Praise Worthy Prize

International Review of Electrical Engineering (I.R.E.E.), Vol. 8, N. 5
ISSN 1827- 6660 September - October 2013

# Sliding Mode Speed Control for Induction Motor Drives with State-Dependent Gain Method

Marizan Sulaiman, Fizatul Aini Patakor, Zulkifilie Ibrahim

**Abstract** – *The main obstacle of conventional sliding mode control is caused by discontinuous function of high control activity which is known as chattering phenomenon. In this research, the chattering phenomenon is significantly reduced by a newly developed algorithm. A fast sigmoid function with varying boundary layer algorithm is designed as a state-dependent to replace the discontinuous function in conventional sliding mode control. It is known that the switching gain of sliding mode control is proportional to the chattering level, and normally a large switching gain is applied to handle the uncertainties. This research proposes a state-dependent sliding mode control which is the switching gain and boundary layer is proportional to the sigmoid function of the sliding mode controller. As a result, the boundary layer and the switching gain will change depend on uncertainties of the motor drives system. The induction motor is controlled by vector control strategy, using indirect field orientation and Space Vector Pulse Width Modulation technique. Experimental result have proved that the proposed state-dependent sliding mode control able to deal with external load disturbances as well as effectively free from chattering phenomenon compared to conventional sliding mode control. The proposed algorithm and the vector control strategy are developed in digital signal processing board. The results have confirmed that the state-dependent sliding mode control is superior with regard to external load disturbances and variation in the reference speed setting when compared to conventional sliding mode control and fixed boundary layer sliding mode control.* 

***Keywords:*** *State-Dependent Gain, Sliding Mode Control, Induction Motor Drive, Fast Sigmoid Function*

## Nomenclature

| | |
|---|---|
| $B$ | Friction coefficient, Nm/(rad/s) |
| $e(t)$ | Speed error, rpm |
| $d$ | Lumped uncertainties |
| $i_{ds}$, $i_{qs}$ | D and q axis stator currents, A |
| $i_{dr}$, $i_{qr}$ | Rotor current in d and q axis, A |
| $J$ | Inertia, kg m$^2$ |
| $K_T$ | Torque constant |
| $L_{ls}$, | Stator-leakage inductance, H |
| $L_{lr}$ | Stator-referred rotor-leakage inductance, H |
| $L_m$ | Magnetizing inductance, H |
| $L_s$ | Stator selfinductance, H |
| $L_r$ | Stator-referred rotor selfinductance, H |
| $R_s$ | Stator resistance, Ω |
| $R_r$ | Stator-referred rotor-phase resistance, Ω |
| $T_r$ | Rotor time constant |
| $V_{ds}$, $V_{qs}$, | D and q axis stator voltage, V |
| $\omega_r$ | Rotor speed, rpm |
| $\omega_r^*$ | Rotor speed reference, rpm |
| $\varphi_{qs}$, $\varphi_{ds}$ | Stator flux linkage in q and d axis, V s |
| $\varphi_{qr}$, $\varphi_{dr}$ | Rotor flux linkage in q and d axis, V s |
| $\beta$ | Switching gain |

## I. Introduction

The induction motors are widely used in industrial application due to their relatively low cost, high reliability and almost free maintenance. In high performance induction motor drive, in which control variables include the torque developed in the motor, vector control (field orientation) technique are necessary [1]. Vector control technique has experienced tremendous growth since its first time introduced. The decouple properties of vector control promised that the AC motor in can be control in easy way as separately exited DC motor. However the dependence of the system to the motor parameter especially, the rotor time-constant parameter that varies with the temperature and saturation of magnetizing inductance will make full decoupling control cannot be achieved [2] and thus, will degraded the performance of the induction motor drives.

A robust control system is the best solution for controlling induction motor since induction motor not only discover with parameter variation but also influent by uncertainties such as mechanical parameter variation, external load disturbances, unstructured uncertainty due to non ideal field orientation in transient state and unmodeled dynamics [3].

*Manuscript received and revised September 2013, accepted October 2013*

Among the robust control algorithms, variable structure control (VSC) using sliding mode has received many attention since the fist paper in [4]. Sliding mode control (SMC) has many good features such as robustness to parameter variation or load disturbances, fast dynamic response, simplicity of design and implementation [5], [6]. The first concept of VSC was first proposed and elaborated in the early 1950's in the Soviet Union by Emel'yanov and several co-researchers. Sliding mode control has successfully implemented in wide area applications such as in mobile robot [7], [8], DC motor control [9], [10], power supplies [11], AC motors [12]-[15] and many other applications. In AC motor drives, sliding mode control is implemented as outer loop in speed controller [16], [17], as inner loop in current controller [18] as speed observer in sensorless methods [19], [20] and other applications [3]. Researchers in the field of sliding mode control are striving to overcome the problem associated with variable structure control, that so-called chattering phenomenon. Chattering is the high-frequency oscillations of the controller output, brought about by the high speed switching necessary for the establishment of a sliding mode. In practical implementation, chattering is highly undesirable because it may excite unmodeled high-frequency plant dynamics, and this can result in unforeseen instability [21]. This harmful phenomenon often leads to undesirable result such as low control accuracy, high wear of moving mechanical parts and in power electronics, high frequency can lead to high losses [22]. Without proper treatment in the control design, chattering can be a major obstacle in implementing sliding mode control in wide range applications.

