Speed Control System of Induction Motor with Fuzzy-Sliding Mode Controller for Traction Applications

Duk-Heon Kim*, Hong-Je Ryoo, Geun-Hie Rim**, Yong-Ju Kim** and Chung-Yuen Won*****

Abstract - The application of a sliding mode control for improving the dynamic response of an induction motor based speed control system is presented in this paper and provides attractive features, such as fast response, good transient performance, and insensitivity to variations in plant parameters and external disturbance. However, chattering is a difficult problem for which the sliding mode control is a popular solution. This paper presents a new fuzzy-sliding mode controller for a sensorless vector–controlled induction motor servo system to practically eliminate the chattering problem for traction applications. A DSP based implementation of the speed control system is employed. Experimental results are presented using a propulsion system simulator. The performance of the drive is shown to be practically free from chattering.

Keywords: adjustable speed drives, fuzzy-sliding mode control

1. Introduction

In high-performance induction motor drives, the drive inertia and load characteristics change widely. The desired drive system can provide fast dynamic response, steady-state operation without error between reference speed and measured speed, nice transient behavior, insensitivity to parameter variations, disturbance rejection, and robustness with respect to unmodeled dynamics.

Recently, the application of a variable structure system (VSS) control using a sliding mode [2] has received wide attention. The sliding mode control law is inherently discontinuous in nature. Directly applying the controller to control the developed torque with the inner loop of a vector-controlled drive results in torque pulsation, current ripple, corresponding speed ripple, and acoustic noise. Therefore, many studies[6–9] proposed using the algorithm to reduce the command torque ripple, which fails to solve the problem completely.

Fuzzy logic or fuzzy set theory has received the attention of a number of power electronics and motion control studies. The fuzzy logic control is somewhat easy to implement because needs no mathematical model of a system. Hence, interest for practical applications [3, 4] of fuzzy logic is growing rapidly. However, guaranteeing the stability of the system is difficult because the fuzzy logic controller is designed based on human experience.

In this paper, a new fuzzy-sliding mode (FSM) control has been applied to a speed control that uses a sensorless vector controlled induction motor not only to overcome the chattering problem of the sliding mode control but also to guarantee the stability of the fuzzy logic control system. The control is accomplished with dual TMS320C44 floating-point digital signal processors. An experiment on the propulsion system simulator, used for the development of the Korean High-Speed Railway Train, verifies the validity of the proposed method.

2. Vector Control of Induction Motor

The fundamental equations of the induction motor with respect to a synchronously rotating reference frame [14] are

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

where $\nu_s = \frac{f_s}{f_b}$ ([p.u.] stator frequency); $\nu_r = \frac{f_r}{f_b}$ ([p.u] rotor frequency); $\nu = \nu_s - \nu_r$ ([p.u.] rotor speed); $\overrightarrow{u_s}$, $\overrightarrow{u_r}$ are [p.u.] stator and rotor phase voltage; $\overrightarrow{i_s}$, $\overrightarrow{i_r}$ are [p.u.] stator

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and rotor phase current; $\overrightarrow{\Psi_s}$, $\overrightarrow{\Psi_r}$ are stator and rotor flux; ω_b is the base angular mechanical speed; and T_m is the mechanical time constant.

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, except time, *t*, which is measured in seconds.

$$\Psi_r = x_m i_{sd} - \frac{x_r}{r_b}\frac{1}{\omega_b}\frac{d\Psi_r}{dt} \ ; \ t_e = \frac{x_m}{x_r}\Psi_r i_{sq} \qquad (2)$$
$$v_r = \frac{r_r}{x_r} x_m \frac{1}{\Psi_r} i_{sq} = s v_s$$

