전력전자학술대회 논문집 1998.7.2~4

시간지연 제어를 이용한 영구자석형 동기전동기의 개선된 비선형 속도제어

백 인철
153-023, 서울 금천구 가산동 327-23
LG전자 리빙시스템 연구소 전력전자팀

Improved Nonlinear Speed Control of PM Synchronous Motor using Time Delay Control

In-Cheol Baik
Power Electronics Team, Living System Research Lab., LG Electronics Inc.
327-23, Kasan-Dong, Keumchun-Gu, Seoul, 153-023, Korea

Abstract - **An improved nonlinear speed control of a permanent magnet synchronous motor(PMSM) is presented. A quasi-linearized and decoupled model including the influence of parameter variations and speed measurement error on the nonlinear speed control of a PMSM is derived. Using this model, to overcome the drawbacks of conventional nonlinear control scheme, the improved nonlinear control scheme that employs time delay control(TDC) is proposed. To show the validity of the proposed control scheme, simulation studies are carried out and compared with the conventional control scheme.**

I. INTRODUCTION

PMSM drives are being increasingly used in a wide range of applications due to their high power density, large torque to inertia ratio, and high efficiency. This paper deals with the nonlinear speed control of a surface mounted permanent magnet synchronous motor with sinusoidal flux distribution. Since the dynamics of the currents are much faster than that of the mechanical speed, the speed is considered as a constant parameter rather than a state variable and they can be approximately linearized by the field orientation and current control [1-4]. However, this approximate linearization leads to the lack of torque due to the incomplete current control during the speed transient and reduces the control performance in some applications such as industrial robots and machine tools [5-6].

A solution to overcome this problem proposed by Le Pioufle [7] is to consider the motor speed a state variable in electrical equations, which results in a nonlinear model. Then the nonlinear control method, so called a feedback linearization technique, is applied to obtain a linearized and decoupled model and the linear design technique is employed to complete the control design [8]. Since the nonlinear controller is very sensitive to the speed measurement error, even small measurement error results in a significant speed error and its robustness can be improved by carefully selecting the gains in the linear control loops [7]. However, besides the speed measurement error, there are parameter variations such as the stator resistance, flux, and inertia due to the temperature rise and load variations. The stator resistance and flux variations also show a steady state speed error and the inertia variations degrade the transient performance. The steady state speed error may also go to zero by properly choosing the linear controller gains. However, the transient performance can still be significantly degraded due to the inertia and flux variations.

The feedback linearization deals with the technique of transforming the original system model into an equivalent model of a simpler form, and then employs the well-known and powerful linear design technique to complete the control design. However, it does not guarantee the robustness in the presence of parameter uncertainties or disturbances. To overcome this problem, the feedback linearization technique is considered as a model-simplifying device for the time delay control.

In this paper, a quasi-linearized and decoupled model including the influence of parameter variations and speed measurement error on the nonlinear speed control of a PMSM is first derived and then the improved control scheme employing a time delay control is designed to improve the control performance. For the above mentioned control scheme, an information on the acceleration is needed and calculated from numerical calculation.

II. NONLINEAR SPEED CONTROL OF PMSM USING INPUT-OUTPUT LINEARIZATION

A. Modeling of PMSM

The machine considered is a surface mounted PMSM and the nonlinear state equation in the synchronous d-q reference frame can be represented as follows :

$$\frac{dx}{dt} = f(x) + Gu \tag{1}$$

where

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} i_d \\ i_q \\ \Omega \end{pmatrix}, \quad u = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} v_d \\ v_q \end{pmatrix} \tag{2), (3}$$

$$G = \begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \end{pmatrix} \tag{4}$$

$$f(x) = \begin{pmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{pmatrix} = \begin{pmatrix} -\frac{R}{L_d}x_1 + P\frac{L_q}{L_d}x_2x_3 \\ -P\frac{L_d}{L_q}x_1x_3 - \frac{R}{L_q}x_2 - P\frac{\Phi}{L_o}x_3 \\ \frac{3}{2}P\frac{\Phi}{J}x_2 - \frac{F}{J}x_3 - \frac{T_L}{J} \end{pmatrix}. \tag{5}$$

The parameters used in these equations are defined as follows:

v_d, v_q : stator voltages in the direct and quadrature axes

i_d, L_d : current and inductance in the direct axis

i_q, L_q : current and inductance in the quadrature axis

R : stator resistance

Ω : mechanical speed of motor

P : number of pole pairs

Φ : flux created by the rotor magnets

J : moment of inertia

F : viscous friction coefficient

T_L : load torque

f_1, f_2, f_3 : nonlinear terms in a PMSM model.