These oscillations that caused by the high-frequencies of a sliding mode controller excite unmodeled dynamics in the closed loop system. Unmodeled dynamics may refer to sensors, actuator data processor neglected in the principles modelling process because they are generally significantly faster than the main system dynamics.

However, since the ideal sliding mode systems are infinitely fast, all system dynamics should be considered in the control design. In addition, chattering level also influence by the value of the switching gain. Switching gain is employed in sliding mode as upper bound of uncertainties. As the system discovered from a large uncertainty or unknown uncertainties which means the higher value of switching gain must be applied. According to sliding mode equation, the control law contains the discontinuous function multiplied with the switching gain. This means, the chattering level is controlled by the switching gain.

Hence, the larger value of switching gain implies the higher oscillation magnitude of chattering. At the same time, the larger value of switching gain also serve a sliding mode system to have faster reaching time, a good robustness and tracking performance [23].

Therefore the dilemma either to have good robustness and tracking performance and at the same time increase the chattering level, or reduce the chattering level with poor robustness and tracking performance. In order to solve this dilemma, the interdependence between the reaching time and chattering level is must be removed.

Fortunately, preventing chattering usually does not require a detail model of all system components [24]. A sliding mode controller may first be designed under idealized assumption of no unmodeled dynamics. In a second step design, is to reduce the chattering phenomenon with difference strategy. This paper will look in depth the robustness of induction motor control drive system using sliding mode speed control [26]-[28] in outer loop of vector control, incorporating with Space Vector Pulse Width Modulation strategy.

A state-dependent gain method for adjusting the switching gain and the thickness of boundary layer based on fast sigmoid function is designed. The state-dependent sigmoid function acted as a variable boundary layer to reduce chattering and to gives good tracking performance. The state-dependent switching gain performs as variable switching gain that changed depends on uncertainties of the systems. The investigation in this paper will cover the performance of the drive systems in term of speed tracking performance and external load rejection. The comparison of the proposed drive systems with conventional sliding mode control and sliding mode control with constant boundary layer will be presented in detail using experimental rig.

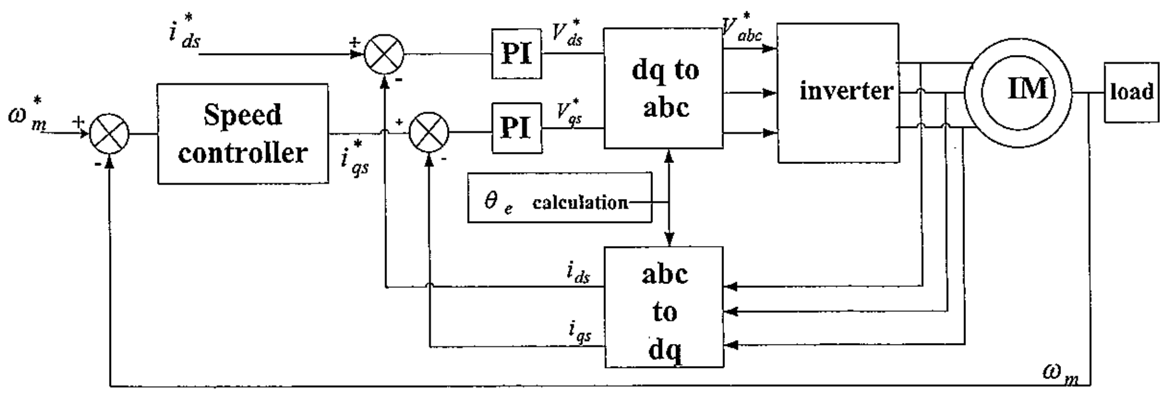



Fig. 1. Block diagram of induction motor drive

## II. Sliding Mode Speed Control Design

Fig. 1 shows the overall block diagram of induction motor drives. The proposed state-dependent gain method of sliding mode control is employed in outer loop, while the current loop is used the conventional PI speed controller. Based on complete indirect field orientation, sliding mode control with integral sliding surface is developed. Under the complete field oriented control, the mechanical equation of three-phase induction motor can be equivalently described as:

$$T_e = K_T i_{qs} \tag{1}$$

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

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

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

$$T_e = J\dot{\omega} + B\omega_m + T_L \tag{3}$$

where, $J$ and $B$ are the inertia constant of the induction motor and viscous friction coefficient respectively; $T_L$ is external load; $\omega_m$ is the rotor mechanical speed and $T_e$ denotes the generated torque of an induction motor.

