전력전자학술대회 논문집 1997. 7. 17-19

적응 관측기를 이용한 영구자석 동기전동기의 센서리스 제어

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Sensorless Control of PM Synchronous Motor Using Adaptive Observer

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Abstract

A new approach to the position sensor elimination of PM synchronous motor drives is presented in this study. Using the position sensing characteristics of PMSM itself, the actual rotor position as well as the machine speed can be estimated by adaptive flux observer and used as the feedback signal for the vector controlled PMSM drive. The adaptive speed estimation is achieved by model reference adaptive technique. The adaptive laws are derived by the Popov's hyperstability theory and the positivity concept. In order to verify the effectiveness of the proposed scheme, computer simulations are carried out for the actual parameters of a PM synchronous motor and the results well demonstrate that the proposed scheme provides a good estimation value of the rotor speed without mechanical sensor. It is also shown that the actual rotor position as well as the machine speed can be achieved under the variation of the magnet flux linkage. Since the flux linkages are estimated by the adaptive flux observer and used for the identification of the rotor speed, robust estimation of the rotor speed can be performed.

I. Introduction

Advances in magnetic materials, semiconductor switching devices, and modern control theory continue to enhance the wide applications of the permanent magnet synchronous motor (PMSM) in industry. The desirable features of PMSM include compact structure, high airgap flux density, high power to inertia ratio, high torque to inertia ratio, and high torque capabilities[4]. The motor requires a rotor position sensor for starting and for providing the proper commutation sequence to turn on the power devices in the inverter bridge. The position sensors such as resolvers, absolute position encoders, and Hall sensors increase cost and size of motor. In some applications, it may not be possible to mount the sensors such as motor drives in a hostile environment or high speed motor drives. Due to these limitations of the motor operation with position sensors, sensorless operation of PMSM is receiving wide attention[2].

Since PM synchronous motor with sinusoidal flux distribution can be regarded as a resolver type rotational sensor, without any mechanical information about system inertia or load torque, the required rotor speed and angle information for proper machine drives can be obtained from only the back emf or stator flux linkage quantities[5].

In this study, a new method of estimating PMSM rotor speed is proposed. Based on a full order adaptive observer, the rotor speed is estimated and used as a feedback signal for the vector controlled inverter-PMSM drive. Since the flux linkages are estimated by the full state observer, the influence of parameter variation on the speed estimation can be removed by the proposed adaptive scheme. The effectiveness of the proposed scheme is shown through the computer simulation.

II. Adaptive Flux Observer and Sensorless Control

2.1 Modeling of PM Synchronous Motor and Flux Observer

The d, q equations of a PM synchronous machine in the rotor reference frame are as following [1]:

$$\frac{d}{dt}\begin{pmatrix} i_s \\ \lambda_s \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}\begin{pmatrix} i_s \\ \lambda_s \end{pmatrix} + \begin{pmatrix} B_1 \\ 0 \end{pmatrix} v_s$$
$$= Ax + Bv_s \qquad (2.1)$$
$$i_s = Cx$$

where

$i_s = \begin{pmatrix} i_{ds} & i_{qs} \end{pmatrix}^T$ stator current

$\lambda_s = \begin{pmatrix} \lambda_{ds} & \lambda_{qs} \end{pmatrix}^T$ stator flux linkage

$v_s = \begin{pmatrix} v_{ds} & v_{qs} \end{pmatrix}^T$ stator voltage

$$
\begin{aligned}
A_{11} &= (-r_s / L_s)I \qquad A_{12} = (-\omega_r / L_s)J \\
A_{21} &= 0 \qquad\qquad\quad\; A_{22} = \omega_r J \\
B_1 &= (1/L_s)I \\
C &= \begin{pmatrix} I & 0 \end{pmatrix} \\
I &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}
\end{aligned}
$$

r_s : stator resistance L_s : stator inductance

ω_r : rotor speed

The state observer, which estimates the stator current and the flux linkage, can be written as the following equation:

$$\frac{d}{dt}\hat{x} = \hat{A}\hat{x} + Bv_s + G(\hat{i}_s - i_s) \tag{2.2}$$

where ^ means the estimated values.(Fig. 2.2) $\hat{A}$ is the matrix in which ω_r is replaced by estimated rotor speed $\hat{\omega}_r$. G is the observer gain matrix. Other parameter values of $\hat{A}$ are assumed to be set as normal values. If the pole position of the observer is assigned as k times ($k \geq 1$) as that of the motor, G will be a function of the rotor speed, and the observer will be stable at any rotor speed[6]. The observer gain matrix is calculated by the following equation. As a result, the estimated states will converge to actual values in any rotor speed range.

