Variable Speed Drives of Induction Motor for Traction Application with Modified Sliding Mode Control

Hong-Je Ryoo, Jong-Soo Kim, Geun-Hie Rim, Dragos Ovidiu Kisck and Chung-Yuen Won

Abstract – In this paper it is proposed an advanced modified sliding mode control of a rotor field oriented control of induction motor. The application of this unconventional control has very good results, such as disturbance rejection and nice dynamic properties. Stability can be guaranteed even in the worst situation. A conventional "sliding mode" controller is characterised by fast switching control signal, which causes the chattering of the drive system. To overcome this problem, a modified law is used, by introducing a hysteresis band and a continuous control, which modifies the conventional law. The control is accomplished with dual TMS320C44 floating-point digital signal processor. The validity of the proposed method was verified by experiment on the propulsion system simulator, used for the development of Korean High-Speed Railway Train (KHSRT).
Key words – Adjustable speed drives, sliding mode control

1. Introduction

The control of electromagnetic torque t_e and rotor flux ψ_r of induction motor, is fundamental to their applications in servo drives. Traditional design techniques using vector control theory for induction machines are well established [Leonhard, 1985], however the availability of micro-processors, microcontrollers, DSP, transputers at low cost allows to improve the technology of regulators and to replace traditional controllers with advanced ones. In high performance electrical drives, fast response, steady-state operation without error between reference speed and measured speed, nice transient behaviour, insensitivity to parameter variations, disturbance rejection and robustness with respect to unmodeled dynamics are required.

A sliding mode speed controller based on the application of sliding mode theory [Utkin, 1978, Bühler, 1986, Benz, 1990], has been proposed in order to cope with these features. A sliding mode controller is intrinsically robust and with a suitable modification of the conventional discontinuous law, is possible to suppress chattering at steady - state.

A conventional "sliding mode" controller is characterised by fast switching control signal, which causes the chattering of the drive system. For the minimisation of chattering problem there are various kinds of algorithm was presented by combine the linear control algorithm[5] or artificial intelligence theory such as fuzzy logic and state observer[6-9].

In this paper, to overcome this chattering problem a simple modified law is used, by introducing a hysteresis band and a continuous control, which modifies the conventional law.

It is presented the proposed methodology of sliding mode control design, the implementation of this controller and the simulation and experimental results on an induction motor rotor field-oriented drive system.

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2. Vector control of induction motor

The fundamental equations of the induction motor with respect to a synchronously rotating reference frame are the following:

$$\begin{cases} \underline{u_s} = r_s\,\underline{i_s} + \dfrac{1}{\omega_b}\dfrac{d\underline{\psi_s}}{dt} + j\,\nu_s\,\underline{\psi_s} \\ -\underline{u_r} = r_r\,\underline{i_r} + \dfrac{1}{\omega_b}\dfrac{d\underline{\psi_r}}{dt} + j\,\nu_r\,\underline{\psi_r} = 0 \\ \underline{\psi_s} = x_s\,\underline{i_s} + x_m\,\underline{i_r} \quad ; \quad \underline{\psi_r} = x_m\,\underline{i_s} + x_r\,\underline{i_r} \\ t_e = \Im\left[\underline{\psi_s}^{*}\cdot\underline{i_s}\right] = \Im\left[\underline{\psi_r}\cdot\underline{i_r}^{*}\right] \quad ; \quad \dfrac{d\nu}{dt} = \dfrac{t_e - t_r}{T_m} \quad ; \quad T_m = \dfrac{J\,\omega_n}{T_n} \end{cases} \tag{1}$$

Where : $\nu_s = \dfrac{f_s}{f_b};\nu_r = \dfrac{f_r}{f_b};\nu = \nu_s - \nu_r$

From this model, the rotor field oriented equations in the rotating reference frame, with d-axis along the rotor field space vector, may be written as the following set. All the quantities are in [p.u.] system, excepting the time t, which is measured in seconds.

$$\psi_r = x_m\,i_{sd} - \frac{x_r}{r_r}\frac{1}{\omega_b}\frac{d\psi_r}{dt} \quad ; \quad t_e = \frac{x_m}{x_r}\psi_r\,i_{sq} \quad ;$$

$$\nu_r = \frac{r_r}{x_r}\,x_m\,\frac{1}{\psi_r}\,i_{sq} = s\,\nu_s \tag{2}$$

The rotor field oriented control is performed, using the indirect-rotor field control method, as is presented in Fig. 1.

