JPE 3-3-7

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

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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 which employs time delay control (TDC) scheme is proposed. To show the validity of the proposed control scheme, simulation studies are carried out and compared with the conventional control scheme.

Keywords: Nonlinear Control, Feedback Linearlization, Time Delay Control, Motion Control

1. 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 as 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]. However, the nonlinear controller is very sensitive to the speed measurement error. Therefore, 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

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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, in some researches, the feedback linearization technique is considered as a model-simplifying device to obtain controllable canonical form to apply sliding mode control and (or) adaptive control[9][10].

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 firstly derived. Using the quasi-linearized and decoupled model, the improved control scheme employing the time delay control scheme which is relatively simpler than those in the above mentioned papers[9][10] 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.

2. Nonlinear Speed Control of PMSM Using Input-Output Linearization

2.1 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:

$$\frac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x}) + \mathbf{G}\mathbf{u} \tag{1}$$

where

$$\boldsymbol{x} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} i_d \\ i_q \\ \Omega \end{pmatrix} \tag{2}$$

$$\boldsymbol{u} = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} v_d \\ v_q \end{pmatrix} \tag{3}$$

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

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

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.

2.2 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]:

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

where, $\mathbf{B}=\begin{pmatrix} f_1 \\ \frac{3}{2}\frac{1}{J}\left\{P\Phi f_2-\frac{2}{3}Ff_3\right\} \end{pmatrix}$,

$$\mathbf{A}=\begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{3}{2}\frac{P\Phi}{L_qJ} \end{pmatrix}. \tag{7}$$

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

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix}=\mathbf{A}^{-1}\left(-\mathbf{B}+\begin{pmatrix} v_1 \\ v_2 \end{pmatrix}\right) \tag{8}$$

where, v_1 and v_2 are the new control inputs. By substituting (8) into (6), the linearized and decoupled model can be given as,

$$\frac{di_d}{dt}=v_1 \tag{9}$$

$$\frac{d^2\Omega}{dt^2}=v_2 \tag{10}$$

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

$$v_1=K_{11}(i_d^*-i_d) \tag{11}$$

$$v_2=\frac{d^2\Omega^*}{dt^2}+K_{21}\frac{d}{dt}(\Omega^*-\Omega)+K_{22}(\Omega^*-\Omega) \tag{12}$$

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,

$$\frac{de_1}{dt}+K_{11}e_1=0 \tag{13}$$

$$\frac{d^2e_2}{dt^2}+K_{21}\frac{de_2}{dt}+K_{22}e_2=0 \tag{14}$$

where, $e_1=i_d^*-i_d$, $e_2=\Omega^*-\Omega$.

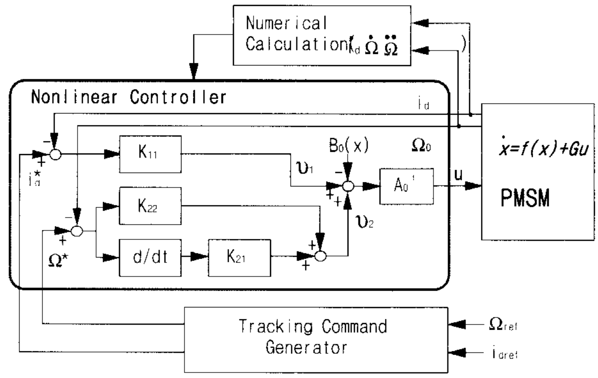


Fig. 1. Block diagram of the conventional nonlinear control scheme.

The poles for the desired error dynamics can be chosen by properly selecting the gains using a binomial standard form, etc.[11]. The overall scheme of the conventional nonlinear speed control system is shown in Fig. 1.