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

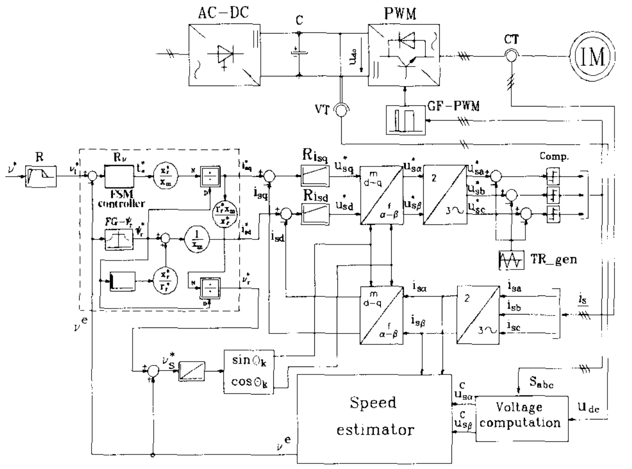


Fig. 1 The indirect-rotor field control of the induction motor with a fuzzy-sliding mode speed controller

The drive system is composed of a speed estimator based on the measured stator quantities, fuzzy-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. Sliding Mode Control with Integral Compensation

The sliding mode control technique has been applied mostly in position drive systems. The required feedback quantities for the position drives are speed and position, which can be easily obtained. However, in the speed drive systems, acceleration and speed signals are required. The acceleration is a high bandwidth signal, and is generally difficult to acquire. In practice, estimation techniques obtain this signal. The accuracy of these feedback signals strongly influence the quality of the sliding mode control. The use of an estimated acceleration signal for sliding mode control speed drive systems introduces complex control dynamics that require additional attention to the design and implementation of these systems. To reduce the steady-state error and easily make the second-order system for speed control, an integral compensation is employed in the feedforward path [12], as shown in Fig. 2.

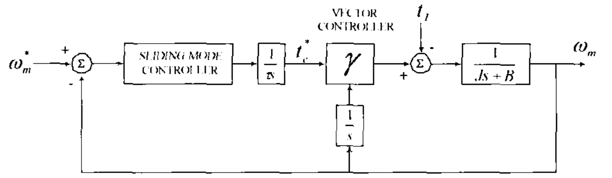


Fig. 2 Sliding mode control with integral compensation

With the inner-loop vector controller incorporated (Fig. 2), the electromechanical governing equation of the machine can be written as

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(\gamma t_e^* - t_L - B\omega_m\right) \qquad (3)$$

where t_e^* is the command torque input of the inner-loop vector controller, and its control structure is represented by γ. An insertion of the integral operation in the feedforward path is essential since the control signal *u*, is a bidirectional PWM signal that should not be fed into the command torque input of the vector controller directly.

For the design of the sliding mode control, using a phase variable state representation (Eq. (3)) of the speed drive system (Fig. 2) is convenient. For design simplicity, all feedback quantities, including acceleration, are assumed to be a constant gain, and this gain is conveniently taken as one in the following design. The phase variable state representation of Fig. 2 can then be simplified as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -a \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} u \qquad (4)$$

where $x_1 = \omega_m - \omega_m^*$, $x_2 = \dot{x}_1$, $a = \frac{B}{J}$, $b = \frac{1}{J\tau}$. The control signal, *u* is generated such that the speed error follows certain prescribed dynamics irrespective of plant parameter (*a*, *b*) variations. The sliding mode is introduced along the sliding line in the phase plane and is described as follows:

$$\sigma = p x_1 + \dot{x}_1 = 0 \qquad (5)$$

The prescribed dynamics in Eq. (5) are a first-order response with p, which is the time constant of the speed response. For the control system, the equivalent control signal is

$$u_{eq} = -(p-a)x_2 \tag{6}$$

Various control laws [13] can be used to force the system to slide along the sliding line (Eq. (5)). The control law that provides faster responses is given by

$$u = \varphi_1 x_1 + \varphi_2 \dot{x}_1 \tag{7}$$

where $\varphi_1 = \begin{cases} \alpha_1, & \sigma x_1 > 0 \\ \beta_1, & \sigma x_1 < 0 \end{cases}$, $\varphi_2 = \begin{cases} \alpha_2, & \sigma x_1 > 0 \\ \beta_2, & \sigma x_1 < 0 \end{cases}$.

