New Methodology for Chattering Suppression of Sliding Mode Control for Three-phase Induction Motor Drives

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Abstract: - Chattering is undesirable phenomenon when dealing with sliding mode control. This paper proposed a new method for addressing chattering with a simple and easy implementation in Digital Signal Processor (DSP). This is realized by replacing the discontinuous function in conventional sliding mode control with state-dependent auto-tuning of boundary layer in fast sigmoid function and state-dependent switching gain, for three-phase induction motor speed control. This method allows chattering reduction in control input, while keeping the robustness characteristics of sliding mode control. The performance of the proposed control is verified in emulation induction motor drives using Digital Signal Processor TMS320F2812 board, with different speed command and load disturbances.

Key-Words: - Sliding mode control, chattering, induction motor, digital signal processor

1 Introduction

The most significant property of sliding mode control (SMC) is its robustness [1-2]. However, ever since the sliding mode control have been introduces, the chattering phenomenon that include in sliding mode control has irritated and sometimes led to rejection of the technique. Fig.1 illustrates the chattering phenomenon that occurs in sliding mode systems. The solution of the chattering problem is of great importance when exploiting the benefit of sliding mode controller. This is because without proper solution in the control design, chattering can be a major obstacle in implementation of sliding mode control. To surmount with chattering phenomenon, one must know the source of chattering in sliding mode control scheme. In [3], summarized that chattering phenomenon is due to three main causes namely; unmodelled dynamics, switching gain value, and discontinuous function in sliding mode control. Unmodelled dynamics may refer to sensors, actuator data processor neglected in the principles modelling process since they are generally significantly faster than the main system dynamics.

For analyzing the influence of mismatch in modelling due to neglecting the small time constant of actuators and sensors, the describing function method can be used to estimate the amplitude and frequency of the chattering [4]. Intuitively, the amplitude of chattering will be related to the value of constant switching gain. The switching gain is employed in sliding mode as upper bound of uncertainties. These uncertainties value is difficult to obtain [5-6]. In order to reduce this high frequency oscillation, the discontinuous function is replaced with a smooth function. One of the techniques is replace the discontinuous function with smooth sigmoid function. In [7-8] hyperbolic tangent function and saturation function is used to alleviate the discontinuous function and applied to position servo systems. In [9-10] modified hyperbolic tangent function is designed with self-tuning law algorithm. However, most of these algorithm is involves complex algorithm and need special treat when applying in digital signal processor by using look-up-table or logarithm function.

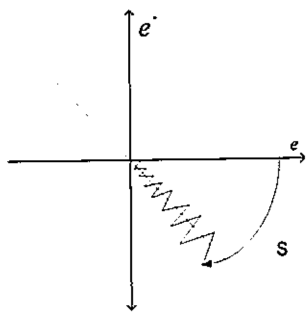

Fig.1: Chattering phenomenon encountered using the discontinuous control law

Another technique to smooth the discontinuous function that widely used, is utilized boundary layer [11-12] with linear saturation function Fig. 2 shows the smoothing out control discontinuity in a thin boundary layer in neighbouring the sliding surface. Different method of boundary layer technique has been used in literature; however, the intention is to limit the use of discontinuous function during the operation system. The larger the boundary layer means the smoother the control signal, however, that may cause steady state error.[13]. Therefore, a trade-off exists between eliminated chattering and to achieve robustness.

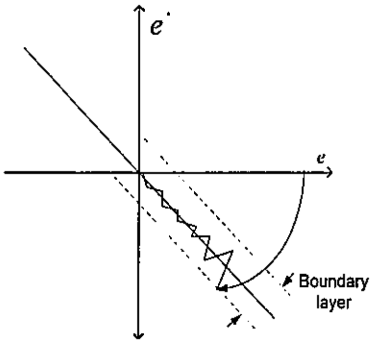

Fig. 2: Sliding plant of smooth controller

In this study, a simple smooth function using fast sigmoid function with auto-tuning state-dependent boundary layer and switching gain for speed control of three-phase induction motor drives is proposed. In the sliding mode controller, a sliding surface with integral operation is designed. The auto-tuning boundary layer and switching gain is based on fast sigmoid function algorithm that not involve complex algorithm. The performance of the proposed sliding mode control is implemented in digital signal processor TMS320F2812 with emulated induction motor, using Code Composer Studio version 3.1. The result shows that the proposed sliding mode control can reduce chattering phenomenon, while maintaining the robust characteristics of the sliding mode control.

2 Three-Phase Induction Motor Drives

To regulate these induction motor in high performance application, one of the most popular technique is indirect field oriented control method [14-16]. It allows, by means a co-ordinate transformation, to decouple the electromagnetic torque control from the rotor flux, and hence manage induction motor controlled as separately exited DC motor. Fig. 3 shows the block diagram of the drives system in real application. The control is divided into two control loops; inner current loop and outer speed control loop.