Using (1) into (2), one can obtain:

$$\dot{\omega}_m(t) = (a+\Delta a)\omega_m(t) + (b+\Delta b)i_{qs} + f \tag{4}$$

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:

$$e(t) = \omega_m(t) - \omega_m^*(t) \tag{5}$$

where, $\omega_m$* is a rotor speed reference. Taking derivative of Eq. (5) with respect to time yields:

$$\dot{e}(t) = ae(t) + b\left(u_{qs}(t) + d\right) \tag{6}$$

where, $d$ is called lumped uncertainties, defined as:

$$d = \frac{\Delta a}{b}\omega_m(t) + \frac{a}{b}i_{qs} + \frac{f}{b} \tag{7}$$

and:

$$u_{qs}(t) = i_{qs}(t) + \frac{a}{b}\omega_m^* \tag{8}$$

The sliding variable $S(t)$ can be defined with integral component as [25]:

$$S(t) = e(t) - \int (a+bK)e(\tau)d\tau \tag{9}$$

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 Eq. (9) is equivalently governed by the following:

$$\dot{e}(t) = (a+bK)e(t) \tag{10}$$

where, $(a+bK)$ is designed to be strictly negative. Based on the sliding surface in Eq. (10), and the following assumption:

$$\beta \geq |d(t)| \tag{11}$$

The variable structure controller is design as:

$$u_{qs} = Ke(t) - \beta\, sgn(S) \tag{12}$$

where $\beta$ is a switching gain, $S$ is the sliding variable and $sgn(.)$ is the signum function defined as:

$$sgn(S(t)) = \begin{cases} 1 & \text{if } S(t) > 0 \\ -1 & \text{if } S(t) < 0 \end{cases} \tag{13}$$

Finally the control effort or q-axis stator current reference $i^*_{qs}(t)$ can be obtained by directly substituting Eq. (12) into (8):

$$i_{qs}^* = Ke(t) - \beta \cdot sgn(S(t)) - \frac{a}{b}\omega_m^* \tag{14}$$

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

The $q$-axis stator current reference of Eq. (14) is depend on the discontinuous control, signum function which leads to chattering. Then in this paper, the signum function is replaced by continuous sigmoid function as follows:

$$sigm(\rho', S) = \frac{S}{\rho' + |S|} \tag{15}$$

with this technique, the discontinuous function is eliminated, and the sigmoid function takes place for the whole operation. Where, $\rho'$ is a state-dependent small positive constant the thickness of the boundary layer.

The boundary layer is obtained from the proposed state-dependent variable the sigmoid function as:

$$\rho' = \rho_1\left[\left(1 - |sigm(\rho', S)|\right) + \delta_1\right] \tag{16}$$

where, $\delta_1$ is sufficiently small and $\rho_1$ is positive constant used to adjust the tuning rate of the sigmoid function.

When the uncertainties are large, $\rho'$ will produce a small boundary layer for control accuracy and better tracking performance.

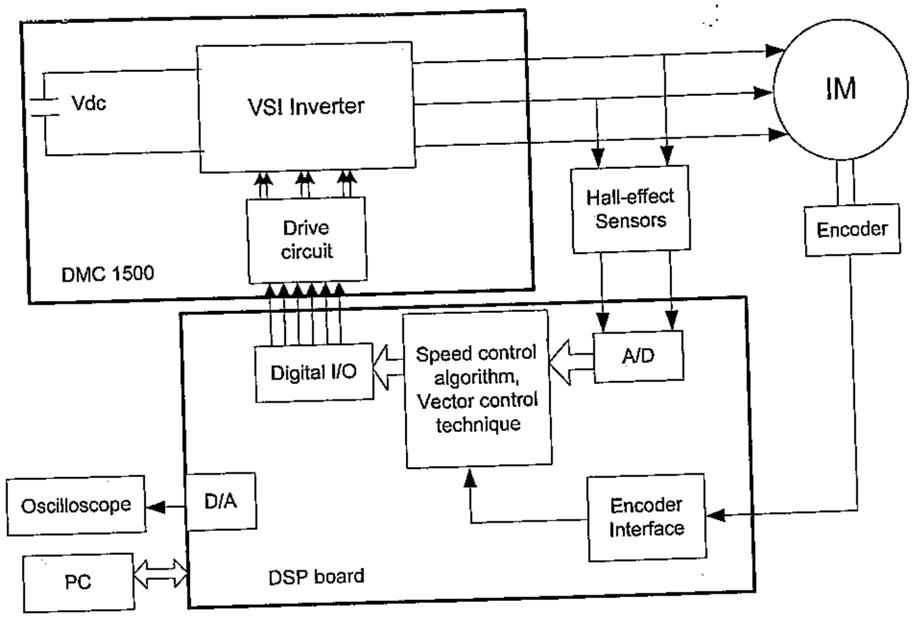



Fig. 2. Hardware configuration

If there is no uncertainty at the system, sliding variable will stay at the origin as well as the sigmoid function; $\rho'$ will produce constant maximum setting boundary layer. While, the state-dependent switching gain is design, to be proportional to the absolute sigmoid function as:

$$\beta' = \beta_1\left(\left|sigm\left(\rho',S\right)\right| + \delta_2\right) \quad (17)$$

where, $\beta_1\delta_2$ is a constant which should be enough to force the sliding mode to occur. If there are uncertainties in the systems, $\beta'$ will be increases, and in normal operation, $\beta'$ will stay in sufficient switching gain value.