The values of the controller gains (φ_1 , φ_2) can be obtained based on the existence condition of the sliding mode control given by

$$\lim_{\sigma \to 0} \sigma\dot{\sigma} \le 0 \tag{8}$$

Eq. (8) implies that the system trajectories should always be directed toward the sliding line (Eq. (5)). With the definition of φ_1 and φ_2 given in Eq. (7), the existence condition can be satisfied if

$$\begin{aligned} &\beta_1 < 0 < \alpha_1 \\ &\beta_2 < \min_{a,b}\left|\frac{p-a}{b}\right|\max_{a,b} < \alpha_2 \end{aligned} \tag{9}$$

If the condition in Eq. (9) is satisfied, the system trajectories from any point in the phase plane will be directed toward the sliding line. Note that in Eq. (9) the maximum allowable sliding slope, p, is limited by the available system gains, (α_2, β_2).

4. Fuzzy-Sliding Mode Speed Controller

Fig. 3 shows the block diagram of the ideal vector controlled servo system with a fuzzy-sliding mode controller. The estimated speed, ω_{est}, is compared to the reference speed, ω_m^*, to produce an error signal, x_1, that is used with the motor acceleration, determining the motor control action.

The control signal, u, is expressed as an equivalent control, u_{eq}, and a switched control, Δu.

$$u = u_{eq} + \Delta u \tag{10}$$

On the condition that $\Delta u = 0$ and $t_L = 0$, the control drive the state onto a sliding surface and convergence to origin in the phase plane. The proposed fuzzy-sliding mode controller is divided into calculating u_{eq} from Eq. (6) and generating Δu and uses fuzzy logic to adjust for the tradeoff between robustness and chatter elimination.

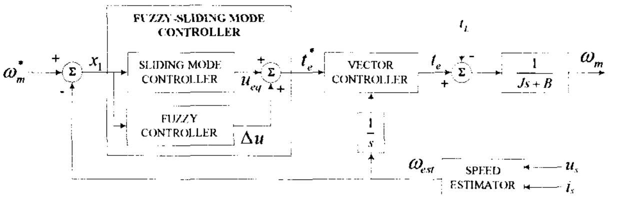


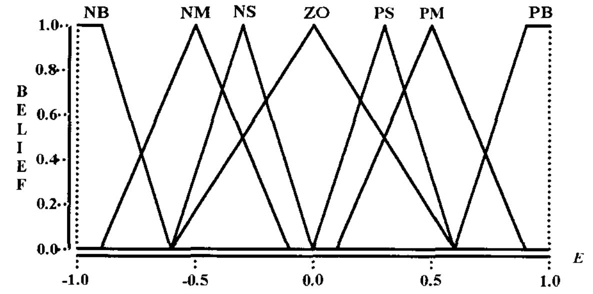
Fig. 3 Speed control of induction motor with fuzzy-sliding mode controller.

4.1 Fuzzification

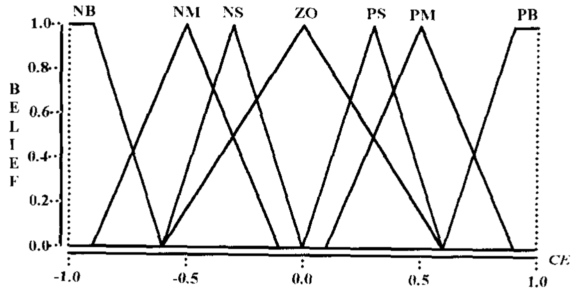
In the case of a general fuzzy controller for speed drive systems, the input variables are motor speed error and its changes. The input variables of the fuzzy-sliding mode controller are the phase state error E and the error changes CE, where E is the difference between the reference sliding line and the actual representative point of the system on the phase plane. At a sampling instant, k, the variables $E(k)$ and $CE(k)$ are expressed as follows

$$\begin{aligned} &E(k) = px_1(k) + \dot{x}_1(k) = \sigma(k) \\ &CE(k) = E(k) - E(k-1) \end{aligned} \tag{11}$$