2.3 Tracking Command Generation

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

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

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

2.4 Asymptotic Load Torque Observer

In many motor drive systems, it is required to estimate an unknown load torque for the control system design and generally required to know all the inputs given to the system. However, in a real system, there are many cases where some of the inputs are unknown or inaccessible. For the unknown and inaccessible inputs, the observer was studied by Meditch and Hostetter and a 0-observer is selected for simplicity[9][10]. Thus, the inaccessible load torque (T_L) is assumed to be an unknown constant. For a PMSM, the system equation for a disturbance torque observer can be expressed as follows:

$$\frac{d\mathbf{z}}{dt} = \mathbf{D}\mathbf{z} + \mathbf{E}w, \quad y = \Omega = \mathbf{C}\mathbf{z} \tag{16}$$

where, $\mathbf{z} = \begin{pmatrix} \Omega \\ T_L \end{pmatrix} = \begin{pmatrix} z_1 \\ z_2 \end{pmatrix}$, $\mathbf{D} = \begin{pmatrix} \frac{-F}{J} & \frac{-1}{J} \\ 0 & 0 \end{pmatrix}$, $\mathbf{E} = \begin{pmatrix} \frac{3P\Phi}{2J} \\ 0 \end{pmatrix}$,

$\mathbf{C} = (1,0)$, $w = i_q$

and for this system, $(\mathbf{D}, \mathbf{C})$ is observable. The well-known asymptotic load torque observer can be designed as,

$$\frac{d\hat{\mathbf{z}}}{dt} = \mathbf{D}\hat{\mathbf{z}} + \mathbf{E}w + \mathbf{L}(y - \mathbf{C}\hat{\mathbf{z}}) \tag{17}$$

where, $\hat{\mathbf{z}} = (\hat{\Omega}, \hat{T}_L)^T$ is the observed value and $\mathbf{L} = (l_1, l_2)^T$ is the observer gain matrix.

3. Quasi-Linearized and Decoupled Model and Proposed Control Strategy

3.1 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]:

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = \mathbf{A}_o^{-1}\left(-\mathbf{B}_o + \begin{pmatrix} v_1' \\ v_2' \end{pmatrix} \right) \tag{18}$$

where v_1' and v_2' are the new control inputs and, $\mathbf{A}_o$ and $\mathbf{B}_o$ are obtained from (7) using the nominal parameter values and measured speed. By substituting (18) into (6), a quasi-linearized and decoupled model can be obtained as follows:

$$\begin{aligned} \frac{di_d}{dt} &= \frac{R_o - R}{L_d} i_d - P\frac{L_q}{L_d} i_q (\Omega_o - \Omega) + v_1' \\ &= f_{n1}(\mathbf{x}, t) + v_1' \end{aligned} \tag{19}$$

$$\begin{aligned} \frac{d^2\Omega}{dt^2} &= -\frac{F}{J}\left(f_3 - f_{3o}\frac{\Phi}{\Phi_o} \right) \\ &\quad + \frac{3}{2}P\frac{\Phi}{J}\left(\frac{R_o - R}{L_q} i_d + \frac{P}{L_q}(\Phi_o\Omega_o - \Phi\Omega) \right. \\ &\quad \left. + P\frac{L_d}{L_q} i_d (\Omega_o - \Omega) \right) \\ &\quad + \frac{\Phi}{\Phi_o}\frac{J_o}{J} v_2' = f_{n2}(\mathbf{x}, t) + b v_2' \end{aligned} \tag{20}$$

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, $f_{n1}(\mathbf{x},t)$ and $f_{n2}(\mathbf{x},t)$, and control input gain b for the quasi-linearized and decoupled model of (19) and (20), which can degrade the control performances.

3.2 Control Strategy for the Quasi-Linearized and Decoupled Model using Time Delay Control Scheme

The unwanted nonlinear terms, $f_{n1}(\mathbf{x},t)$ and $f_{n2}(\mathbf{x},t)$, 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, $f_{n1}(\mathbf{x},t)$ and $f_{n2}(\mathbf{x},t)$, a particularly efficient estimation method can be obtained using the concept of time delay control[12-14]. 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 (19), let v_1' as shown below.

$$v_1' = -\hat{f}_{n1}(\mathbf{x}, t) + K_{11}(i_d^* - i_d) \tag{21}$$

From (19) and (21), the following error dynamics can be obtained as,

$$\frac{de_1}{dt} + K_{11}e_1 = f_{n1}(\mathbf{x},t) - \hat{f}_{n1}(\mathbf{x},t) \tag{22}$$

Then with $\hat{f}_{n1}(\mathbf{x},t) \cong f_{n1}(\mathbf{x},t)$, the right hand side of (22) may go to zero.