Finally the torque current command or q-axis stator current reference $i_{qs}$* for the proposed sliding mode controller can be obtained as:

$$i_{qs}^* = Ke(t) - \beta' \cdot sigm\left(\rho' S\right) - \frac{a}{b}\omega_m^* \quad (18)$$

with the proposed state-dependent sliding mode controller (SDSMC), the width of boundary layer and the switching gain are tuned to cause the tracking error to approach zero. Therefore, the $\beta'$ is exhibit a varying switching gain depend on uncertainties of the system and $\rho'$ exhibit in varying boundary layer in sigmoid function which effectively eliminate input chattering and better tracking performance.

## III. Experimental Implementation

The proposed state-dependent gain of sliding mode control is firstly simulated in DSP emulated drive. Then a real time experimental is implemented using DSP-board TMS320F2812 through both hardware and software. The hardware configuration for this work can be depicted in Fig. 2. The control and drives board is consist of DSP TMS320F2812 and Digital Motor Control DMC1500 from Texas Instrument and auxiliary circuit, Hall Effect current sensor and interface of encoder input.

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 vector control technique in "C" language code for DSP controller. Two input currents of the induction motor, $i_a$ and $i_b$ are measured using current sensor and rotor speed was monitored using an encoder.

Then, the data are sent to the DSP board via analogue-to-digital converters. Fig. 3 shows the laboratory setup for the experiment. The induction motor used in this experiment is 1.5 kW, 1400rpm.

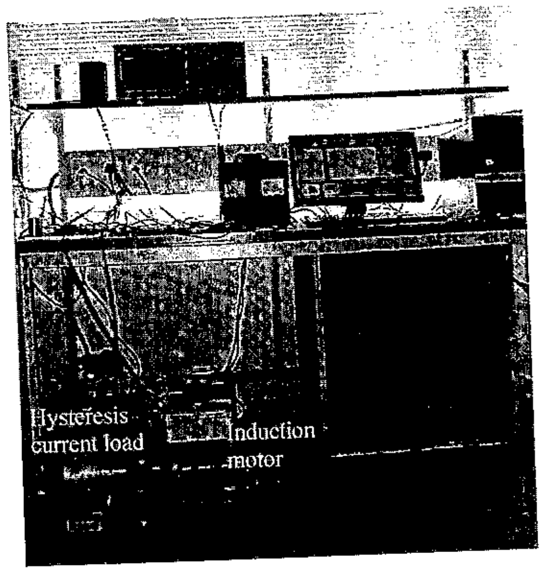



Fig. 3. Laboratory set up for the experiment

The parameter of the motor are, $R_s$=4.6 Ω $R_r$=5.66, $L_s$=0.3153H, $L_r$=0.3153H and $L_m$=0.3H. The encoder type is incremental optical encoder 500 pulses per revolution. The encoder type is incremental optical encoder 500 pulses per revolution. The load is give using hysteresis current brake from Magtrol Inc. DC voltage is limited to 380V, i.e maximum value of the Digital Motor Control DMC1500 can achieve, which means that the rated speed is reduced to 900 rpm. It should be noted that using higher DC voltage will result in a higher rate of change of torque. The stator $q$-axis current reference is limit to 5A all the time. The controller parameters used for are $K$=-0.2, $\beta$=0.35 and for the SDSMC the constant value for $\delta_1$ and $\delta_2$ are 0.01 and 0.95, which will gives range switching gain value range from 0.28 to 0.59 and range of boundary layer from 0.05 to 0.0005.

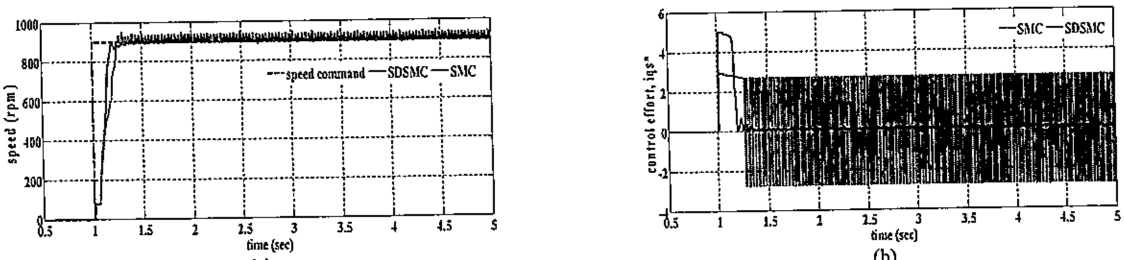
## IV. Results and Discussions

Several tests were performed to evaluate the performance of the state-dependent gain method of sliding mode control in experimental test. The results are presented in overlapping condition in the same figure.

