtained for the entire three controllers during transient; steady state and reduction of speed from 130(rad/sec) to 30(rad/sec). Fig. 2(b), (e) and (h), show the phase current for the corresponding speed command. Through these figures, adaptive sliding mode controller with smooth function shows lower ripple, compare to the other controller. Fig. 2(c), (f) and (i) show the associated control effort of the above three type of controller. The results show that the control effort of adaptive SMC with smooth function is smaller than the other two types and the chattering phenomena were reduced. Fig. 3 presents the estimated sliding gain for the corresponding speed command. From the result, the sliding gain is starts from zero and increases until the value is high enough to compensate the system uncertainties at 53.2. When reductions of speed command are applied at 1 second, the sliding gain increase and remain at 82.9 at 1.4 second. By using an adaptive sliding mode controller, it is not necessary to choose sliding gain. The value of gain will change depend on uncertainties of the system.



(a)



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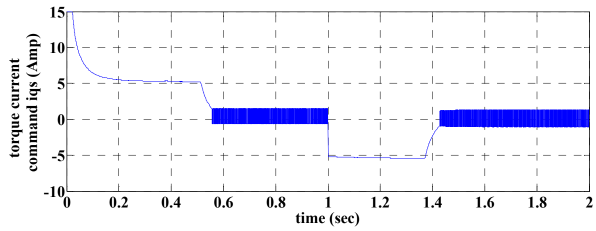

(c)

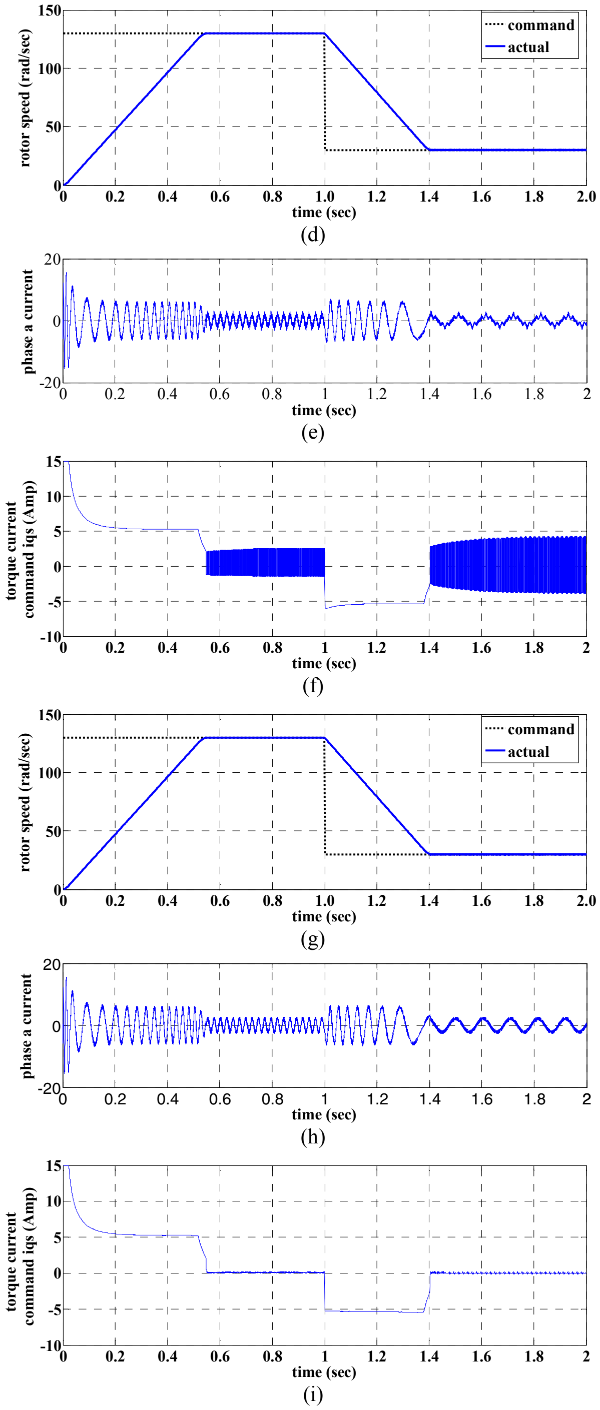

Figure 2. Rotor tracking performance, phase current and torque current command i^*_{qs} ,for (a)-(c) sliding mode (d)-(f) adaptive sliding mode, (g)-(i)adaptive sliding mode with smooth function