$$G = \begin{pmatrix} g_1 I + g_2 J \\ g_3 I + g_4 J \end{pmatrix} = \begin{pmatrix} g_1 & g_2 & g_3 & g_4 \\ -g_2 & g_1 & -g_4 & g_3 \end{pmatrix}^T \tag{2.3}$$

where

$$
\begin{aligned}
g_1 &= (k-1)(-r_s / L_s) \\
g_2 &= (k-1)\hat{\omega}_r \\
g_3 &= -k(k-1)r_s \\
g_4 &= -(k-1)L_s\hat{\omega}_r
\end{aligned} \tag{2.4}
$$

2.2 Adaptive scheme for speed estimation

From (2.1) and (2.2), the estimation error of the stator current and flux linkage is described by the following equation.

$$
\begin{aligned}
\frac{d}{dt}e &= (A + GC)e + \Delta A\hat{x} \\
&= (A + GC)e - W
\end{aligned} \tag{2.5}
$$

where

$$
\begin{aligned}
e &= x - \hat{x} = \begin{pmatrix} e_{id} & e_{iq} & e_{\lambda d} & e_{\lambda q} \end{pmatrix}^T \\
\Delta A &= \begin{pmatrix} 0 & -\Delta\omega_r J / L_s \\ 0 & \Delta\omega_r J \end{pmatrix} \\
\Delta\omega_r &= \omega_r - \hat{\omega}_r
\end{aligned}
$$

and W is a nonlinear time-varying block and is defined as

$$W = -\Delta A \begin{pmatrix} \hat{i}_s & \hat{\lambda}_s \end{pmatrix}^T \tag{2.6}$$

According to (2.5), a MRAS representation of the system is shown in Fig. 2.3, which is constructed from a linear time invariant forward path transfer matrix and a nonlinear feedback block. $\Phi(e)$ is the identifying mechanism of rotor speed. The system is hyperstable if the forward path transfer matrix is strictly positive real, and the input and output of the nonlinear feedback block satisfies Popov's criterion of (2.7) [3]:

$$\int_0^{t0} e^T W dt \geq -\gamma^2, \quad \gamma = \text{const.} \tag{2.7}$$

It can be verified that the forward path transfer function transfer matrix $[sI - (A + GC)]^T$ is a strictly positive real[7]. For the nonlinear feedback block, following (2.7), there is an integral as follows:

$$
\begin{aligned}
\int_0^{t0} e^T W dt &= -\int_0^{t0} (e_i, e_\lambda) \begin{pmatrix} 0 & -\Delta\omega_r J / L_s \\ 0 & \Delta\omega_r J \end{pmatrix} \begin{pmatrix} \hat{i}_s \\ \hat{\lambda}_s \end{pmatrix} dt \\
&= -\int_0^{t0} (L_s + 1/L_s)\Delta\omega_r (e_i^T J\hat{\lambda}_s) dt
\end{aligned}
$$

To estimate the rotor speed, the following adaptive law is defined:

$$\hat{\omega}_r = \int_0^t \Phi(e) dt + \hat{\omega}_r(0) \tag{2.8}$$

where $\hat{\omega}_r(0)$ is the initial estimated value of rotor speed and $\Phi(e)$ is a nonlinear function of the state error which is determined in order that (2.8) satisfies the inequality (2.7) as follows:

$$-\int_0^{t0} (L_s + 1/L_s)\Delta\omega_r (e_i^T J\hat{\lambda}_s) dt \geq -\gamma^2 \tag{2.9}$$

This type of inequality can be solved with the following well-known relation:

$$\int_0^{t0} \{\frac{df(t)}{dt}\} kf(t) dt = \frac{k}{2}\{f^2(t_0) - f^2(0)\} \geq -\frac{1}{2}kf^2(0) \tag{2.10}$$

for $k > 0$. Using this inequality and letting $kf(t) = -(L_s + 1/L_s)\Delta\omega_r$ and $\frac{df(t)}{dt} = e_i^T J\hat{\lambda}_s$, the rotor speed can be estimated as follows:

$$
\begin{aligned}
\hat{\omega}_r &= k\int_0^t (L_s + 1/L_s)^{-1}(e_i^T J\hat{\lambda}_s) dt + \hat{\omega}_r(0) \\
&= k'\int_0^t (e_i^T J\hat{\lambda}_s) dt + \hat{\omega}_r(0)
\end{aligned} \tag{2.11}
$$

where the stator inductance L_s is assumed to be constant. To improve the transient response, the PI adaptation is generally adopted[6]. With the PI adaptation, (2.11) can be expressed as follows:

$$\hat{\omega}_r = (k_P + k_I / s)(e_{id}\hat{\lambda}_q - e_{iq}\hat{\lambda}_d) \quad (2.12)$$

where $1/s$ is the integral operator, and k_P, k_I are PI parameters of speed identifiers.