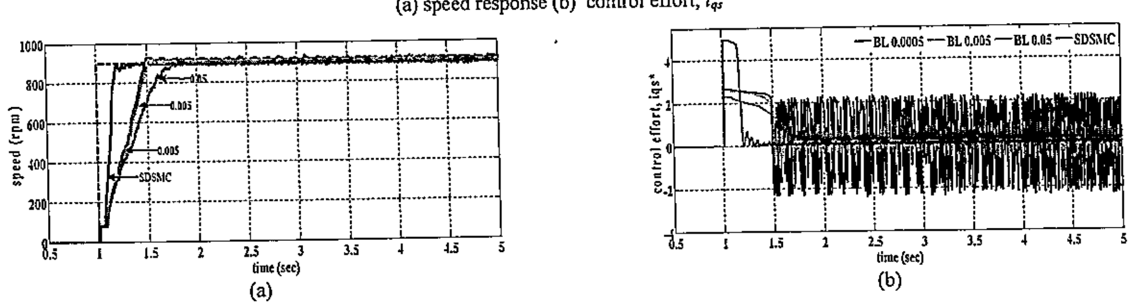
The figure is plot through Matlab from oscilloscope data that have been save from (*.csv*) file from oscilloscope. Figs. 4 show the starting performances of the induction motor drive at rated speed with a conventional SMC as in Eq. (14) and the proposed SDMC as in Eq. (18). The controller is tuned at rated condition in order to make fair comparison. From the results, the speed responses for the controllers give approximation the same rise time. Good tracking responses are obtained for the both controllers during transient. High amplitudes of chattering occur in stator q-axis stator current reference of SMC and gives affect in oscillation of speed response during steady state.

However, the chattering effect is significantly reduced by proposed state-dependent sliding mode control method. In many sliding mode application, the utilization of boundary layer is common in term of eliminating chattering. The second test is focused the comparison of SDSMC and SMC with constant switching gain and constant boundary layer. For this reason, three value of switching gain is choose for experiment rig; 0.3, 0.35 and 0.43. The value is chosen from the near smallest to the medium of switching gain value of SDSMC. While three fixed boundary layer is chosen (0.05, 0.005 and 0.0005), that is the range of maximum and minimum boundary layer in SDSMC. A higher value of switching gain is not tested to avoid high chattering when operates with small boundary layer.

The response of step speed command from standstill for rated speed command for different fixed value of switching gain is depicted in Figs. 5 to Figs. 7. It is obviously shown that response with combination small boundary layer and large switching gain value gives fast speed response in settling time. However, a great chattering occurs in stator $q$-axis current reference for small boundary layer which affects the oscillation of speed response. From the figure, it is demonstrate that the chattering in stator $q$-axis current reference is increases as the switching gain value is increases. Thus, it can be concluded that very small boundary layer will act as signum function and chattering level is directly proportional to switching gain value. Therefore, an appropriate selection must be made to get desired response in fixed gain of sliding mode control. Since the boundary layer 0.0005 produce large chattering, the purpose of uses the boundary layer to reduce chattering effect is not achieve. So in the next test only two boundary layer is considered, that is; 0.05 and 0.005.




Figs. 4. Experimental results for step speed response at 900rpm for conventional sliding mode control and state-dependent sliding mode control (a) speed response (b) control effort, $i_{qs}$*

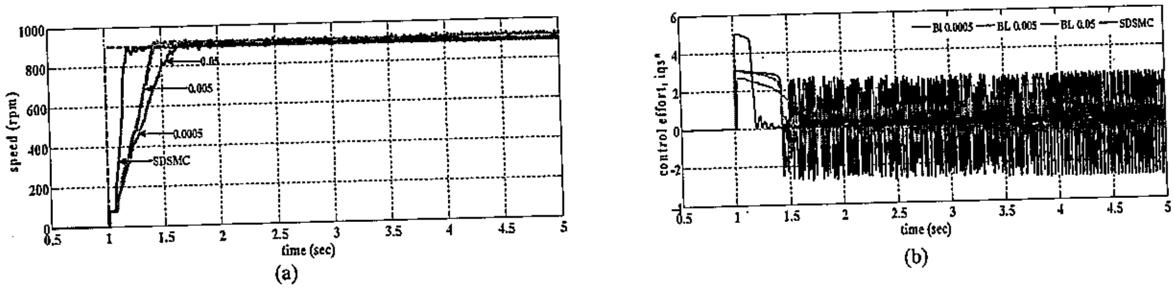



Figs. 5. Overlap speed response with switching gain 0.3, different boundary layer and SDSMC (a) speed response (b) control effort, $i_{qs}$*

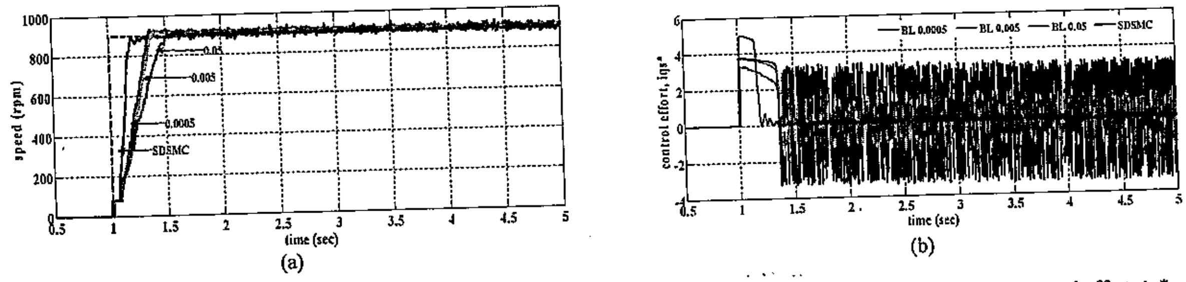
The third test of operation under loaded condition is involves the step application of the load torque. The load is applied by connecting the motor with hysteresis current brake. In order to avoid the chattering phenomenon only two boundary layers is test that is 0.05 and 0.005 for switching gain 0.3, 0.35 and 0.43.