The three-phase squirrel cage induction motor in synchronously rotating reference frame can be represent in mathematical form [14] 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:

$$\varphi_{qs} = L_{Ls} i_{qs} + L_m (i_{qs} + i_{qr}) \tag{5}$$

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

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

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

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:

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

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

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

The rotor flux quantities are estimate using computational rotor time constant, rotor angular velocity and stator current as in (11).

$$\frac{d\theta_e}{dt} = \frac{1}{Tr}\frac{i_{qs}}{i_{ds}} + \omega_r \tag{11}$$

The rotor speed ω_r is compared to rotor speed command ω_r^* and the resulting error is processed in the sliding mode speed controller. The sliding mode speed controller will generate stator q-axis current reference i_{qs}^*. Both reference current in d-axis and q-axis is compared to the feedback from the motor current through Clark and Park Transformation. From the respective error the voltage command signal is generated through PI current controller and converted to two phase voltage through Inverse Park

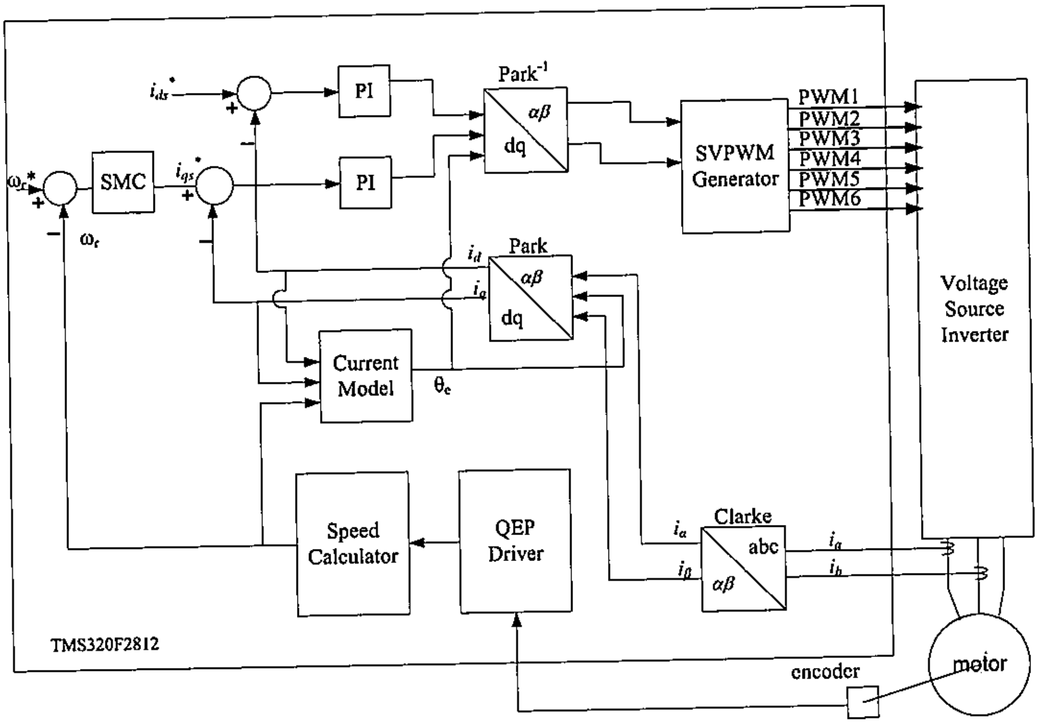

Fig. 3: Overall block diagram for indirect field oriented controlled of induction motor drives

Transformation and fed to Space Vector PWM which generates switching signal for Voltage Source Inverter (VSI). These in turn, control the stator winding current of induction motor, so controlling the speed of the motor.

3 Principle of Sliding Mode Speed Control

With the advantage of integral sliding mode control, and the practice explain in electric drives systems in [17], this section will derive the sliding mode speed control for induction motor drives. Based on complete indirect field orientation, sliding mode control with integral sliding surface is discussed. Under the complete field oriented control, the mechanical equation of three-phase induction motor can be equivalently described as:

$$T_e = K_T i_{qs} \tag{12}$$

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

$$K_T = \frac{3}{2}\frac{4}{2}\frac{L_m}{L_r}\varphi_{dr} \tag{13}$$

Whereas, the mechanical equation of an induction motor can be written as:

$$T_e = J\dot{\omega}_m + B\omega_m + T_L \tag{14}$$

Where, J and B are the inertia constant of the induction motor and viscous friction coefficient respectively; T_L is external load; ω_m is the rotor mechanical speed and T_e denotes the generated torque of an induction motor. Using (12) into (14), one can obtain;

$$\dot{\omega}_m(t) = (a + \Delta a)\omega_m(t) + (b + \Delta b)i_{qs} + f \tag{15}$$

Where, $a = {-B}/{J}$, $b = {K_T}/{J}$, $f = T_L/J$ and $\Delta a = \Delta B/J$, $\Delta b = \Delta K_T/J$