B. Nonlinear Speed Control of PMSM

In order to avoid any zero dynamics and to get a total input-output linearization, the direct axis current and mechanical speed are chosen as outputs. From (1) and the assumption that the load torque is constant, the relationship between the outputs and inputs of the model can be obtained as follows [7] :

$$\begin{pmatrix} \frac{di_d}{dt} \\ \frac{d^2\Omega}{dt^2} \end{pmatrix} = B + A\begin{pmatrix} v_d \\ v_q \end{pmatrix} \tag{6}$$

where

$$B = \begin{pmatrix} f_1 \\ \frac{3}{2}\frac{1}{J}\left\{P\Phi f_2 - \frac{2}{3}Ff_3\right\} \end{pmatrix}, \quad A = \begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{3}{2}\frac{P\Phi}{L_qJ} \end{pmatrix}. \tag{7}$$

The nonlinear control input which permits a linearized and decoupled behavior is deduced from this relationship as follows :

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = A^{-1}\left(-B + \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}\right) \tag{8}$$

where ν_1 and ν_2 are the new control inputs. By substituting (8) into (6), the linearized and decoupled model can be given as

$$\frac{di_d}{dt} = \nu_1 \quad , \quad \frac{d^2\Omega}{dt^2} = \nu_2 . \tag{9),(10}$$

As the control laws for the new control inputs, the linear controller suggested by Le Pioufle becomes as follows :

$$\nu_1 = K_{11}(i_d^* - i_d) \tag{11}$$

$$\nu_2 = \frac{d^2\Omega^*}{dt^2} + K_{21}\frac{d}{dt}(\Omega^* - \Omega) + K_{22}(\Omega^* - \Omega) \tag{12}$$

where K_{11}, K_{21}, and K_{22} are the gains. Also, i_d^* and Ω^* are the tracking commands of the direct axis current and mechanical speed of a PMSM, respectively. As a result, the following error dynamics can be obtained as

$$\frac{de_1}{dt} + K_{11}e_1 = 0 \;, \frac{d^2e_2}{dt^2} + K_{21}\frac{de_2}{dt} + K_{22}e_2 = 0 \tag{13),(14}$$

where $e_1 = i_d^* - i_d$, $e_2 = \Omega^* - \Omega$. The poles for the desired error dynamics can be chosen by properly selecting the gains using a binomial standard form, etc. [9]. The overall scheme of the conventional nonlinear speed control system is shown in Fig. 1.

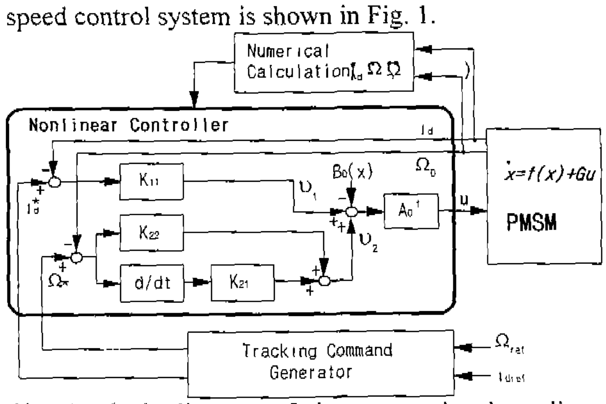


Fig. 1 Block diagram of the conventional nonlinear control scheme

C. Generation of Tracking Commands

The desired tracking commands which have sufficient smoothness are assumed as shown below.

$$\Omega^* = \frac{\Omega_{ref}}{T_f}t - \frac{\Omega_{ref}}{2\pi}\sin(\frac{2\pi t}{T_f}) \quad when \quad t \le T_f$$
$$otherwise \quad \Omega^* = \Omega_{ref}$$
$$\frac{d\Omega^*}{dt} = \frac{\Omega_{ref}}{T_f} - \frac{\Omega_{ref}}{T_f}\cos(\frac{2\pi t}{T_f}) \quad when \quad t \le T_f$$
$$otherwise \quad \frac{d\Omega^*}{dt} = 0$$
$$\frac{d^2\Omega^*}{dt^2} = \frac{2\pi\Omega_{ref}}{T_f^2}\sin(\frac{2\pi t}{T_f}) \quad when \quad t \le T_f$$
$$otherwise \quad \frac{d^2\Omega^*}{dt^2} = 0 \tag{15}$$

where Ω_{ref} and T_f are the steady state speed command and acceleration time, respectively.