In this test 2.5Nm is applied to steady state at rated speed at $t$=2s. Figs. 8 to Figs. 10 show the load rejection transient of the different fixed value. As expected, a combination large switching gain value and small boundary layer will manage to get better load rejection behaviour. However, a small chattering occurs in small fixed boundary layer, which means the chattering effect is not completely removes. This is support that the state-dependent sliding mode control has superior performance when compared to fixed gain sliding mode control.

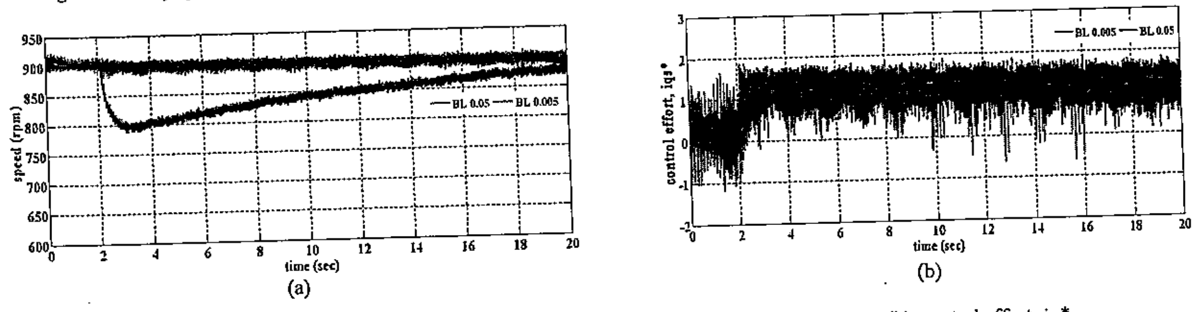
To make the comparison more clearly an overlapping of the speed response is done and compared to the result obtain from SDSMC. For considering chattering reduction techniques and good load rejection behaviour, a combination of switching gain 0.43 and boundary layer 0.05 is choose for comparison. From Figs. 11, it is shown that the SDSMC have better tracking performances. The control effort is slightly higher for SDSMC because of the increasing value of switching gain to surmount the load disturbances.



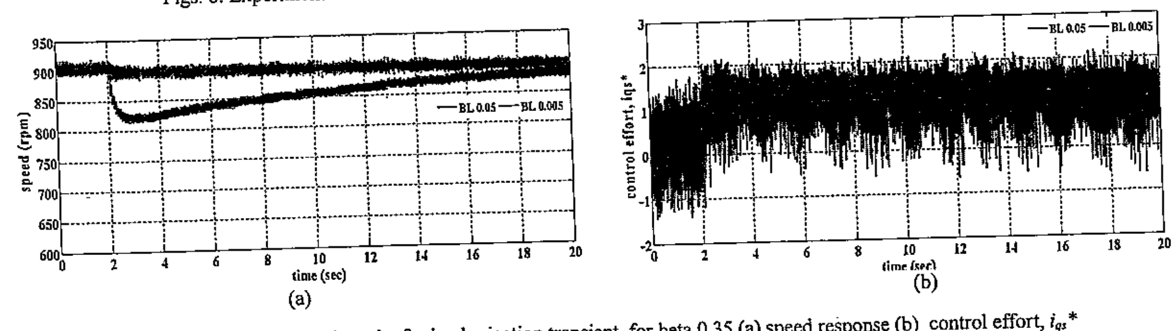

Figs. 6. Overlap speed response with switching gain 0.35, different boundary layer and SDSMC (a) speed response (b) control effort, $i_{qs}$*



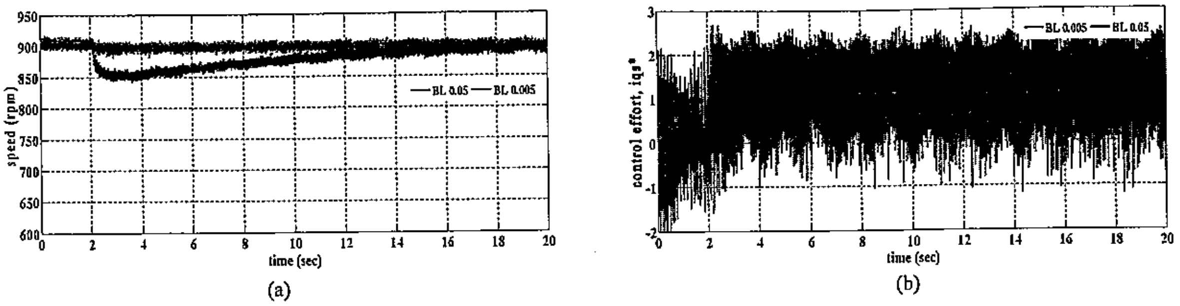

Figs. 7. Overlap speed response with switching gain 0.43, different boundary layer and SDSMC (a) speed response (b) control effort, $i_{qs}$*