The tracking speed error is defined as

$$e(t) = \omega_m(t) - \omega_m^*(t) \tag{16}$$

where, ω_m^* is a rotor speed reference. Taking derivative of Equation (16) with respect to time yields:

$$\dot{e}(t) = ae(t) + b[u_{qs}(t) + d] \tag{17}$$

Where, d is called lumped uncertainties, defined as

$$d = \frac{\Delta a}{b}\omega_m(t) + \frac{a}{b}i_{qs} + \frac{f}{b} \tag{18}$$

and

$$u_{qs}(t) = i_{qs}(t) + \frac{a}{b}\omega_m^* \tag{19}$$

The sliding variable *S(t)* can be defined with integral component as [18]:

$$S(t) = e(t) - \int_0^t (a + bK)e(\tau)d\tau \qquad (20)$$

where, K is a linear feedback gain. When the sliding mode occurs on the sliding surface, then $S(t) = \dot{S}(t) = 0$ and therefore the dynamical behaviour of the tracking problem in Equation (20) is equivalently governed by the following:

$$\dot{e}(t) = (a + bk)e(t) \qquad (21)$$

Where, $(a+bK)$ is designed to be strictly negative. Based on the sliding surface (20), and the following assumption,

$$\beta \geq |d(t)| \qquad (22)$$

The variable structure controller is design as:

$$u_{qs}(t) = ke(t) - \beta sgn(S) \qquad (23)$$

where β is a switching gain, S is the sliding variable and sgn(.) is the sign function defined as:

$$sgn(S(t)) = \begin{cases} 1 & if S(t) > 0 \\ -1 & if S(t) < 0 \end{cases} \qquad (24)$$

Finally the torque current command or q-axis stator current reference $i^*_{qs}(t)$ can be obtained by directly substituting equation (23) into (19).

$$i^*_{qs} = ke(t) - \beta . sgn(S(t)) - \frac{a}{b}\omega^*_m \qquad (25)$$

Therefore, the sliding mode controller resolves the speed tracking problem for the induction motor, with bounded uncertainties in parameter variation and load disturbances.

The proof of this theorem is carried out using Lyapunov stability theory. Define the Lyapunov function candidate:

$$V(t) = \frac{1}{2}S(t)S(t) \qquad (26)$$

By substitute equation (17),(21) and (23) the time derivative of Lyapunov function is calculated as:

$$\begin{aligned}
\dot{V}(t) &= S(t)\dot{S}(t) \\
&= S.[\dot{e} - (a + bk)e] \\
&= S.[\dot{e} - (ae + bke)] \\
&= S.[ae + b(u + d) - (ae + bke)] \\
&= S.[bu + bd - bke] \\
&= S.[b(ke - \beta sgn(S)) + bd - bke)] \\
&= S.[bke - b\beta sgn(S) + bd - bke] \qquad (27) \\
&= S.[-b\beta sgn(S) + bd] \\
&= S.[bd - b\beta sgn(S)] \\
&\leq b(|d| - \beta)|S| \\
&\leq 0
\end{aligned}$$

Using the Lyapunov's direct method, since the $V(t)$ is clearly positive-definite, $\dot{V}(t)$ is negative definite and $V(t)$ tends to infinity as S(t) tends to infinity. Then the equilibrium at the origin $S(t)=0$ is globally asymptotically stable. Therefore $S(t)$ tends to zero as the time tends to infinity. Moreover, all the trajectories starting off the sliding surface S=0 must reach it in finite time and then will remain on the surface.

4 Proposed Sliding Mode Speed Control

Integral sliding mode control has been developed in section 3. The control law in (23) is depend on the discontinuous control, signum function which leads to chattering. This chattering level is directly controlled by the switching gain β. However, reaching speed also increase with the high value of β. The best of sliding mode-control is to have fastest reaching time and small chattering phenomenon. Therefore, the independence between reaching time and chattering level should be removed. Many analytical design methods were proposed to reduce the chattering effect [19-21], so that the robust control is operating correctly, since it remains to be the only obstacle for sliding mode control and become one of the most significant discoveries in modern control theory. In this section the development of the proposed new methodology of sliding mode control law with chattering suppression will be explained.

With this technique, the discontinuous signum function is replaced with state dependent auto-tuning of sigmoid function and the switching gain is designed [4, 22] as

$$i^*_{qs} = ke(t) - \beta' . sgm(\rho', S) - \frac{a}{b}\omega^*_m \qquad (28)$$

Where, $sgm(\rho, S)$ is called fast sigmoid function [23],

$$sgm(\rho', S) = \frac{\lambda S}{\rho' + |\lambda S|} \qquad (29)$$

Where, ρ' is an approximation small positive constant the thickness of the boundary layer and λ is positive constant used to adjust the tuning rate of the sigmoid function. The state dependent boundary layer ρ' and the switching gain β' are design as

$$\rho' = (1 - |sgm(\rho', S)|) + \delta_1 \qquad (30)$$

$$\beta' = \beta_1(|sgm(\rho', S)| + \delta_2) \qquad (31)$$

Where, δ_1 is sufficiently small and $\beta_1\delta_2$ is a constant, which should be enough to force the sliding mode to occurs. With this fast sigmoid function, no complex algorithm such as exponential function or hyperbolic function involved, so it is easy to implement in fixed point digital signal processor. Fig. 4 shows the effect of choosing the parameter λ, with fixed $\rho' = 1$ and as in contrast with constant λ=9, and variation ρ'. From the figure, we found that the parameter λ and ρ' determines the steepness of continuous function $sgm(S(t))$. With the proposed sliding mode controller, the width of boundary layer and the switching gain are tuned to cause the tracking error to approach zero. Therefore, the β' is exhibit a varying switching gain depend on uncertainties of the system and ρ' exhibit in varying boundary layer in sigmoid function which effectively eliminate input chattering and steady state error.