III. QUASI-LINEARIZED AND DECOUPLED MODEL AND PROPOSED CONTROL STRATEGY USING TIME DELAY CONTROL

A. Quasi-Linearized and Decoupled Model

The actual nonlinear control input which employs the nominal parameter values and measured mechanical speed is expressed as follows [7] :

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = \boldsymbol{A}_o^{-1}\left(-\boldsymbol{B}_o + \begin{pmatrix} v_1' \\ v_2' \end{pmatrix}\right) \tag{16}$$

where v_1' and v_2' are the new control inputs and, $\boldsymbol{A}_o$ and $\boldsymbol{B}_o$ are obtained from (7) using the nominal parameter values and measured speed. By substituting (16) into (6), a quasi-linearized and decoupled model can be obtained as follows :

$$\frac{di_d}{dt} = \frac{R_o - R}{L_d}i_d - P\frac{L_q}{L_d}i_q(\Omega_o - \Omega) + v_1'$$
$$= f_{n1}(x,t) + v_1' \tag{17}$$

$$\frac{d^2\Omega}{dt^2} = -\frac{F}{J}\left(f_3 - f_{3o}\frac{\Phi}{\Phi_o}\right)$$
$$+\frac{3}{2}P\frac{\Phi}{J}\left(\frac{R_o - R}{L_q}i_d + \frac{P}{L_q}(\Phi_o\Omega_o - \Phi\Omega)\right.$$
$$\left. + P\frac{L_d}{L_q}i_d(\Omega_o - \Omega)\right) + \frac{\Phi}{\Phi_o}\frac{J_o}{J}v_2'$$
$$= f_{n2}(x,t) + bv_2' \tag{18}$$

where the subscript "o" denotes the nominal parameter values and measured mechanical speed of motor. Unlike the linearized and decoupled model of (9) and (10), there are unwanted nonlinear terms, $f_{n1}(x,t)$ and $f_{n2}(x,t)$, and control input gain b for the quasi-linearized and decoupled model of (17) and (18), which can degrade the control performances.

B. Control Strategy for the Quasi-Linearized and Decoupled Model using Time Delay Control

The unwanted nonlinear terms, $f_{n1}(x,t)$ and $f_{n2}(x,t)$, are unknown and the range of control input gain b is known. Even though we do not have any further information about the unwanted nonlinear terms, $f_{n1}(x,t)$ and $f_{n2}(x,t)$, a particularly efficient estimation method can be obtained using the concept of time delay control [10-12]. Now, the feedback linearization technique is considered as a model-simplifying device for the time delay control, and the control laws for the new control inputs v_1' and v_2' are derived using a time delay control to overcome the drawbacks of the conventional nonlinear control scheme.

For the quasi-linearized and decoupled model of (17), let v_1' as shown below.

$$v_1' = -\hat{f}_{n1}(x,t) + K_{11}(i_d^* - i_d) \tag{19}$$

From (17) and (19), the following error dynamics can be obtained as

$$\frac{de_1}{dt} + K_{11}e_1 = f_{n1}(x,t) - \hat{f}_{n1}(x,t) \tag{20}$$

Then with $\hat{f}_{n1}(x,t) \cong f_{n1}(x,t)$, the right hand side of (20) may go to zero.

For the estimation of $f_{n1}(x,t)$ in (17), it is known $f_{n1}(x,t)$ in (17) is a continuous function. For a sufficiently small time L,

$$f_{n1}(x,t) \cong f_{n1}(x,t-L) \tag{21}$$

Using (17) together with (21), following relationship can be obtained

$$f_{n1}(x,t)\left(\cong \hat{f}_{n1}(x,t)\right) = \frac{di_d(t)}{dt} - v_1'(t)$$
$$\cong \frac{di_d(t-L)}{dt} - v_1'(t-L) \tag{22}$$

Substituting this approximate estimation into (19) leads to the following TDC control law.

$$v_1' = -\hat{f}_{n1}(x,t-L) + K_{11}(i_d^* - i_d)$$
$$= -\frac{di_d(t-L)}{dt} + v_1'(t-L) + K_{11}(i_d^* - i_d) \tag{23}$$

The bound on the control input gain b in (18) depends on the flux and inertia variations. However, the only information required for the design of TDC control law is the range of control input gain that is positive real. By rearranging (18), with $\hat{b}(=1.)$ which represent the known range of control input gain, the relationship shown (24) can be obtained.