For the estimation of $f_{n1}(\mathbf{x},t)$ in (19). It is known $f_{n1}(\mathbf{x},t)$ in (19) is a continuous function. For a sufficiently small time L,

$$f_{n1}(\mathbf{x},t) \cong \mathrm{f}_{n1}(\mathbf{x},t-L) \tag{23}$$

Using (19) together with (23), following relationship can be obtained.

$$\begin{aligned} f_{n1}(\mathbf{x},t)\left(\cong \hat{f}_{n1}(\mathbf{x},t)\right) &= \frac{di_d(t)}{dt} - v_1'(t) \\ &\cong \frac{di_d(t-L)}{dt} - v_1'(t-L) \end{aligned} \tag{24}$$

Substituting this approximate estimation into (21) leads to the following TDC control law.

$$\begin{aligned} v_1' &= -\hat{\mathrm{f}}_{n1}(\mathbf{x},t-L) + K_{11}(i_d^* - i_d) = \\ &-\frac{di_d(t-L)}{dt} + v_1'(t-L) + K_{11}(i_d^* - i_d) \end{aligned} \tag{25}$$

The bound on the control input gain b in (20) 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 which is positive real. By rearranging (20), with $\hat{b}(=1.)$ which represent the known range of control input gain, the relationship shown (26) can be obtained.

$$\frac{d^2\Omega}{dt^2} = \{f_{n2}(\mathbf{x},t) + (b-\hat{b})v_2'\} + \hat{b}v_2' = \bar{f}_{n2}(\mathbf{x},t) + v_2' \tag{26}$$

For the quasi-linearized and decoupled model of (26), let v_2' as shown below.

$$\begin{aligned} v_2' &= -\hat{f}_{n2}(\mathbf{x},t) + \frac{d^2\Omega^*}{dt^2} + K_{21}\frac{d}{dt}(\Omega^* - \Omega) \\ &+ K_{22}(\Omega^* - \Omega) \end{aligned} \tag{27}$$

From (26) and (27), the following error dynamics can be obtained as,

$$\frac{d^2e_2}{dt^2} + K_{21}\frac{de_2}{dt} + K_{22}e_2 = \bar{f}_{n2}(\mathbf{x},t) - \hat{f}_{n2}(\mathbf{x},t) \tag{28}$$

Then with $\hat{f}_{n2}(\mathbf{x},t) \cong \bar{f}_{n2}(\mathbf{x},t)$, the right hand side of (28) may go to zero.

For the estimation of $\bar{f}_{n2}(\mathbf{x},t)$ in (26). It is known $\bar{f}_{n2}(\mathbf{x},t)$ in (26) is a continuous function. For a sufficiently small time L,

$$\bar{f}_{n2}(\mathbf{x},t) \cong \bar{\mathrm{f}}_{n2}(\mathbf{x},t-L) \tag{29}$$

Using (26) together with (29), following relationship can be obtained.

$$\begin{aligned} \bar{f}_{n2}(\mathbf{x},t)\left(\cong \hat{f}_{n2}(\mathbf{x},t)\right) &= \frac{d^2\Omega(t)}{dt^2} - v_2'(t) \\ &\cong \frac{d^2\Omega(t-L)}{dt^2} - v_2'(t-L) \end{aligned} \tag{30}$$

Substituting this approximate estimation into (27) leads to the following TDC control law.

$$\begin{aligned} v_2' &= -\hat{\mathrm{f}}_{n1}(\mathbf{x},t-L) + \frac{d^2\Omega^*}{dt^2} + K_{21}\frac{d}{dt}(\Omega^* - \Omega) \\ &+ K_{22}(\Omega^* - \Omega) = -\frac{d^2\Omega(t-L)}{dt^2} + v_2'(t-L) \\ &+ \frac{d^2\Omega^*}{dt^2} + K_{21}\frac{d}{dt}(\Omega^* - \Omega) + K_{22}(\Omega^* - \Omega) \end{aligned} \tag{31}$$