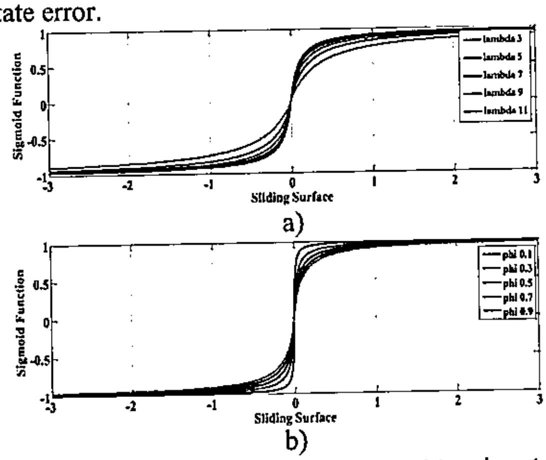

Fig. 4. Bipolar sigmoid function a) with $\rho' = 1$ and variation λ, b) with λ=9 and variation ρ'

5 Emulation of Induction Motor Drives system

Fig. 5 shows the emulation of the drives system and Fig. 6 shows the hardware use for emulation the experiment, which consists of DSP board TMS320F2812, XDS510PP JTAG Emulator and SPI110LV JTAG Opto-isolator. The computer is the host during debugging the program and connected to DSP using parallel port. The Code Composer Studio (CCS) version 3.1 is used to translate the field oriented control and the induction motor model in "C" language or assembly language code for DSP controller. The induction motor use for this simulation is 1.5KW, 1400rpm. The parameter of the motor are, R_s=4.6Ω R_r=5.66, L_s=0.3153H, L_r=0.3153H, L_m=0.3H and J=0.004kgm^2. The stator q-axis current reference is limit to 5A. The sliding mode controller parameters are: K=-0.03, β=0.55, $\beta_1\delta_2 = 0.33$, $\delta_1 = 0.001$ and the PI speed controller parameters are: K_p=5.5, K_i=0.000035. All the parameters are chosen to achieve superior transient control performance and to get the similar performance in term of percentage of overshoot and settling time in rated speed. Therefore, the notion comparison made will be fair and equitable. This emulated motor drive is a good tool to validate the efficiency of the speed controller improvement and also to check the software code before applying to the real experiment.