$$\frac{d^2\Omega}{dt^2} = \{f_{n2}(x,t) + (b - \hat{b})v_2'\} + \hat{b}v_2'$$
$$= \bar{f}_{n2}(x,t) + v_2' \tag{24}$$

For the quasi-linearized and decoupled model of (24), let ν'_2 as shown below.

$$\nu'_2 = -\hat{f}_{n2}(x,t) + \frac{d^2\Omega^*}{dt^2} + K_{21}\frac{d}{dt}(\Omega^* - \Omega) + K_{22}(\Omega^* - \Omega) \quad (25)$$

From (24) and (25), the following error dynamics can be obtained as

$$\frac{d^2 e_2}{dt^2} + K_{21}\frac{de_2}{dt} + K_{22}e_2 = \bar{f}_{n2}(x,t) - \hat{f}_{n2}(x,t) \quad (26)$$

Then with $\hat{f}_{n2}(x,t) \cong \bar{f}_{n2}(x,t)$, the right hand side of (26) may go to zero.

For the estimation of $\bar{f}_{n2}(x,t)$ in (24), it is known $\bar{f}_{n2}(x,t)$ in (24) is a continuous function. For a sufficiently small time L,

$$\bar{f}_{n2}(x,t) \cong \bar{f}_{n2}(x,t-L) \quad (27)$$

Using (24) together with (27), following relationship can be obtained

$$\bar{f}_{n2}(x,t)\left(\cong \hat{f}_{n2}(x,t)\right) = \frac{d^2\Omega(t)}{dt^2} - \nu'_2(t) \cong \frac{d^2\Omega(t-L)}{dt^2} - \nu'_2(t-L) \quad (28)$$

Substituting this approximate estimation into (25) leads to the following TDC control law.

$$\begin{aligned}\nu'_2 &= -\hat{f}_{nl}(x,t-L) + \frac{d^2\Omega^*}{dt^2} + K_{21}\frac{d}{dt}(\Omega^* - \Omega) + K_{22}(\Omega^* - \Omega) \\ &= -\frac{d^2\Omega(t-L)}{dt^2} + \nu'_2(t-L) + \frac{d^2\Omega^*}{dt^2} \\ &\quad + K_{21}\frac{d}{dt}(\Omega^* - \Omega) + K_{22}(\Omega^* - \Omega) \end{aligned} \quad (29)$$

The overall scheme of the proposed robust nonlinear speed control system is shown in Fig. 2.

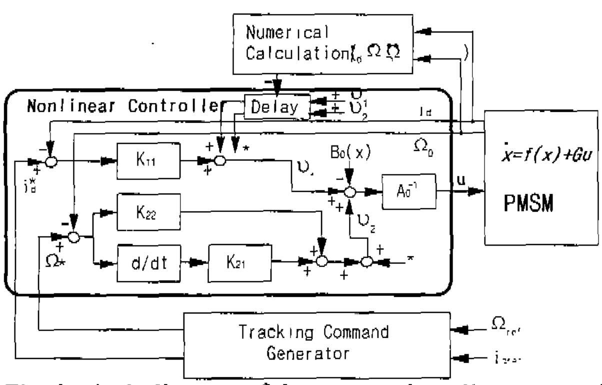


Fig. 2 Block diagram of the proposed nonlinear control scheme

IV. SIMULATION RESULTS

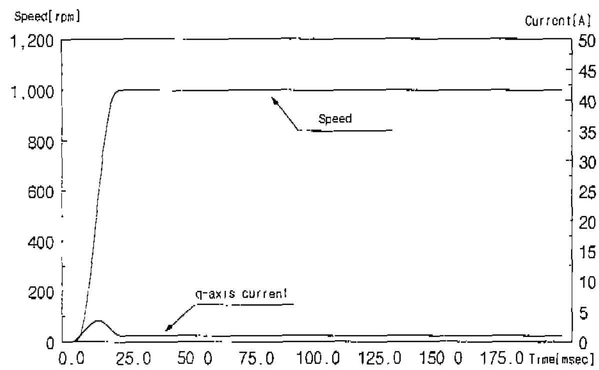
A. System Configuration

The simulations are carried out for the PMSM with the specifications listed as in Table 1.