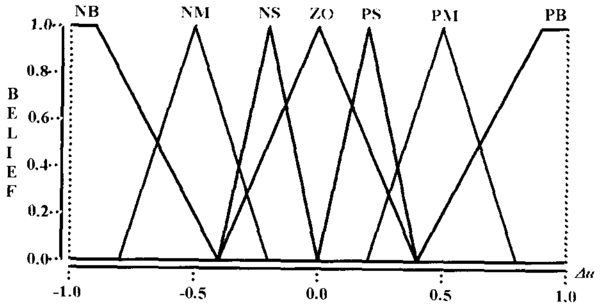
The values of the membership function are assigned to the linguistic variables, using seven basic fuzzy subsets: *PB* (Positive Big), *PM* (Positive Medium), *PS* (Positive Small), *ZO* (Zero), *NS* (Negative Small), *NM* (Negative Medium) and *NB* (Negative Big). Fig. 4 shows the fuzzy linguistic variables for the control. In particular, we select a wide range of *ZO* to prevent torque current ripple in steady-state.



(a) Input variable E



(b) Input variable CE



(c) Output variable Δu

Fig. 4 Membership function of linguistic variables

4.2 Inference method

Table 1 shows the rules of the fuzzy-sliding mode controller where all the entries of the matrix are fuzzy sets of E, CE, and Δu for the speed control of the induction motor.

In the case of the fuzzy-sliding mode control and to satisfy the existence condition (Eq. (8)), the control rule must be designed so that the actual trajectory always turns toward but does not cross the reference sliding line on the phase plane.

The stability is analyzed using the Lyapunov theorem, and the results become the design tool for the proposed control rule. Let V be a semipositive definite function as

$$V = (px_1 + \dot{x}_1) = \sigma^2 \tag{12}$$

The derivative of V becomes

$$\dot{V} = 2\dot{\sigma}\sigma < 0 \tag{13}$$

Table 1 Rule base of the fuzzy-sliding mode control

E \ CE	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PB	PB	PB	PB
NM	PB	PB	PM	PM	PM	PB	PB
NS	PB	PM	PS	PB	PS	ZO	NS
ZO	PB	PM	PS	ZO	NS	NM	NB
PS	PS	PM	NS	NB	NS	NM	NB
PM	NB	NM	NM	NM	NM	NB	NB
PB	NB	NB	NB	NB	NB	NB	NB

The function in Eq. (12) is a Lyapunov function along a line perpendicularly. The fuzzy controller makes the closed loop system stable if the existence condition is satisfied. An example control rule in Table 1 is

IF ***E*** is ***NB*** and ***CE*** is ***NS***, THEN Δu is ***PB.***

This control rule states that IF the phase state error is Negative Big and its change is Negative Small, THEN the change of the torque current should be Positive Big.

The MAX-MIN composition is chosen as the fuzzy inference method and we can get

$$\begin{aligned} C^o(\Delta u) &= R(E^o, CE^o, \Delta u) \\ &= \bigvee_{i=1}^{N} \left[A_i(E^o) \wedge B_i(CE^o) \wedge C_i(\Delta u^o) \right] \end{aligned} \tag{14}$$

where R is the fuzzy relation function.

4.3 Defuzzification

The output of the fuzzy controller is a fuzzy set of controls. Since the plant usually requires a nonfuzzy value of a control, a defuzzification stage is needed. Two algorithms, the center of gravity (COG) and the mean of maximum (MOM), can normally perform defuzzification. For a sampled data representation, the center of gravity, Δu , is computed point-wise by

$$\Delta u = \frac{\sum_{j=1}^{n} C^o(\Delta u_j) \cdot \Delta u_j}{\sum_{j=1}^{n} C^o(\Delta u_j)} \tag{15}$$

where n is the number of quantization levels of the output, Δu_j is the amount of control output at the quantization level j, and $C^o(\Delta u_j)$ represents its membership value.

5. Experimental Results

In this paper, the experiments are performed to verify the performance of the proposed algorithm. The experimental tests were made on the propulsion system simulator, used for the development of the Korean High-Speed Railway Train (KHSRT). From the baseline model of the KHSRT, a down-scaled model of the propulsion system was developed [11].

This simulator can be divided into two parts: the electrical part consisting of traction and electrical braking units and the 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 540Hz. The maximum speed of the KHSRT is 350km/h, which corresponds to the motor speed of 4200rpm. The specification of the induction motor used in the simulation and experiments is presented in Table 2.