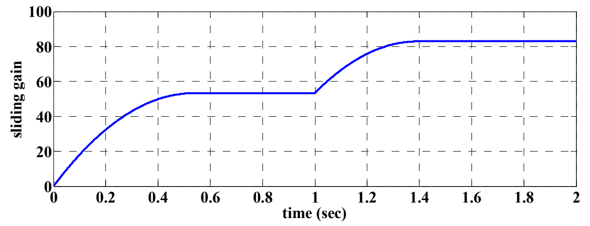

Figure 3. Estimated sliding gain

Fig. 4 shows the comparison performance sliding mode control, adaptive sliding mode control and adaptive sliding mode control with smooth function when load T_L=10Nm is applied to the system at 0.8 sec. The results show that the adaptive sliding mode controller gives smaller slope when the load is applied compared to the only sliding mode controller. However, all the three system show that only a small drop of speed from the steady state condition occurred and the system recovered within 0.01 second. These conditions show that sliding mode controller maintain robust to the load disturbances.

Next, Fig. 5 shows the speed respond of adaptive sliding mode control under parameter variation. In case1, the system is tested under deviation +50% of R_s and R_r and +20% of L_s, L_r and L_m with respect to nominal value, then in case2 the system is tested with inertia 1.5 greater than a nominal value. As shown in Fig. 5, parameter variation does not allocate the performance of the purposed control. The system maintain robust to parameter variation. Also from the figure, shows that by multiplying inertia to 1.5J, the system takes 0.8 second to reach steady state, delay about 0.26 second when compared to nominal condition. While Fig. 6 show the adaptive sliding gain for the two different cases. It is shows that different sliding gain occurs, and the sliding gain is adapt depend on uncertainties of the system.

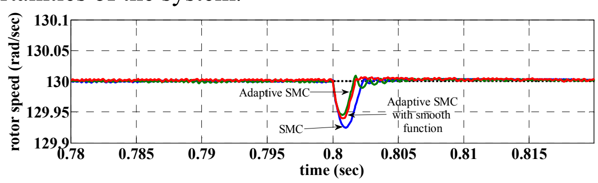

Figure 4. Comparison of speed response obtain when T_L=10Nm is applied to the system at 0.8 sec

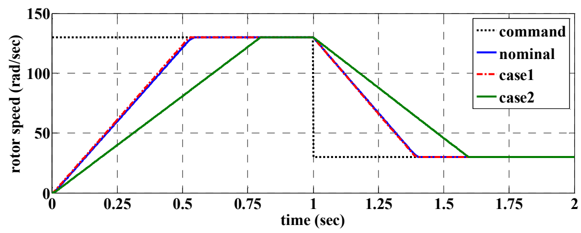

Figure 5. Rotor tracking performance under parameter variation

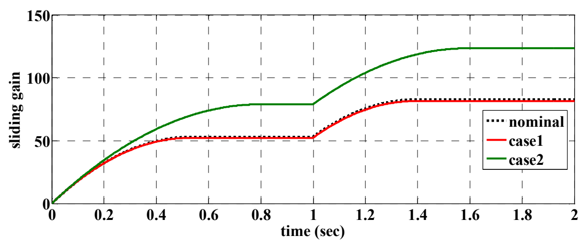

Figure 6. Adaptive sliding gain for two different cases

V. CONCLUSION

An adaptive sliding mode control for three-phase induction motor has been developed for this paper. From the result obtained, it is found that adaptive sliding mode gives better result in external load rejection and maintains the robust characteristics of sliding mode controller. With this technique, the requirement knowledge for upper bound of uncertainties does not require. The control efforts also reduce using smooth function then the chattering phenomena can be reduced.

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VII. APPENDIX

TABLE I. PARAMETER OF TESTED MOTOR

No	Motor Specifications	Value
1	Power	3HP
2	Rated Torque	10Nm
3	Stator resistance, R_s	7.383Ω
4	Rotor resistance, R_r	7.55Ω
5	Stator inductance, L_s	0.4751H
6	Rotor inductance, L_r	0.4751H
7	Magnetizing inductance, L_m	0.4535H
8	Moment of inertia, J	0.06Kgm^2
9	Viscous friction coefficient, B	0.01Nm/(rad/s)
10	Number of poles	4
11	Flux command	1Wb