Figs. 8. Experimental results for load rejection transient, for beta 0.3 (a) speed response (b) control effort, $i_{qs}$*




Figs. 9. Experimental results for load rejection transient, for beta 0.35 (a) speed response (b) control effort, $i_{qs}$*




Figs. 10. Experimental results for load rejection transient, for beta 0.43 (a) speed response (b) control effort, $i_{qs}$*

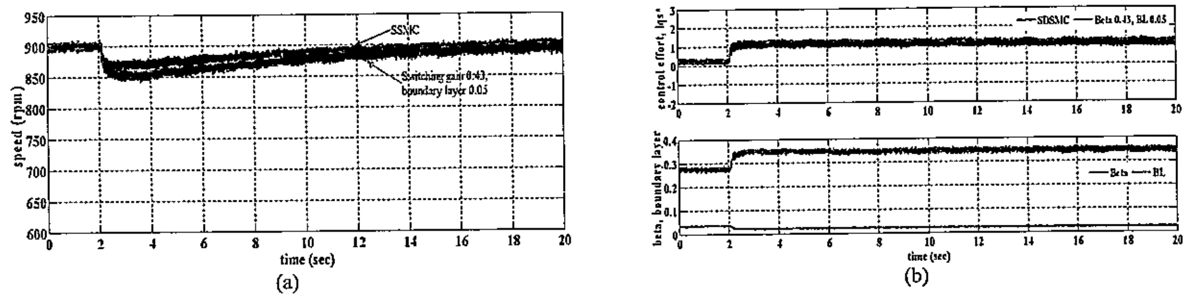



Fig. 11. Overlap speed response with switching gain 0.43 with boundary layer 0.05 and SDSMC (a) speed response (b) control effort, $i_{qs}$* and state dependent gain

Thus, it is proven that the proposed SDSMC with the used of state-dependent switching gain and boundary layer that depend on sigmoid function is very efficient in load transient response with considerably reduces chattering phenomenon. The switching gain value and the boundary layer value will change within the range depend on uncertainties.

The switching gain value will stay in minimum value in order to reduce chattering due to high switching gain in normal operation (without external load), conversely the boundary layer value will gives a maximum setting value for chattering reduction if there is no uncertainties.

## V. Conclusion

A new algorithm has been developed for speed control based on existing robust SMC. A fast sigmoid function with varying boundary layer and switching gain algorithm is designed as a state-dependent to replace the discontinuous function in conventional sliding mode control. This controller is employ in outer-loop of indirect field oriented control of three-phase induction motor drives. In this research the indirect field oriented control is given emphasis which consists of two control loops; inner current loop and outer speed loop. The inner loop is using a standard PI controller and the outer loop control is using proposed SDSMC, with Space Vector Pulse Width Modulation strategy. A comparative performance of conventional SMC, SMC with fixed boundary layer and SDSMC has been made in experimental rig. Most of the results support that SDSMC has shown superior performances when tested with no-load and load disturbances. With SDSMC, the chattering phenomenon that occurs in SMC is completely reduced.

## Acknowledgment

The authors wish to thanks Universiti Teknikal Malaysia Melaka for financing the research under the Grant ERGS/2011/FKE/TK02/1-E0001.

## References

[1] 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.

[2] R. J. Wai, *et al.*, "Rotor Time-Constant Estimation Approaches Based on Energy Function and Sliding Mode for Induction Motor Drive," *Electric Power Systems Research*, vol. 52, pp. 229-239, 1999.

[3] R. J. Wai, *et al.*, "Total Sliding-Mode Speed Control of Field-Oriented Induction Motor Servo Drive," 2004, pp. 1354-1361 Vol. 2.

[4] V. Utkin, "Variable Structure Systems with Sliding Modes," *IEEE Transactions on Automatic Control*, vol. 22, pp. 212-222, 1977.

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

[6] R. Ortega and I. Mareels, "Indirect Field Oriented Control of Induction Motors Is Robustly Globally Stable," 1995.

[7] J. M. Yang and J. H. Kim, "Sliding Mode Control for Trajectory Tracking of Nonholonomic Wheeled Mobile Robots," *Robotics and Automation, IEEE Transactions on*, vol. 15, pp. 578-587, 1999.

[8] J. M. Yang and J. H. Kim, "Sliding Mode Motion Control of Nonholonomic Mobile Robots," *Control Systems Magazine, IEEE*, vol. 19, pp. 15-23, 1999.

[9] H. Choi, *et al.*, "Global Sliding-Mode Control. Improved Design for a Brushless Dc Motor," *Control Systems Magazine, IEEE*, vol. 21, pp. 27-35, 2001.

[10] J. Zhang and T. Barton, "Robustness Enhancement of Dc Drives

with ' a Smooth Optimal Sliding-Mode Control," *IEEE Transactions on Industry Applications,* vol. 27, pp. 686-693, 1991.