Table 2 Induction motor ratings and parameters.

Quantity	*Symbol*	*Value*
Phase voltage, rms.	U_{sn}	220 V
Phase current. rms.	I_{sn}	15 A
Stator frequency	f_n	60 Hz
Rotor speed	n	1730 rpm
Pole-pairs	p	2
Stator resistance	r_s [p.u.]	0.02245
Rotor resistance	r_r [p.u.]	0.011
Stator leakage reactance	x_s [p.u.]	0.1211
Rotor leakage reactance	x_r [p.u.]	0.09007
Magnetising reactance	x_m [p.u.]	1.903
Apparent torque	T_n	52.61 Nm

To prove a very good time response in induction motor speed estimation, Fig. 5 shows the system behaviour of the indirect rotor field control, including plots of the ramp-reference speed, the estimated motor speed, the real motor speed, the difference between the real and estimated motor speed

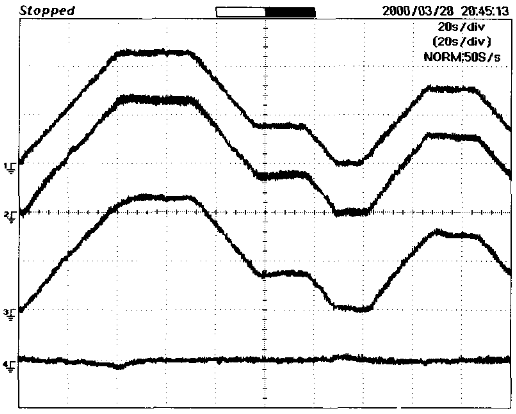
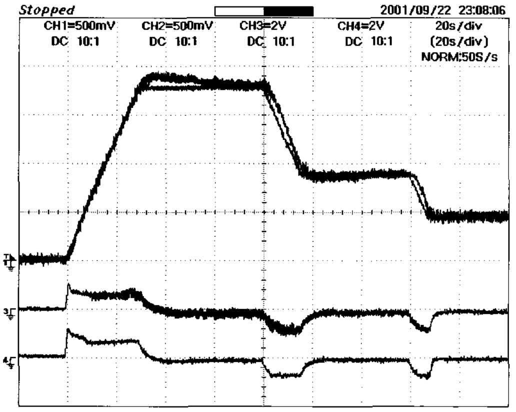
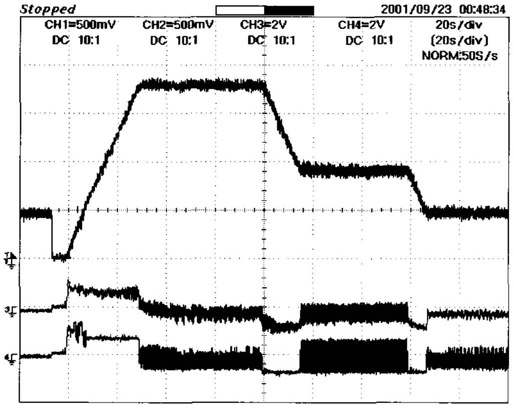


Fig. 5 The system behaviour of the indirect rotor field control (1: ramp-reference speed, 2: estimated speed, 3: real speed, 4: speed error, 652rpm/div., 20s/div.)

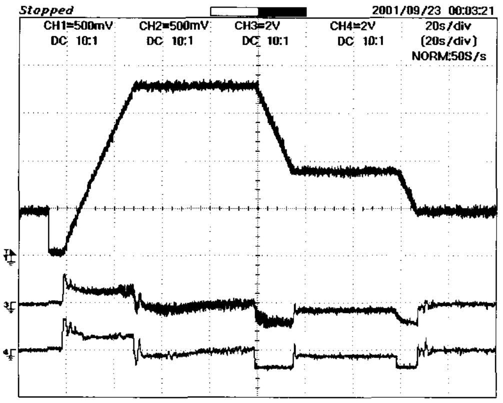
To illustrate the performances of the proposed fuzzy-sliding mode control, experiments were conducted using three kinds of speed controllers: a PI controller (Fig. 6(a)), a conventional sliding mode controller (Fig. 6(b)) and fuzzy- sliding mode controller (Fig. 6(c)). The proposed fuzzy-sliding mode control can be seen to have the best response avoiding overshoot and chattering in steady-state operation. Another main advantage of the fuzzy-sliding mode controller over the PI controller is that the overshoot can also be cut in the same manner also at low speed. A PI controller is known to lead to different overshoot, which depends on the reference speed. Observe that, in the case of the fuzzy-sliding mode controller, the perturbation is practically rejected and, comparing the sliding mode controller, chattering is also avoided.