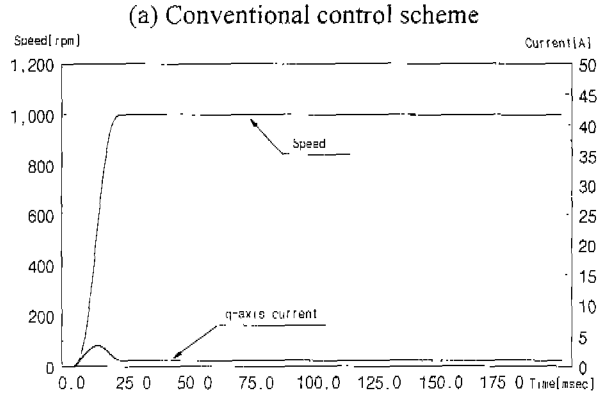
To examine the performance of the proposed control scheme, the dynamic behavior of the control system is tested under the inertia or flux variations in the acceleration region with the acceleration time of 20 msec. The sampling period of the control system is set as 100 μ sec.

B. Simulation Results

To show the validity of the proposed control scheme, the simulation studies are carried out for the systems shown in Figs. 1 and 2 under various conditions. Fig. 1 shows the overall block diagram of the conventional nonlinear speed control scheme and Fig. 2 shows the proposed improved nonlinear speed control scheme. The design parameters used for the conventional and proposed nonlinear control schemes are selected as $K_{11} = 2700$, $K_{21} = 900$, and $K_{22} = 810000$. The observer gains are selected as $l_1 = 796.67$ and $l_2 = -21.024$ to locate the double observer poles at -400 when there are no parameter variations.



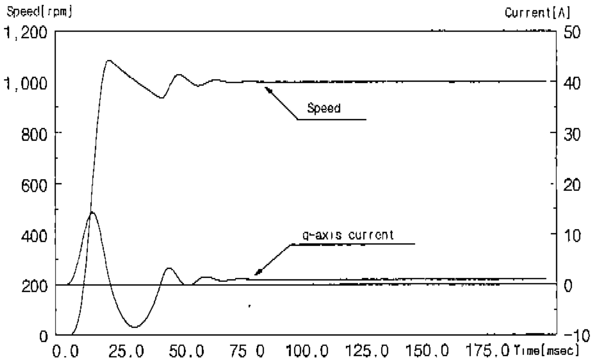
(a) Conventional control scheme



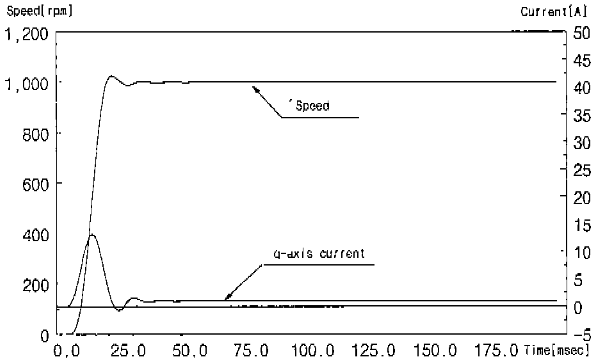
(b) Proposed control scheme

Fig. 3. Speed response and q-axis current under no inertia variation

Figs. 3(a) and (b) show the speed response and quadrature axis current under no inertia variation($J = J_0$) for both control schemes. Figs. 4(a) and (b) show the same phenomena under the inertia variation of 4 times the nominal value($J = 4J_o$). As shown in Figs. 3(a) and 4(a), the conventional nonlinear control scheme shows a significant degradation in the transient response. Under the inertia variation of 4 times the nominal value, it shows the enhanced overshoot of 8 % and prolonged settling time of 50msec. However, as shown in Figs. 3(b) and 4(b), the proposed improved nonlinear control scheme shows a good performance of 2% overshoot without prolonged