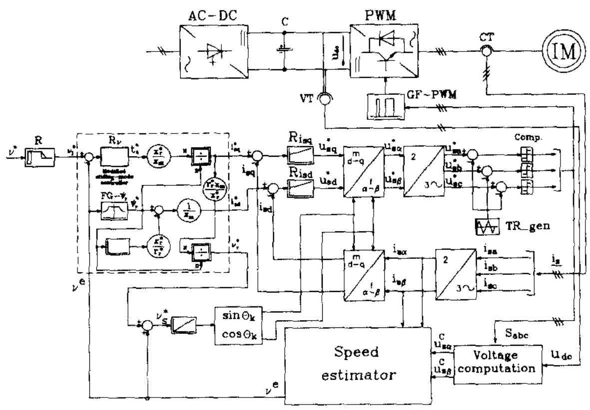


Fig. 1 The indirect-rotor field control of the induction machine with modified sliding mode speed controller.

The drive system is composed of a speed estimator based on the measured stator quantities, a modified sliding mode speed controller, two PI controllers (one for the rotor flux control and the other for the electromagnetic torque control), a function generator to set the rotor flux in the weakening region and a voltage controlled PWM inverter.

3. Modified sliding mode speed-controller

A modified sliding mode controller is used for speed control, in order to increase the performance of standard (PI) proportional, integral or derivative (PID) controllers.

In the general case, the sliding mode control leads to discontinuous output of the controller which is based on the calculus of the absolute value and sign of the following functional, resulting a null steady-state error between the reference quantity and the controlled one:

$$s(x_s) = k_w \cdot y^* - k_s^T \cdot x_s \tag{3}$$

Where: x_s is the state vector with m dimension of the controlled system, y^* is the reference quantity with the corresponding weight k_w, k_s^T is the vector with m dimension, which contains the corresponding feedback coefficients.

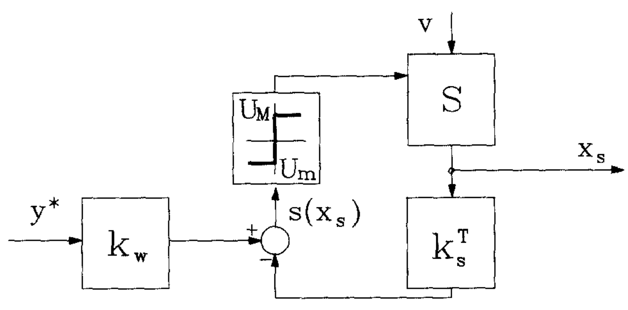


Fig. 2 The base structure of *sliding mode* control.

The structure of a sliding mode system is presented in Fig. 2.

In the above figure, S represents the controlled system and v represents the perturbation.

The command quantity u (the controller's output), for the simplest case, can take two distinct constant values:

$$u = \begin{cases} U_M & ; \quad s(x_s) \geq 0 \\ U_m & ; \quad s(x_s) < 0 \end{cases} \tag{4}$$

In this case, the commutation frequency is extremely high, theoretically infinite. The system will operate in the sliding mode regime. The dynamic behaviour of the controlled system is imposed by the condition $s(x_s) = 0$. In the particular case of speed control of the induction motor, the state vector is:

$$x_s^T = \begin{bmatrix} y & \dot{y} \end{bmatrix}^T \tag{5}$$

Where: $y = \nu$ is the motor speed and $\dot{y} = d\nu/dt$ is the motor acceleration.

The first order functional s can be written as follows:

$$s = k_w \cdot \nu^* - \begin{bmatrix} k_{s1} & k_{s2} \end{bmatrix} \cdot \begin{bmatrix} \nu \\ \dot{\nu} \end{bmatrix} \tag{6}$$

The different quantities are written in [p.u.] system. The coefficients k_w and k_{s1} must be equals ($k_w = k_{s1}$). The final equation of the first order functional s is the following:

$$s = k_{s1} \cdot (\nu^* - \nu) - k_{s2} \cdot \dot{\nu} \tag{7}$$

The equation s=0 which represents in the state plane the *"commutation line"*, depending on the constant k_{s2} , as Fig. 3. shows.