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

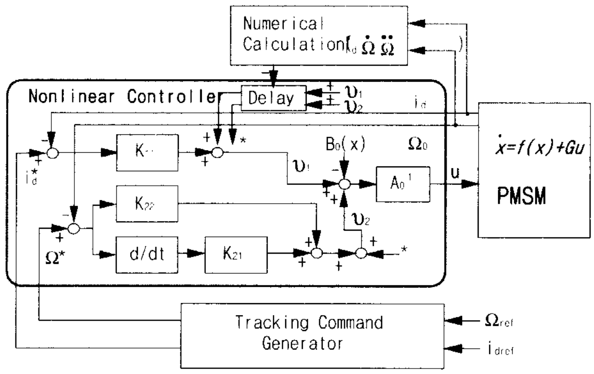


Fig. 2. Block diagram of the proposed nonlinear control scheme.

4. Simulation Results

4.1 System Configuration

The simulation studies 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. Therefore the time period L for the TDC scheme is integral multiple of above mentioned sampling period.

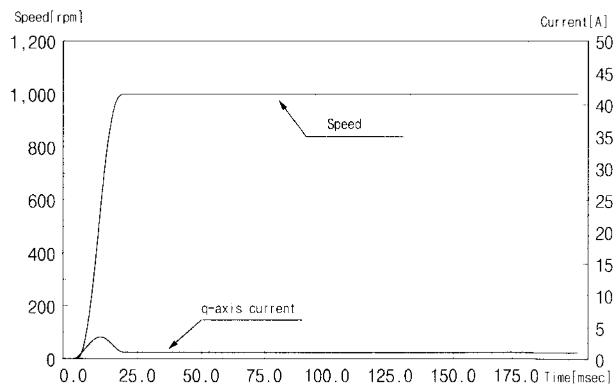
Table 1. Specifications of PMSM.

Rated Power	400 W
Rated Torque	1.274 Nm
Number of Pole Pairs	2
Stator Resistance	3 Ohm
Rated Speed	3000 RPM
Rated Voltage	190 V
Flux Linkage	0.167 Wb
Stator Inductance	7 mH

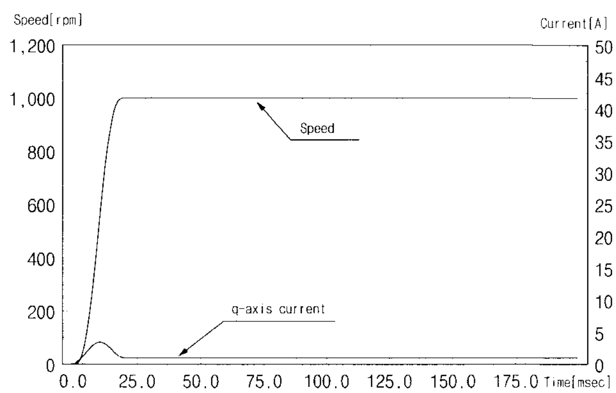
4.2 Simulation Results

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. Figs. 3(a) and (b) show the speed response and quadrature axis current under no inertia variation ($J = J_o$) for both control schemes.

Figs. 4(a) and 4(b) show the same phenomena under the inertia variation of 4 times the nominal value ($J = 4J_o$). Figs. 5(a) and 5(b) show the speed response and quadrature axis current under +30% flux variation. As shown in Fig. 4(a), the conventional nonlinear control scheme shows a significant degradation in the transient