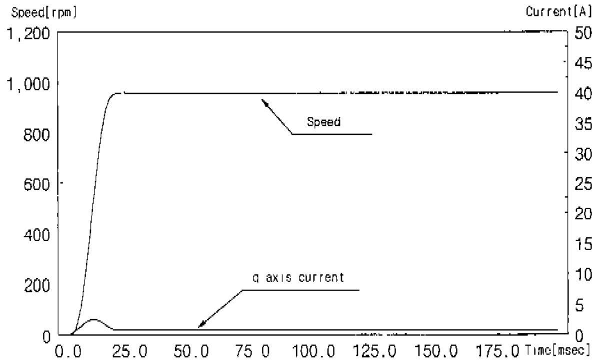


(a) Conventional control scheme

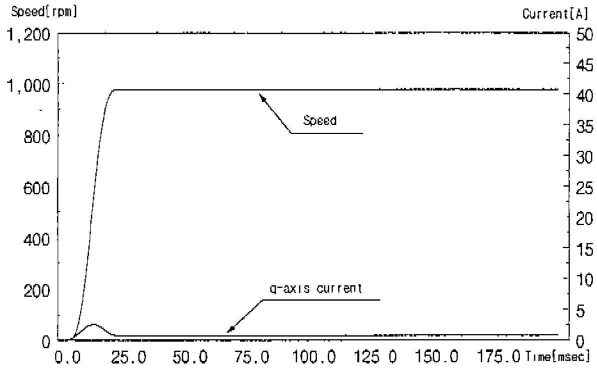


(b) Proposed control scheme

Fig. 4. Speed response and q-axis current under inertia variation($J = 4J_o$)



(a) Conventional control scheme



(b) Proposed control scheme

Fig. 5. Speed response and q-axis current under +30% flux variation

settling time. Figs. 5(a) and (b) show the speed response and quadrature axis current under flux variation of +30 % for both control schemes. As shown in Fig. 5(a), the conventional nonlinear control scheme shows a steady state error of 4.17 %. Fig. 5(b) shows that there is also a steady state error of 2.13 %. From Figs. 5(a) and (b), it can be noted that quadrature axis currents are different for the same load condition. It may be useful to compare this result with that of the case where parameter estimation schemes such as RLSM or MRAS-based technique are employed.

V. CONCLUSION

This paper proposes an improved nonlinear speed control scheme for a PMSM that guarantees the robustness in the presence of parameter variations and speed measurement error. The influence of parameter variations and speed measurement error on the nonlinear speed control of a PMSM is investigated and a quasi-linearized and decoupled model is derived. Based on this model, the design methods for the proposed control scheme have been given using the time delay control. The bounds of parameter uncertainties or informations on the unwanted nonlinear terms are not required for the proposed control scheme. It can be noted that the proposed control scheme employing TDC is as simple as conventional control scheme employing PD control while the proposed control scheme shows much better performance under parameter variations and disturbances.

To show the validity of the proposed control scheme, the simulation studies have been carried out under various conditions. Compared with the conventional nonlinear control scheme, the proposed improved nonlinear control scheme provides good transient responses under the inertia variations. It can be said from these results that the proposed control scheme has the robustness against the unknown parameter variations and disturbances.

REFERENCES

[1] G. Champenois, P. Mollard, and J. P. Rognon, "Synchronous servo drive: a special application", *IEEE-IAS Conf. Rec.*, 1986, pp. 182-189.

[2] M. Fadel and B. De Fornel, "Control laws of a synchronous machine fed by a PWM voltage source inverter", *EPE*, Aachen, RFA, Oct. 1989.W. Leonhard, *Control of electrical drives*. Springer Verlag,1985.

[3] T. Rekioua, F. Meibody Tabar, J. P. Caron, and R. Le Doeuff, "Study and comparison of two different methods of current control of a permanent magnet synchronous motor", *Conf. Rec. IMACS-TC1*, Nancy, France, Vol.1, pp. 157-163, 1990.

[4] B. Le Pioufle and J. P. Louis, "Influence of the dynamics of the mechanical speed of a synchronous servomotor on its torque regulation, proposal of a robust solution", *EPE*, Florence, Vol. 3, pp. 412-417, 1991.

[5] J. J. Carroll Jr. and D. M. Dawson, "Integrator backstepping techniques for the tracking control of permanent magnet brush DC motors", *IEEE Trans. IA*, Vol. 31, no. 2, pp. 248-255, Mar./April 1995.

[6] B. Le Pioufle, "Comparison of speed nonlinear control strategies for the synchronous servomotor", *Electric Machines and Power Systems*, Vol.21, pp. 151-169, 1993.

[7] A. Isidori, *Nonlinear control systems: an introduction*. Springer-Verlag, 1985.

[8] I. J. Nagrath, M. Gopal, *Control systems engineering*. John Wiley & Sons, 1982.

[9] K. Y. Toumi and O. Ito, "A time delay controller for systems with unknown dynamics", *ASME, J. of Dynamic Systems, Measurement, and Control*, Vol.112, pp. 133-142, 1990.

[10] P. H. Chang, D. S. Kim, and K. C. Park, "Robust force/position control of a robot manipulator using time-delay control", *Control Engineering Practice*, Vol.3, no.9, pp. 1255-1264, 1995.

[11] P. H. Chang, *Nonlinear Control System Design: ME761 Course Note*, Dept. of M.E., KAIST, 1997.