가속 토오크 궤환을 이용한 영구자석 동기전동기의 강인제어

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A Robust Control of PM Synchronous Motor Using Accelerating Torque Feedback

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ABSTRACT - **A robust control technique of the PM synchronous motor is presented using an accelerating torque feedback. The accelerating torque is estimated by using an adaptive torque observer and then this estimated torque is controlled by a VSC technique. By employing the proposed torque control, the speed control performance of the motor is improved and the load independency can be realized. The simulations carried out for the PM synchronous motor to verify the effectiveness of the proposed control.**

LIST OF SYMBOLS

r_s	=	stator resistance
L_q, L_d	=	q and d axis inductances, respectively
λ_m	=	linkage flux of the permanent magnet
J	=	inertia moment of the rotor and load
B	=	viscous friction coefficient
P	=	number of poles
i_q, i_d	=	q and d axis currents, respectively
V_q, V_d	=	q and d axis voltages, respectively
ω_r	=	electrical angular speed of the rotor
T_e	=	electromagnetic torque
T_L	=	load torque

I. INTRODUCTION

Permanent magnet(PM) synchronous motors are generally utilized in a wide range of high performance applications such as industrial robots and machine tools because of their high power density, high torque to inertia ratio, and free maintenance. However, the control of the PM synchronous motor is more difficult than that of the DC motor because of its nonlinear characteristics and complicate drives. Since the PM synchronous motor is generally driven by the current regulated PWM(CRPWM) technique associated with the concept of the field orientation, the speed controller can be designed without considering the electrical dynamics. However, there still exist some factors of degrading the control performance such as the load torque and inertia variations. Therefore, most of previous approaches dealing with the control of the PM synchronous motor mainly consider the rejection of the effects on these factors.

In order to reject the effects of the load variations, the accelerating torque feedback is proposed in this paper. Since the dynamic behavior of the PM synchronous motor mainly depends on the difference of the developed and load torques, that is an accelerating torque, the speed controller can simply be designed by introducing the proposed controller and the indepedency of the load variations can be realized. However, since the accelerating torque is generally not accessible, an estimating technique is employed in the proposed scheme. This paper describes the estimating and control techniques of the accelerating torque using the adaptive and variable structure control techniques. The effectiveness of the proposed scheme are finally verified through the simulations.

II. MODELING OF PM SYNCHRONOUS MOTOR

The motor considered in this paper is a three phase PM synchronous motor with sinusoidal back EMF. The nonlinear state equations of this motor in the synchronous reference frame can be expressed as follows[1]:

$$\frac{di_q}{dt} = -\frac{r_s}{L_q} i_q - \frac{L_d}{L_q}\omega_r i_d + \frac{1}{L_q}V_q - \frac{\lambda_m}{L_q}\omega_r \tag{1.a}$$

$$\frac{di_d}{dt} = \frac{L_q}{L_d}\omega_r i_q - \frac{r_s}{L_d} i_d + \frac{1}{L_d}V_d \tag{1.b}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)[\lambda_m i_q + (L_d - L_q) i_q i_d] \tag{1.c}$$

$$= J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} + B\left(\frac{2}{P}\right)\omega_r + T_L . \tag{1.d}$$

By employing the field oriented control, it can be assumed that the d axis current i_d is controlled to be zero. Then, the developed torque in (1.c) can be linearized as

$$T_e = k_t i_q \tag{2}$$

where $k_t = \frac{3}{2}\left(\frac{P}{2}\right)\lambda_m$.

Therefore, the resultant dynamic equation considered for designing the speed controller can be represented as

$$\begin{pmatrix} \dot{i}_q \\ \dot{\omega}_r \end{pmatrix} = \begin{pmatrix} -\frac{r_s}{L_q} & -\frac{\lambda_m}{L_q} \\ \frac{k_t P}{2J} & -\frac{B}{J} \end{pmatrix}\begin{pmatrix} i_q \\ \omega_r \end{pmatrix} + \begin{pmatrix} \frac{1}{L_q} \\ 0 \end{pmatrix}\cdot V_q + \begin{pmatrix} 0 \\ -\frac{P}{2J}T_L \end{pmatrix}. \tag{3}$$