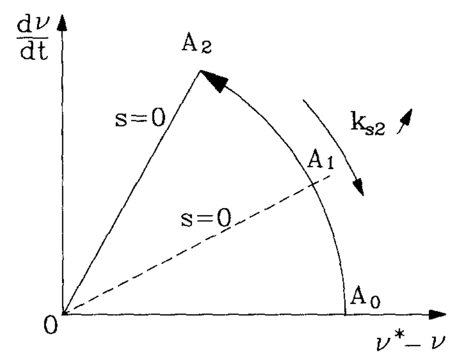


Fig. 3 The first order functional s, in the state plane.

A discrete model for the first order functional from (7) can be obtained by applying Euler integration formula on the sampling interval T_S .

The constant k_{s1} can be equals with 1, because it only acts like a proportional gain, the controller proportional gain being selected using proper rules.

The constant k_{s2} from (7) is responsible of the speed response. It can be determined experimentally, starting with a very low value, then increasing gradually till the desired speed response is achieved.

Theoretically, this constant can be computed using the following algorithm, taking into account the unfavourable operating conditions. For the speed controller, these conditions are: the no load operation ($t_r = 0$) and the low supply voltage rezerve. The low supply voltage reserve leads to a very fast saturation of the torque controller (R_{iq}). The output of this controller represents the maximum value of the electromagnetic torque.

It is considered the moment t-t0 when the speed controller is getting out of saturation level (the system is carrying out the condition s=0). The equation (7) of the first order functional s becomes:

$$\nu^* - \nu(t_0) = k_{s2}\frac{d\nu}{dt} \tag{8}$$

Because of no load condition:

$$\frac{d\nu}{dt} = \frac{t_{e\max}}{T_m} \tag{9}$$

where: $t_{e\max} = U_M$ represents the maximum allowed torque that is equals with the output U_M of the speed controller.

Taking into account equations (8) and (9), the k_{s2} constant becomes:

$$k_{s2} = \frac{\left[\nu^* - \nu(t_0)\right]\cdot T_m}{U_M} \tag{10}$$

This constant is calculated for the case of rated speed $\nu^* = 1$, covering the whole domain of operation. The growing of the constant k_{s2} determines the regressing of commutation line slope and the increasing of the speed response immunity at the sudden torque variation. For a fast response, the constant k_{s2} must be at least with an order less than mechanical time constant T_m.

The system is sliding along a given path in the state space trajectory irrespective of parameter variation, inertia and load disturbance, provided they are below given limits.

In this case of sliding mode control, as was already pointed in this paper, the controller's output u, can take only two distinct values with a high frequency, that is why, the electrical and mechanical stress of the drive system can increase very much. So, to avoid this, it is introduced a hysteresis band h, that leads to a continuous control.

The particular form of sliding mode control, is the following:

$$u = \begin{cases} U_M & ; \quad s(x_s,t) \geq h \\ U_m & ; \quad s(x_s,t) < -h \\ k_P\ s(x_s,t) + k_I \int s(x_s,t)\,dt & ; \quad |s(x_s,t)| \leq h \end{cases} \tag{11}$$

Where: U_M, U_m are the speed controller's saturation levels, and $s(x_s,t)$ is the first order differential equation (7).

The coefficients k_P and k_I from (11) may be constant or non-linearly depending on the error ν^*-ν; a particular simple choice is as follows:

$$k_P(\nu^* - \nu) = \frac{k_P}{1 + c_P|\nu^* - \nu|} \quad ; \quad k_I(\nu^* - \nu) = \frac{k_I}{1 + c_I(\nu^* - \nu)^2} \tag{12}$$

The non-linear proportional action reduces to the classical one if $c_P|\nu^* - \nu| \gg 1$, while in the limit $c_P|\nu^* - \nu| \ll 1$ we obtain a relay action. Of course k_P and k_I can be chosen accordingly to the usual tuning rules (Roots Locus, Zingler and Nichols). Similar remarks hold for the coefficient k_i; the dependence $c_I(\nu^* - \nu)^2 \gg 1$ ensures that the integral action reduce or else vanish whenever $c_I(\nu^* - \nu)^2 \ll 1$. In this way, the wind-up and instability problems are effectively removed. So, in any case of starting or load torque conditions – in the dynamic operation, the reference speed is different of the measured speed and, in this case, the proportional and integral coefficients are decreased automatically. This action leads to a better stability of the system and also, the decreasing of the both coefficients remove the wind-up of the classical PI controller. The smoothed transition from relay to proportional action due to (12) eliminates the drawbacks due to chattering, this solution being very simple and easy to implement.

4. Simulation and experimental results

In this paper, the experiments is performed to verify the performance of the proposed algorithm and supplementary simulation is added to show the robust control characteristics over the sudden load change which cannot be tested by the given experimental system.