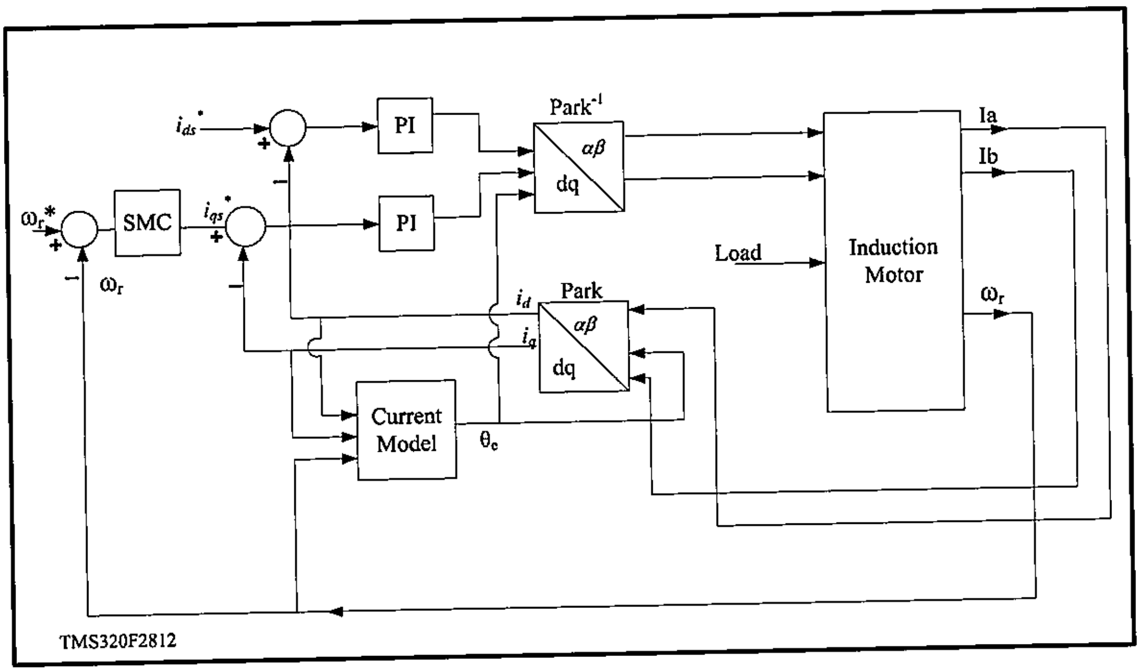

Fig. 5. The emulated induction motor drives using DSP TMS320F2812

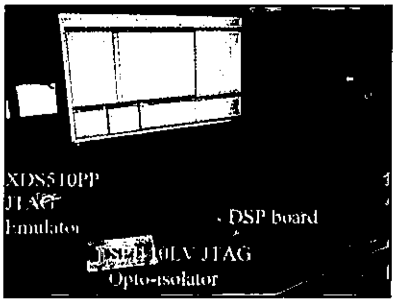

Fig. 6. The hardware use for emulation

6 Results of Emulated Drives

In order to demonstrate the effectiveness of the proposed control systems, three analyses were conduct, the first is standard PI speed control, second is using conventional sliding mode speed control, and third using the proposed sliding mode technique. The first test is to run the motor from standstill to rated speed 1400rpm and half rated speed 700rpm. Fig. 7 show the responses of the speed command and its associate q-axis stator current reference. Good tracking performance for the three controllers, the rotor speed track the speed command with small overshoot. The acceleration under no-load condition is extremely rapid. High chattering occurs in control effort q-axis stator current reference in conventional sliding mode controller; this is due to discontinuous function and switching gain parameter. For the proposed sliding mode controller, there are no chattering phenomena in q-axis stator current reference; the fast sigmoid function algorithm is takes over the discontinuous function. The q-axis stator current reference in auto-tuning sliding mode controller has high value during transient, due to high switching gain and small boundary layer based on state-dependent auto-tuning boundary layer and switching gain parameter.