III. BASIC CONCEPTS

The basic concept of the proposed scheme is derived from the well known torque and speed relation as shown in Fig. 1. It can be observed in this figure that the dynamic behavior of the motor depends on not the developed torque T_e but the difference between the developed torque and load torque $T_a = T_e - T_L$ which is referred to as accelerating torque. However, most existing approaches mainly con-

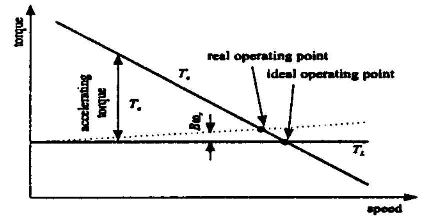

Fig. 1 Typical torque vs speed curve of PM synchronous motor.

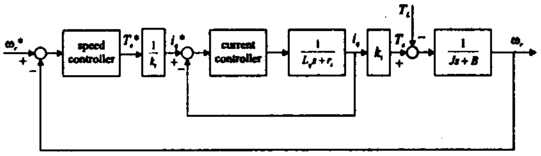

Fig. 2 Speed control system of PM synchronous motor employing conventional CRPWM.

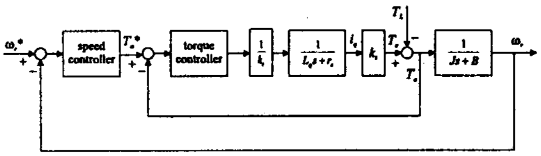

Fig. 3 Speed control scheme of PM synchronous motor employing proposed accelerating torque feedback.

sider the control of the developed torque of the motor and thus the load torque is regarded as a disturbance which largely affects the speed control performance. Fig. 2 shows the conventional speed control scheme of the PM synchronous motor employing a CRPWM drive. If the torque constant k_t is exactly known, the developed torque can be controlled by the inner loop current controller. However, to obtain high quality control performance, the effect of the load torque should be rejected by the speed controller in the outer control loop.

To deal with this problem, an accelerating torque feedback control is proposed. Fig. 3 shows the concept of the proposed control. If the accelerating torque is perfectly controlled in the inner control loop, the speed dynamics of the motor is independent on the load torque. Therefore, the speed controller in the outer control loop can be simply designed without considering the effect of the load torque. Unfortunately, the major difficulty of this scheme is how to obtain the information on the accelerating torque which is not accessible. Since the measuring system of this torque is very expensive and bulky, it can not be employed in industrial servo systems. Therefore, a estimating technique is introduced in this paper. By using an adaptive torque observer, the accelerating torque is estimated and then this estimated torque is fed to the torque controller.

III. Design of Proposed Torque Controller

A. Design of torque estimator

Under the assumption that the load torque is constant as $\dot{T}_L = 0$, the observer to estimate the load torque is given

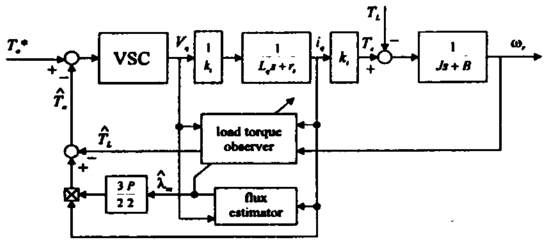

Fig. 4 Proposed torque control scheme employimg torque estimator and controller.

as follows[4,5]

$$\begin{pmatrix}\dot{\hat{i}}_q \\ \dot{\hat{\omega}}_r \\ \dot{\hat{T}}_L\end{pmatrix} = \begin{pmatrix} -\frac{r_s}{L_q} & -\frac{\lambda_m}{L_q} & 0 \\ \frac{k_t J}{2P} & -\frac{B}{J} & -\frac{P}{2J} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix}\hat{i}_q \\ \hat{\omega}_r \\ \hat{T}_L\end{pmatrix} + \begin{pmatrix}\frac{1}{L_q} \\ 0 \\ 0\end{pmatrix} \cdot V_q + \begin{pmatrix} l_{11} & l_{12} \\ l_{21} & l_{22} \\ l_{31} & l_{32}\end{pmatrix} \begin{pmatrix} i_q - \hat{i}_q \\ \omega_r - \hat{\omega}_r \end{pmatrix}. \quad (4)$$