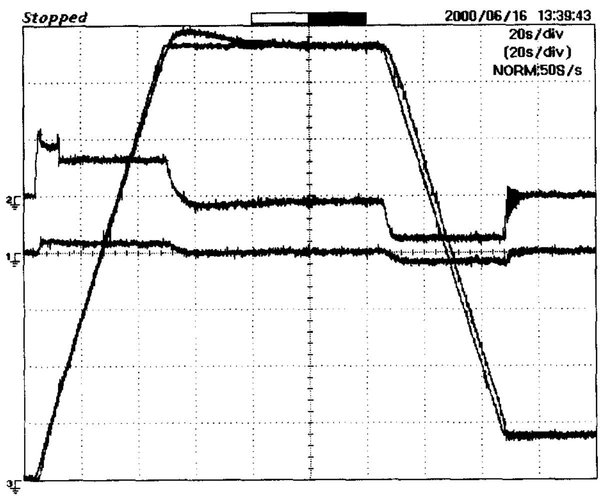
The experimental tests were made on the propulsion system simulator, used for the development of Korean High-Speed Railway Train. From the baseline model of KHSRT, a downscaled model of a propulsion system was developed [10]. This simulator can be divided into two parts. One is the electrical part consisting of traction and electrical braking units and the other is a mechanical part simulating train characteristics and the mechanical brakes. Electrical parts of the system consist of a main transformer, two traction units and four traction motors, two rheostat braking systems and an Eddy current brake system. The PWM inverter generates the three-phase voltages for two induction motors at a switching frequency of 540 [Hz]. The maximum speed of KHSRT is 350 [km/h], which corresponds to the motor speed of 4200 [rpm].

The specification of the induction motor used in simulation and experiments is presented in Table 1.

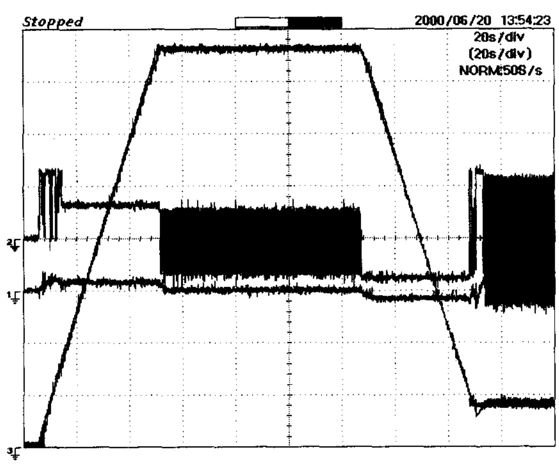
For showing the performances of the proposed modified sliding mode control, were made experiments using three kind of speed controllers: conventional PI controller (Figure 4.a.), sliding mode controller (Figure 4.b.) and

Table 1 Induction motor ratings and parameters

Quantity	*Symbol*	*Value*
Output power	P_n	7500 W
Phase voltage, rms	U_{sn}	220 V
Phase current, rms	I_{sn}	26 A
Stator frequency	f_n	60 Hz
Synchronous speed	n_n	1800 rpm
Rotor speed	n	1730 rpm
Pole-pairs	p	2
Stator resistance	$r_{\sigma s}$ [p.u.]	0.02245
Rotor resistance	$r_{\sigma r}$ [p.u.]	0.011
Stator leakage reactance	x_s [p.u.]	0.1211
Rotor leakage reactance	xr [p.u.]	0.09007
Magnetising reactance	x_m [p.u.]	1.903
Apparent torque	M_n	52.61 Nm



(a)



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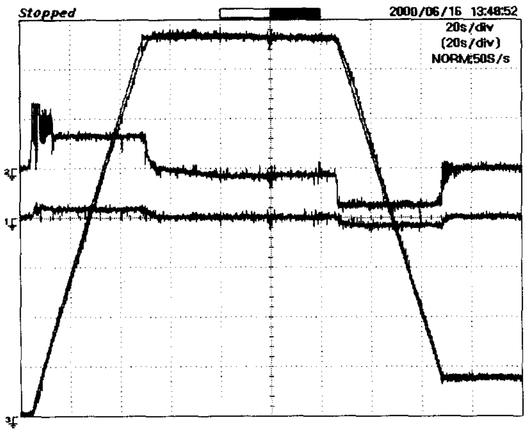