(a) PI speed controller



(b) Sliding mode speed controller



(c) Fuzzy-sliding mode speed controller

Fig. 6 Experimental results (1: reference speed, 2: real speed, 3: real torque current, 4: reference torque current, 278[rpm/div], 37.5[A/div], 20[s/div])

6. Conclusion

In this paper, a new fuzzy-sliding mode controller has been presented. This new controller was applied to improve the speed response, reduce the overshot of a PI controller, and avoid chattering in steady-state of a conventional sliding mode controller, which causes unacceptable vibration stress of the load. With the proposed fuzzy-sliding mode controller, the main goals of a well-tuned system, such as the disturbance rejection and the minimizing of the overshoot, have been obtained. The performance improvement of this fuzzy-sliding mode controller over the PI controller or the standard sliding mode controller is clearly shown in the experimental results.

A fully digital realization 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.

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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] W. Pedrez, *Fuzzy Control and Fuzzy Systems*, John Willy & Sons, Inc., 1989.

[4] L. A Zadeh, "Fuzzy set," *Information and Control*, Vol. 8, pp. 338–353, 1985.

[5] K.T. Hung, *A Slip Gain Error Model-Based Correction Scheme of Near-Deadbeat Response for Indirect Field Orientation*, Masters Thesis, Univ. of Wisconsin-Madison, 1990.

[6] A. Kawamura, K. Miura, and T. Ishizava, "Trajectory Control of Two Axis Robot by Sliding Mode Control with Observer," *IEEE Proc. of IECON89*, pp. 640–645, 1989.

[7] M.H. Park and K.S. Kim, "Chattering Reduction in the Position Control of Induction Motor using Sliding Mode," *IEEE Trans. Power Electronics*, Vol. 6, No. 3, pp. 317–325, 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 IECON92*, pp. 60- 66, 1992.

[9] G. Cordeschi and F. Parasiliti, "A Variable Structure Approach for Speed Control of Field-Oriented Induction Motor," *EPE'91, Firenze, Italy*, pp. 2/222–2/226, 1991.

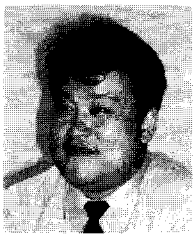
[10] J. Moerschell, "Digital Sliding Mode Torque Control for Induction Servo Drives," *Motion Control for Intelligent Automation, Perugia'92, Italy*, pp. 227-282, 1992.

[11] Hong-Je Ryoo, Jong-Soo Kim, Myung-Ho Woo, Won-Ho Kim, and Geun-Hie Rim, "Propulsion System Simulator of a High-Speed Railway Train," *MET99, Warsaw, Poland*, pp. 1–5, 1999.

[12] Edward Y. Y. Ho and Paresh C. Sen, "Control Dynamics of Speed Drive Sytems Using Sliding Mode Controllers with Integral Compensation," *IEEE Trans. on Ind. Appl.*, Vol. 27, No. 5, pp. 883–892, 1991.

[13] F. Harashima, H. Hashimoto, and S. Kondo, "Mosfet Converter-Fed Position Servo System with Sliding Mode Control," *IEEE Trans. Ind. Electron.*, Vol. IE-32, No. 3, 1985.

[14] Dragos Ovidiu Kisck, Hong-Je Ryoo, Jong-Soo Kim, and Geun-Hie Rim, "Sensorless Control For Rotor Field Oriented Induction Motor Used in Traction Application," Optim2002, pp. 525–530, May 2002.



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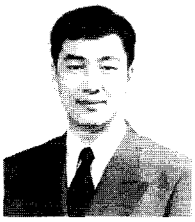

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