Since it is difficult to obtain the exact information on the flux λ_m, the adaptive estimator is introduced as

$$\dot{\hat{\lambda}}_m = -\gamma\omega_r(i_q - \hat{i}_q). \quad (5)$$

From the above results, the accelerating torque can be estimated as follows:

$$T_a = \hat{k}_t i_q - \hat{T}_L \quad (6)$$

where $\hat{k}_t = \frac{3}{2}\left(\frac{P}{2}\right)\hat{\lambda}_m$.

B. Design of torque controller using VSC

To control the accelerating torque, a VSC is introduced. The sliding surface can be chosen as[5]

$$s_T = x_T + c_T \int_{-\infty}^{t} x_T(\varsigma)d\varsigma \quad (7)$$

$$s_i = x_i + c_i \int_{-\infty}^{t} x_i(\varsigma)d\varsigma \quad (8)$$

where $x_T = T_a - T_a^*$, $x_i = i_{ds} - i_{ds}^*$, and the superscript '*' denotes the reference. The control input of the proposed scheme can be given as

$$V_q = K_{T1}x_T + K_{T2} \quad (9)$$

$$V_d = K_{i1}x_i + K_{i2}\ . \quad (10)$$

Using the well known sliding mode existence condition as

$$s_T\dot{s}_T < 0\,, \qquad s_T\dot{s}_T < 0$$

the switching gains in (9) and (10) can be determined as

$$K_{T1} = \begin{cases} K_{T1}^+ > \max\left[-\frac{L_q}{k_t}\left(c_T - \frac{r_s}{L_q}\right)\right] & for\ \ s_T x_T < 0 \\ K_{T1}^- < \min\left[-\frac{L_q}{k_t}\left(c_T - \frac{r_s}{L_q}\right)\right] & for\ \ s_T x_T > 0 \end{cases} \quad (11)$$

$$K_{T2} = \begin{cases} K_{T2}^+ > \max\left[L_d\omega_r i_d + \lambda_m\omega_r + \frac{r_s}{k_t}T_a^* + \frac{L_q}{k_t}\dot{T}_a^*\right] & for\ \ s_T < 0 \\ K_{T2}^- < \min\left[L_d\omega_r i_d + \lambda_m\omega_r + \frac{r_s}{k_t}T_a^* + \frac{L_q}{k_t}\dot{T}_a^*\right] & for\ \ s_T > 0 \end{cases} \quad (12)$$

$$K_{T1} = \begin{cases} K_{i1}^+ > \max\left[-L_d\left(c_i - \frac{r_s}{L_d}\right)\right] & for\ \ s_i x_i < 0 \\ K_{i1}^- < \min\left[-L_d\left(c_i - \frac{r_s}{L_d}\right)\right] & for\ \ s_i x_i > 0 \end{cases} \quad (13)$$

$$K_{T2} = \begin{cases} K_{i2}^+ > \max\left[-L_q\omega_r i_q + r_s T_a^* + L_d\dot{T}_a^*\right] & for\ \ s_i < 0 \\ K_{i2}^- < \min\left[-L_q\omega_r i_q + r_s T_a^* + L_d\dot{T}_a^*\right] & for\ \ s_i > 0 \end{cases} \quad (14)$$

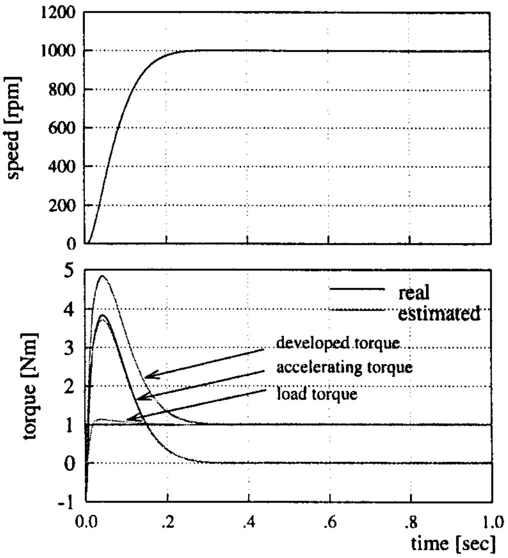

Fig. 5 Simulation results of proposed torque control scheme (upper : speed response, lower : developed torque, load torque, accelerating torque, speed reference = 1000rpm, load torque = 1.0Nm).