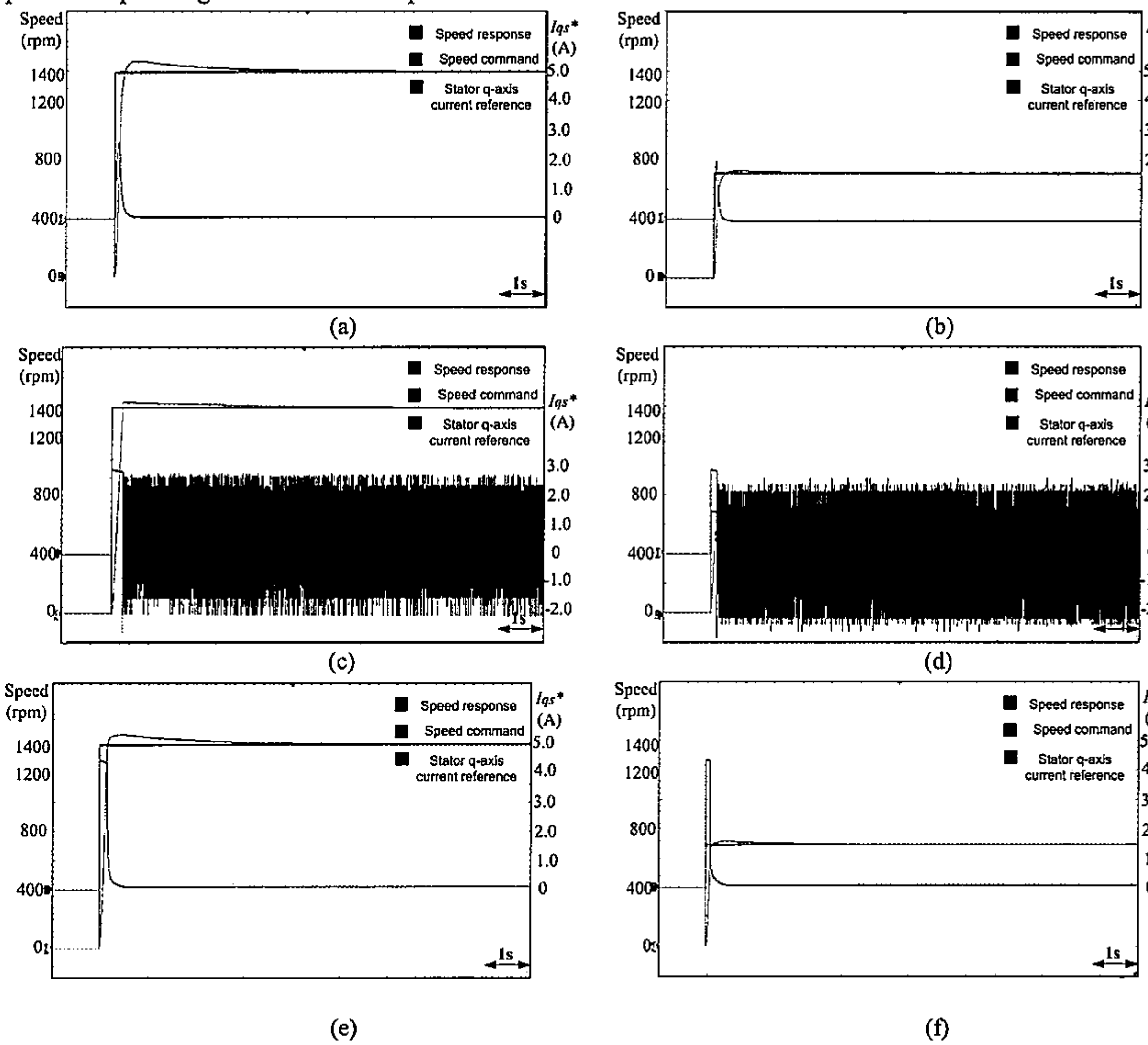

Fig. 7.Speed response and q-axis stator current reference, for 1400rpm (a),(c),(e) and 700rpm(b),(d),(f).
(a)-(b) PI controller (c)-(d) Conventional SMC (e)-(f) Proposed SMC

The third test is to investigate the robustness of the speed controllers. One is with external disturbances condition that is run the motor at rated speed, and then 2.5Nm load occurring at system. The other is the 5.0Nm load condition. Fig. 8 shows the speed response for both conditions. From the results, robust tracking performance showed for sliding mode controller and the proposed sliding mode controller when compared to the PI speed controller in load disturbance rejection, and chattering phenomenon is removed in proposed sliding mode control according state-dependent auto-tuning fast sigmoid function. Although the conventional sliding mode controller has better performance in load rejection behaviour, large chattering phenomenon exists that might excite unstable system dynamics and will degraded the overall controller performance in real application.. Therefore, the proposed sliding mode controller is suitable in hardware application since it has good load disturbance rejection, as well as eliminates chattering.

Fig. 9 shows the effect of changing speed and applying load for the system to parameter β' and ρ'. First the motor is operate in 700rpm, and then increases to 1400rpm. Then load 2.5Nm is applied. From the result, both parameters changes when the speed is changes. The parameter β' is increasing according the applied load and parameter ρ' is reducing as the load increases. Therefore the proposed sliding mode controller's parameter is changes according to uncertainties of the systems.