[11] G. Spiazzi, *et al.*, "Application of Sliding Mode Control to Switch-Mode Power Supplies," *Journal of Circuits, Systems and Computers (JCSC),* vol. 5, pp. 337-354, 1995.

[12] A. Sabanovic and F. Bilalovic, "Sliding Mode Control of Ac Drives," *IEEE Transactions on Industry Applications,* vol. 25, pp. 70-75, 1989.

[13] 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.

[14] A. Mohamed, *et al.*, "Siding Mode Speed and Flux Control of Field-Oriented Induction Machine," *Acta Electrotechnica et Informatica No,* vol. 7, p. 1, 2007.

[15] M. Abid, *et al.*, "Sliding Mode Application in Position Control of an Induction Machine," *Journal of Electrical Engineering,* vol. 59, pp. 322-327, 2008.

[16] Y. Wang, *et al.*, "Speed Regulation of Induction Motor Using Sliding Mode Control Scheme," presented at the Industry Application Conference, 2005, Fourtieth IAS Annual Meeting, Conference Record of the 2005.

[17] Sulaiman, M., Patakor, F.A., Ibrahim, Z., A new state-dependent of sliding mode control for three-phase induction motor drives, (2013) *International Review on Modelling and Simulations (IREMOS),* 6 (3), pp. 728-735.

[18] J. L. Lin and L. G. Shiau, "On Stability and Performance of Induction Motor Speed Drives with Sliding Mode Current Control," *Asian Journal of Control,* vol. 2, pp. 122-131, 2000.

[19] Y. S. Han, *et al.*, "Sensorless Pmsm Drive with a Sliding Mode Control Based Adaptive Speed and Stator Resistance Estimator," *IEEE Transactions on Magnetics,* vol. 36, pp. 3588-3591, 2000.

[20] C. Wu, *et al.*, "Sliding Mode Observer for Sensorless Vector Control of Pmsm," *Advanced Technology of Electrical Engineering and Energy,* vol. 25, p. 1, 2006.

[21] O. Kaynak, *et al.*, "The Fusion of Computationally Intelligent Methodologies and Sliding-Mode Control-a Survey," *IEEE Transactions on Industrial Electronics,* vol. 48, pp. 4-17, 2001.

[22] H. Lee and V. I. Utkin, "Chattering Suppression Methods in Sliding Mode Control Systems," *Annual Reviews in Control,* vol. 31, pp. 179-188, 2007.

[23] C. J. Fallaha, *et al.*, "Sliding-Mode Robot Control with Exponential Reaching Law," *Industrial Electronics, IEEE Transactions on,* vol. 58, pp. 600-610, 2011.

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

[25] 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.

[26] Salehi, S.J., Manoochehri, M., A nonlinear sliding mode control of induction motor based on second order speed and flux sliding mode observer, (2011) *International Review on Modelling and Simulations (IREMOS),* 4 (3), pp. 1057-1065.

[27] Mezouar, A., Terras, T., Fellah, M.K., Hadjeri, S., Composite sliding mode control of induction motors using singular perturbation theory, (2012) *International Review of Automatic Control (IREACO),* 5 (6), pp. 901-910.

[28] Moutchou, M., Abbou, A., Mahmoudi, H., Induction machine speed and flux control, using vector-sliding mode control, with rotor resistance adaptation, (2012) *International Review of Automatic Control (IREACO),* 5 (6), pp. 804-814.


## Authors' information


Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka


**Marizan Bin Sulaiman** was born in April 16, 1962 in Kuala Besut, Terengganu. He received the Bachelor of Science in Electrical Engineering in May 1984, the Master of Science in Electrical Engineering in December 1985, and Doctor of Philosophy in Electrical Engineering in May 1989 from the University of Missouri-Columbia. He is a registered member of the Board of Engineers, Malaysia (BEM) and the Institution of Engineers, Malaysia (IEM). He is Professor Electrical Engineering and had been appointed as Dean of Faculty of Electrical Engineering, the Dean of Centre for the Graduate Studies and the Assistant Vice Chancellor for Student Affairs and Alumni in UTeM. At present, the research interests include Electrical Power System and Control Engineering.

**Fizatul Aini Patakor** was born in Selangor, Malaysia in 1978. She received the degree in electrical engineering (power electrical) from Universiti Sains Malaysia, in 2001 and Msc Occupational Safety and Health from Universiti Utara Malaysia in 2008. She is a lecturer at Politeknik Sultan Abdul Halim Muadzam Shah. Currently, she is a PhD research student of Universiti Teknikal Malaysia Melaka. Her interest includes safety and health in engineering education, power electronic and drives control system.


E-mail: fizatulaini@gmail.com


**Zulkifilie Bin Ibrahim** was born in January 7, 1966 in Singapore. He received the B.Eng. (Electrical Engineering) from UTM - Malaysia in 1989. He received the Ph.D (Power Electronics & Control), Liverpool John Moores University in 1999. He has been assistant Professor and appointed as Dean of Faculty of Electrical Engineering, UTeM. At now, he focuses on Power Electronics, Electric Motor Drives, Fuzzy Logic, and Embedded Control Design & Application.