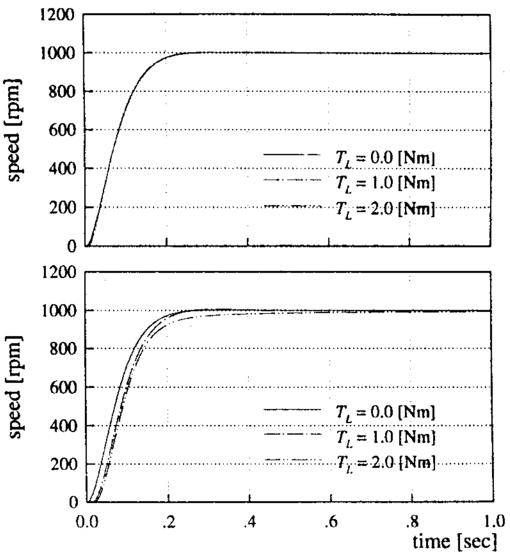

Fig. 6 Speed responses of both schemes under load variations (upper : proposed scheme, lower : CRPWM).

Fig. 4 shows the proposed scheme which consists of torque estimator and a robust torque controller.

IV. SIMULATIONS

To verify the effectiveness of the proposed scheme, the computer simulations are carried out for the actual parameters of the PM synchronous motor as follows:

Rated Power = 750W,	*Rated Speed = 3000rpm*
Rated Torque = 2.35Nm,	*Resistance = 1.07Ω*
Inductance = 2.1mH,	*Inertia = 0.0001313Nms²*
Magnet flux = 0.170Wb,	*No. of Pole = 4.*

Fig. 5 shows the simulation results of the proposed torque control scheme. It is observed that the accelerating torque can be effectively estimated by the proposed estimator. The control performance of the proposed scheme is compared with that of the CRPWM scheme. Fig. 6 shows

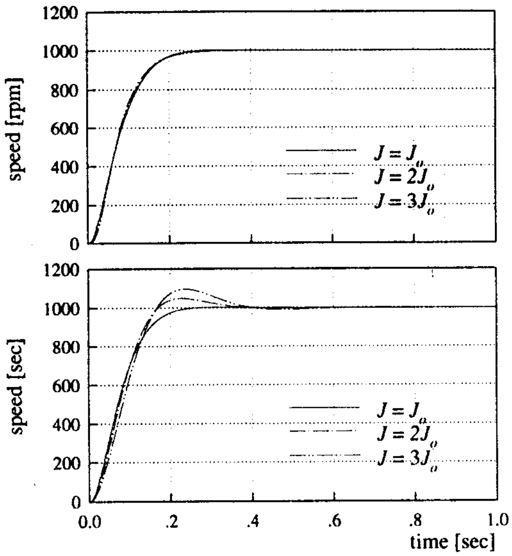

Fig. 7 Speed responses of both schemes under inertia variations (upper : proposed scheme, lower : CRPWM).

the speed responses of the conventional and proposed schemes for various load conditions, where the PI control is used as a speed regulator in both schemes. As the load torque is increased, it is shown that the dynamic performance is degraded. However, in the proposed scheme, the nearly same results can be obtained under the load variations. Figs. 7 show the effects of the inertia variation. It is shown in this figure that the proposed scheme also provides a good performance under the inertia variation.

V. CONCLUSIONS

An accelerating torque feedback control scheme is proposed for the robust control of the PM synchronous motor. The accelerating torque is estimated by using the adaptive torque observer and this torque is controlled by using the VSC technique. The simulations are carried out for the actual parameters of the PM synchronous motor and the results well demonstrate that the proposed scheme provides a robust control performance against the load torque and inertia variations. It is expected that the proposed scheme is applied to high performance applications of the PM synchronous motor. As a further works, the experimental verifications are being considered.

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