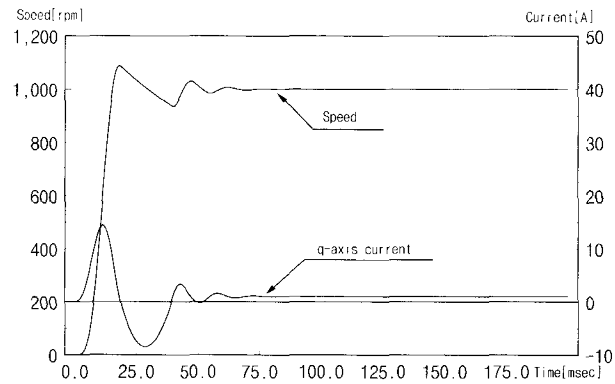


(a) Conventional control scheme

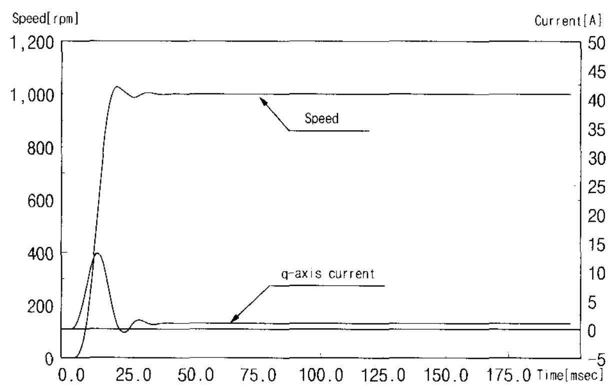


(b) Proposed control scheme

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

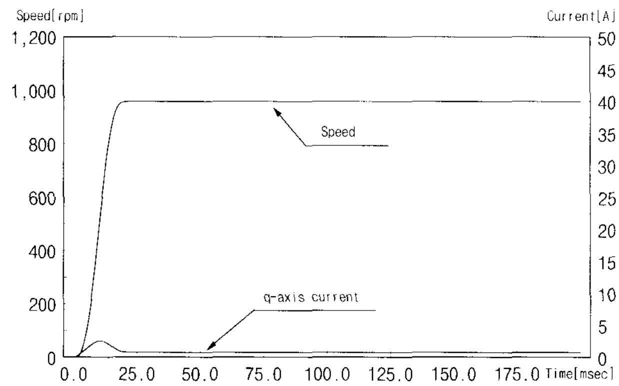


(a) Conventional control scheme

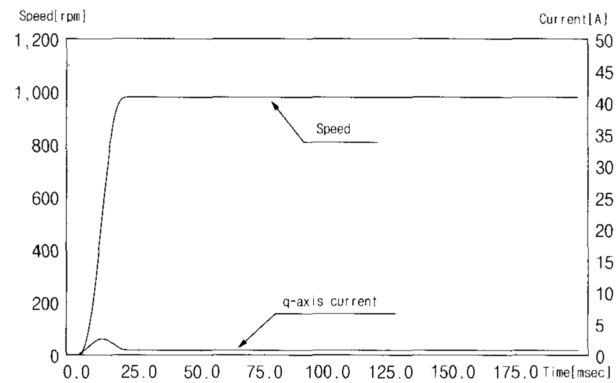


(b) Proposed control scheme

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.

response. Under the inertia variation of 4 times the nominal value, it shows the enhanced overshoot of 8% and prolonged settling time of 50msec. As shown in Fig. 5(a), the conventional nonlinear control scheme shows about 4% steady state error under +30% flux variation. However, as shown in Fig. 4(b), the proposed improved nonlinear control scheme shows a good performance of about 2% overshoot without prolonged settling time under the inertia variation of 4 times the nominal value. Under the flux variation of +30%, as shown in Fig. 5(b), the proposed improved nonlinear control scheme shows a much more reduced steady state error of about 1.5%.

5. Conclusion

This paper proposes an improved nonlinear speed control scheme for a PMSM which 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 information 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 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 of 4 times the nominal value. Also, the proposed improved nonlinear control scheme shows reduced steady state error under the flux variation of 30%. From these results, it can be said that the proposed control scheme has the robustness against the unknown parameter variations and disturbances.

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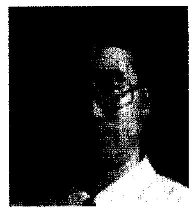

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