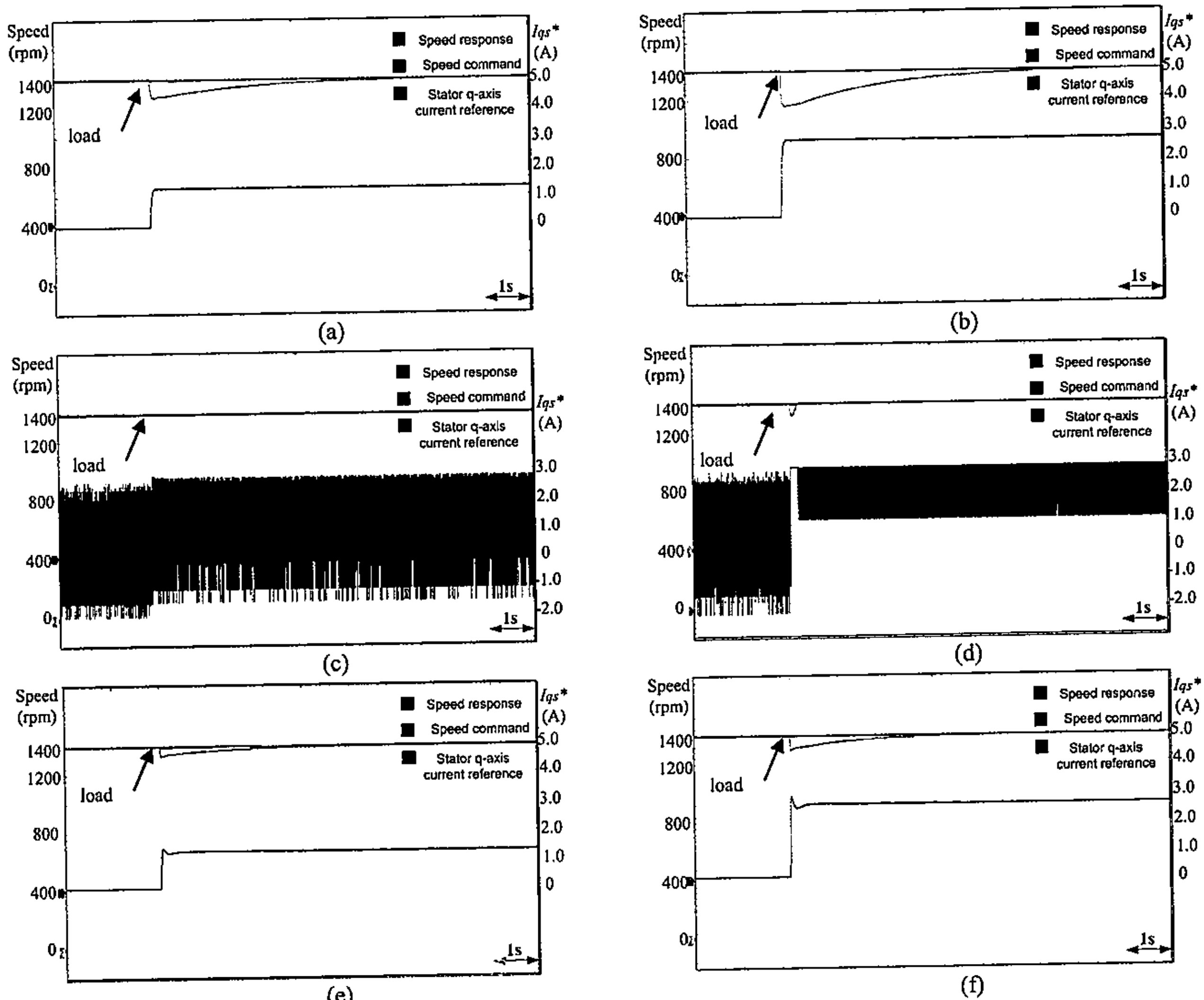

Fig. 8.Speed response for 2.5 Nm load disturbance (a),(c),(e) and 5.0 Nm load disturbance (b),(d),(f). (a)-(b) PI controller (c)-(d) Conventional SMC (e)-(f) Proposed SMC

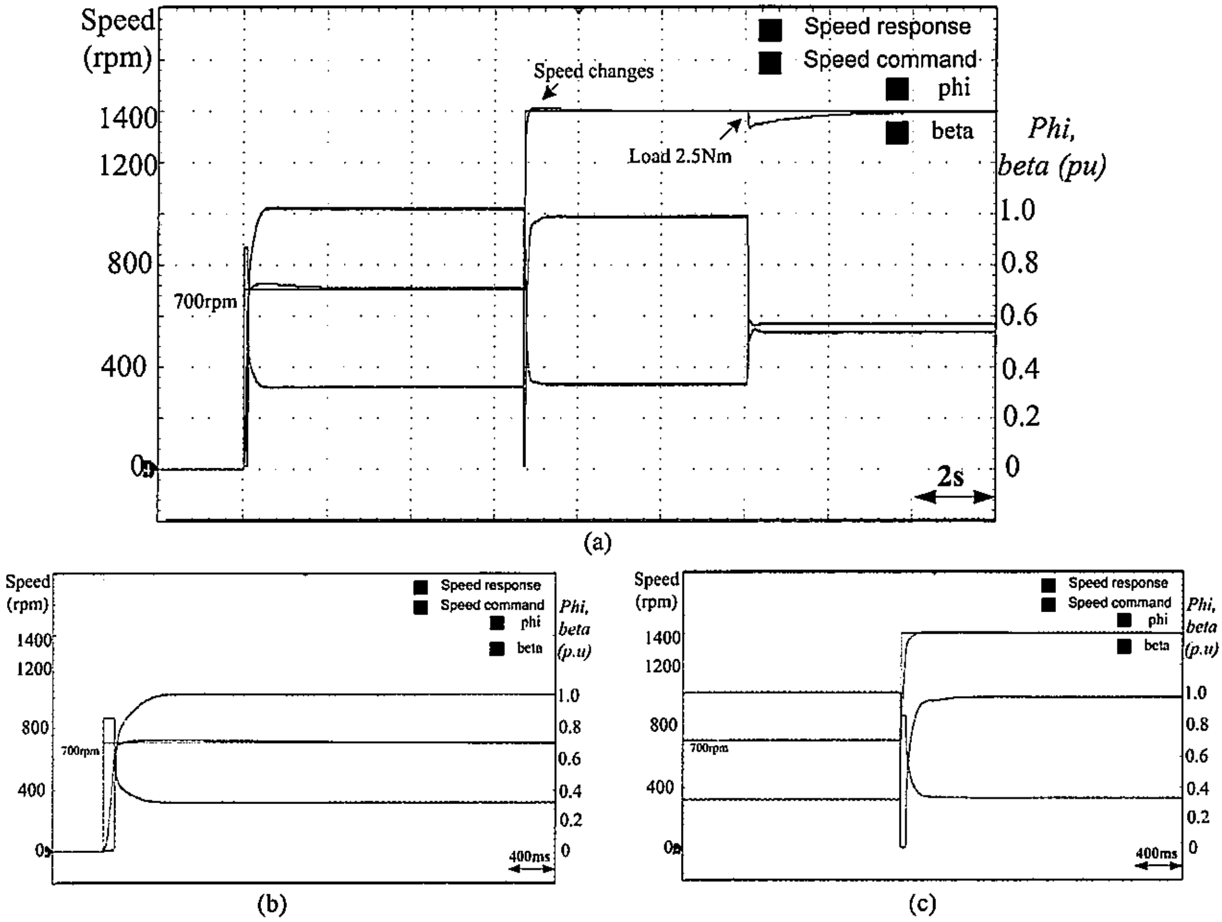

Fig. 9 The effect of speed and load changes to parameter β and ρ (a) overall (b) zoomed within speed changes 0rpm-700rpm (c) zoomed within speed changes 700rpm-1400rpm

Conclusion

This study has successfully demonstrated the application of the proposed state-dependent auto-tuning boundary layer and the switching gain of fast sigmoid function to an indirect field oriented induction motor drives system for tracking speed command. Without the use of complex algorithm, such as exponential and logarithmic functions, the proposed fast sigmoid function algorithm is easy to implement in fixed point digital signal processor board TMS320F281 and the performance is so promising. The proposed sliding mode speed control can maintain the robust performance of the sliding mode control as well as suppressing the chattering phenomenon. The control methodologies design in this study can easily extended to the real electric drive.