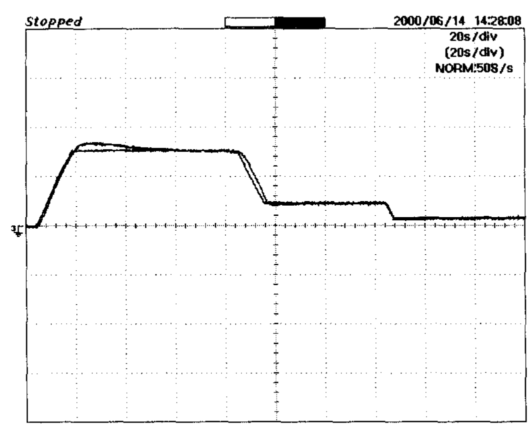
(c)

Fig. 4 The system behaviour with: (a) *PI* speed controller, (b) *sliding mode* speed controller, (c) *modified sliding mode* speed controller. 1 - d*v*/dt , 2 - i_q^* , 3 - n_I^* , 4 - n . (3,4 - 197 rpm/div.; 2 – 75 A/div.; 1 – 4.34 m/s^2/div.; 20 s/div.).

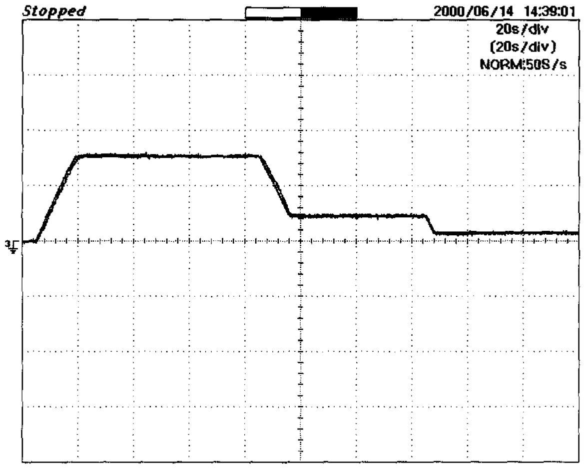
modified sliding mode controller (Figure 4.c.). All these figures show from bottom to top the plots of the speed controller's output $u = i_q^*$, the system acceleration d*v*/dt, the ramp-reference speed n_I^* and the motor speed n.

It can be seen that the proposed modified sliding mode control has the best response avoiding the overshoot and the chattering at steady - state.

Another main advantage of the modified sliding mode controller over the PI controller is that the overshoot can be cut in the same manner also at low speed. It is known that a PI controller leads to different overshoot, which depends on the reference speed. In Fig, 5.a. and Fig. 5.b. are presented the performances of the controllers at low speed, maximum speed being 500 rpm.



(a)



(b)

Fig. 5 The system behaviour and steady state operation at low speed with:
(a) *PI* speed controller, (b) *modified sliding mode* speed controller.
3 - n_I^* , 4 - n (3,4 - 333 rpm/div. ; 20 s/div.).

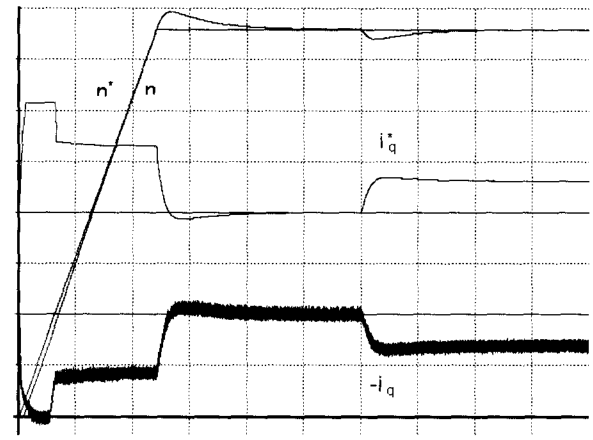
Because the propulsion system simulator, has a large inertia and the sudden load torque change is impossible, the paper presents the simulation operation taking into account the step load variation for the same system without a big inertia (step speed response and step perturbation-load torque).

The speed controller k_p and k_I coefficients are the same for each experiment and simulation.

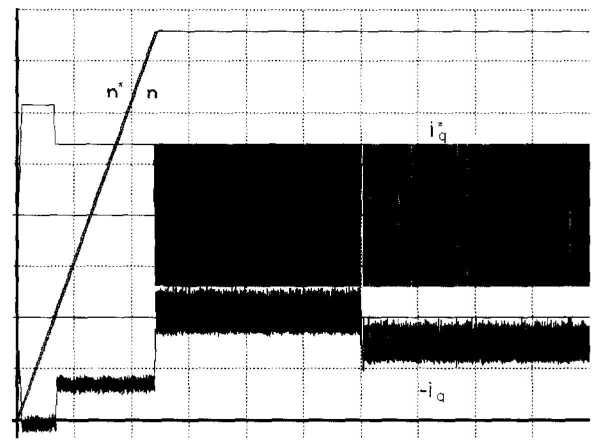
One can be seen that, in the case of modified sliding mode controller, the perturbation is practically rejected and, comparing the sliding mode controller, the chattering is also avoided.

6. Conclusions

In this paper, a robust modified sliding mode controller has been presented. It was applied to improve the speed response; to reduce the overshot of a standard PI controller and also to avoid chattering at steady-state of a standard sliding mode controller which causes unacceptable vibration stress of the load. With the proposed modified sliding mode controller, the main goals of a well-tuned system such as, the disturbance rejection, and also the minimising of the overshoot have been obtained. The performance improvement of this modified sliding mode controller over the classical PI controller or standard sliding mode controller is clearly shown in the experimental and simulated results. A fully digital realisation of drive system with induction motor using the indirect rotor flux orientation was studied and experimented on the propulsion system simulator, used for the development of KHSRT.



(a)



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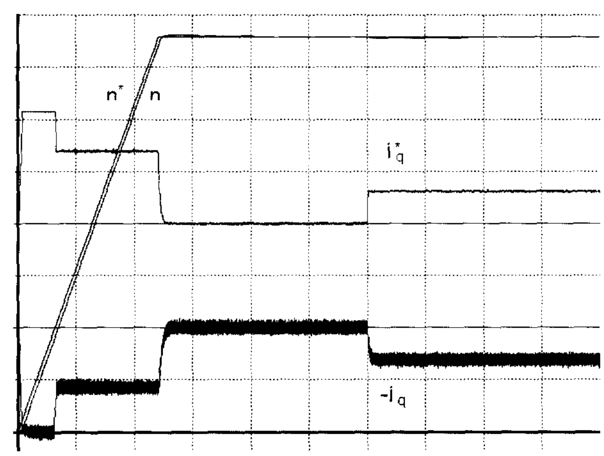

(c)

Simulation

Fig. 6 The simulation of the system behaviour for load torque variation and steady state operation:
(a) *PI* speed controller, (b) *sliding mode* speed controller, (c) *modified sliding mode* speed ontroller.
(n_I^* , n- 197 rpm/div.; i_q^* , i_q – 38 A/div.; 20 s/div.).

References

[1] W.Leonhard, "***Control of Electrical Drives***", Springer Verlag, 1985.

[2] V.I.Utkin, "***Sliding Modes and their Applications in Variable Structure Systems***", MIR, Moscow, 1978.

[3] H.Bühler, "***Réglage par mode de glissement***", Supplement to the Traité d'électricité, PPUR Lausanne, 1988.

[4] K.T.Hung, "***A slip gain error model-based correction scheme of near-deadbeat response for indirect field orientation***", Master thesis, Univ. of Wisconsin-Madison, 1990.

[5] C.Namurami, P.C. Sen "***A Servo-control system using a self-controlled synchronous motor with sliding mode controller***", IEEE Trans. Ind. Appl., vol. IA-23,no.2, pp283-295, 1987

[6] A. Kawamura, K. Miura and T. Ishizawa, "***Trajectory control of two axis robot by sliding mode control with observer***," IEEE Proc. of IECON'89, pp.640-645, 1989.

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

[8] C. Y. Won, D. H. Kim and B. K. Bose, "***An induction motor servo system with improved sliding mode control***," IEEE Proc. of IECON'92, pp.60-66, 1992.

[9] 고종선, 이정훈, 윤명중, "훠지로직을 이용한 브러쉬 없는 직류전동기의 파라미터의 변화와 외란에 둔감한 위치제어", 대한전기학회논문지, Vol.40, No.10, pp.1037-1048, 1991.

[10] Hong-Je Ryoo, Jong-Soo Kim, Myung-Ho Woo, Won-Ho Kim, Geun-Hie Rim, "***Propulsion System Simulator of a High-Speed Railway Train***", MET'99, Warsaw, Poland, pp.1 – 5.

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