References:

[1] V. I. Utkin, "Sliding Mode Control Design Principles and Applications to electric Drive," *IEEE Transaction Industrial Electronics,* vol. 40, pp. 23-36, 1993.

[2] K.-K. Shyu, *et al.*, "Robust Variable Structure Speed Control for Induction Motor Drive," *IEEE Transaction on Aerospace and Electronic System,* vol. Vol. 35, pp. 215-224, 1999.

[3] V. Utkin, *et al.*, *Sliding Mode Control in Electromechanical System*: CRC Press, 1999.

[4] H. Lee and V. I. Utkin, "Chattering suppression methods in sliding mode control systems," *Annual Reviews in Control,* vol. 31, pp. 179-188, 2007.

[5] E. E. El-kholy, "High Performance Induction Motor Drive Based on Adaptive Variable Structure Control," *Journal of Electrical Engineering,* vol. 56, pp. 64-70, 2005.

[6] R. J. Wai, "Fuzzy sliding-mode control using adaptive tuning technique," *Industrial Electronics, IEEE Transactions on,* vol. 54, pp. 586-594, 2007.

[7] D. Gao, *et al.*, "Adaptive fuzzy sliding mode control for robotic manipulators," in

2010 8th World Congress on Intelligent Control and Automation (WCICA), , Jinan, China, 2010, pp. 4811-4816.

[8] M. Jalili-Kharaajoo, *et al.*, "Sliding mode control of voltage-controlled magnetic levitation systems," presented at the Proceedings of 2003 IEEE Conference on Control Applications, 2003. CCA 2003. , 2003.

[9] T. C. Kuo, *et al.*, "Sliding mode control with self-tuning law for uncertain nonlinear systems," *ISA transactions,* vol. 47, pp. 171-178, 2008.

[10] Q. Zong, *et al.*, "Brief paper: Higher order sliding mode control with self-tuning law based on integral sliding mode," *Control Theory & Applications, IET,* vol. 4, pp. 1282-1289, 2010.

[11] F. A. Patakor, *et al.*, "Adaptive Sliding Mode for indirect field oriented controlled of induction motor," in *2011 IEEE Student Conference on Research and Development (SCOReD),* 2011, pp. 289-293.

[12] O. Barambones and P. Alkorta, "A robust vector control for induction motor drives with an adaptive sliding-mode control law," *Journal of the Franklin Institute,* vol. 348, pp. 300-314, 2011.

[13] Y. Huang and S. Chang, "Self-tuning sliding mode control with smooth control input," in *Computational Intelligence in Robotics and Automation, 2005. CIRA 2005. Proceedings. 2005 IEEE International Symposium on,* 2005, pp. 621-624.

[14] B. K. Bose, *Modern Power Electronics and AC Drives*: Prentice Hall, 2002.

[15] D. W. Novotny and T. A. Lipo, *Vector Control and Dynamics of AC Drives*: Oxford Science Publication, 1996.

[16] J. A. Santisteban and R. M. Stephan, "Vector control methods for induction machines: an overview," *Education, IEEE Transactions on,* vol. 44, pp. 170-175, 2001.

[17] V. Utkin and J. Shi, "Integral sliding mode in systems operating under uncertainty conditions," in *Proceeding of th IEEE Conference on Decision and Control* Kobe, 1996, pp. 4591-4596

[18] F. J. Lin, *et al.*, "Robust control of induction motor drive with rotor time-constant adaptation," *Electric Power Systems Research,* vol. 47, pp. 1-9, 1998.

[19] M. H. Park and K. S. Kim, "Chattering reduction in the position control of induction motor using the sliding mode," *Power Electronics, IEEE Transactions on,* vol. 6, pp. 317-325, 1991.

[20] D. Zhang and S. Panda, "Chattering-free and fast-response sliding mode controller," in *Control Theory and Applications Conference, IEE Proceedings*, 1999, pp. 171-177.

[21] M. L. Tseng and M. S. Chen, "Chattering reduction of sliding mode control by low-pass filtering the control signal," *Asian Journal of Control,* vol. 12, pp. 392-398, 2010.

[22] M. Dal and R. Teodorescu, "Sliding mode controller gain adaptation and chattering reduction techniques for DSP-based PM DC motor drives," *Turk J Elec. Eng & Comp Sci,* vol. 19, 2011.

[23] V. Beiu, *et al.*, "Closse Approximations of Sigmoid Functions by Sum of Step for VLSI Implementation of Neural Networks," *Sci. Ann. Cuza Univ.*, vol. 3, pp. 5-34, 1994.