III. Computer Simulation Results

The overall block diagram of the proposed sensorless control system is shown in Fig. 3.1. The control system consists of the speed controller, current controller, PWM inverter, full state current observer and, speed estimator. IP speed controller and space vector PWM current controller is employed.

The parameters of PM synchronous motor used in simulation are given as follows:

Rated power : 120 [*W*]

Rated speed : 3000 [*rpm*]

Stator resistance (R_s) : 1.09 [Ω]

Stator inductance (L_s) : 2.1 [*mH*]

PM flux linkage : 0.17 [*Wb*]

Rotor inertia : 1.313×10^{-4} [$kg.m^2$]

Viscous friction : 8.75×10^{-4} [*N.m.sec*]

The step responses of the proposed sensorless algorithm is shown in Fig. 3.2 when the speed command is changed from +3000[rpm] to -3000[rpm] with 50% load. And, for the low speed case ±300[rpm], is shown in Fig. 3.3.

Fig. 3.4 shows the influence of parameter variation to the proposed scheme. In the figure, actual and estimated values of the rotor angle and speed quantities are displayed when the magnet flux linkage is changed to 90% of its nominal value. As shown in the figures, the estimation is not affected by the parameter variation.

IV. Conclusions

A new method of estimating the rotor speed of PM synchronous motor without position sensor is proposed. Based on a full order adaptive observer, the rotor speed is considered as a unknown parameter of the system matrix. The state equations of PM synchronous motor is used for a reference model and the full state flux observer is used for an adjustable model. The errors between the reference model and the adjustable model are used to drive the adaptive mechanism for identifying the rotor speed.

Computer simulations are carried out for the actual parameters of a PM synchronous motor and the results well demonstrate that the proposed scheme provides a good estimation value of the rotor speed without mechanical sensor. It is also shown that the actual rotor position as well as the machine speed can be achieved under the variation of the magnet flux linkage. Since the flux linkages are estimated by the adaptive flux observer and used for the identification of the rotor speed, robust estimation of the rotor speed can be performed.

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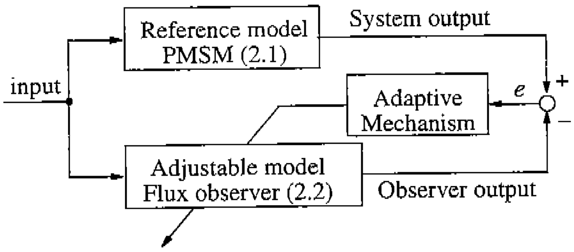

Fig. 2.1 Basic structure of model reference adaptive system

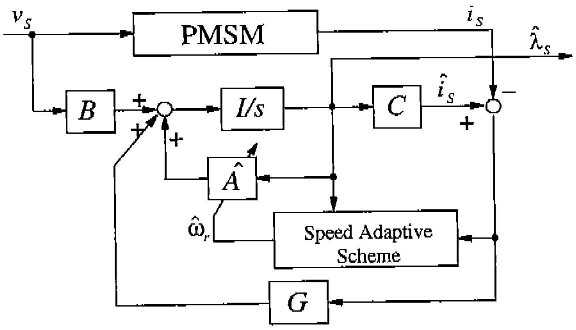

Fig. 2.2 Block diagram of speed adaptive observer

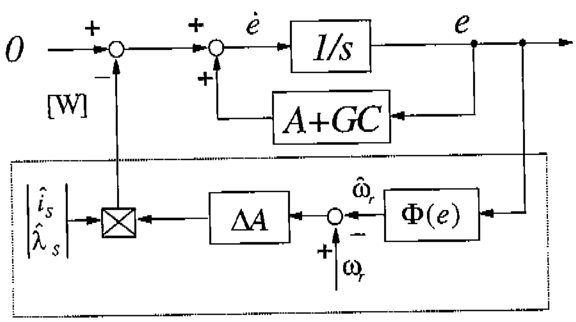

Fig. 2.3 MRAS representation of identifying the rotor speed

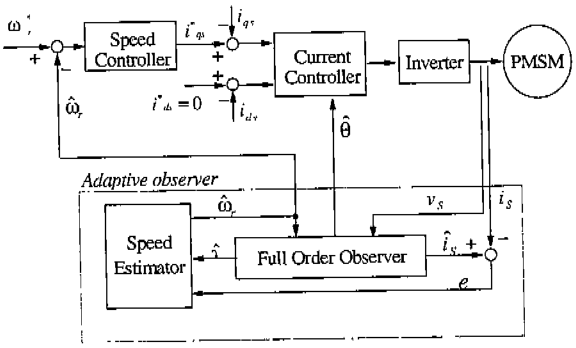

Fig. 3.1 Configuration of the vector-controlled speed sensorless control system

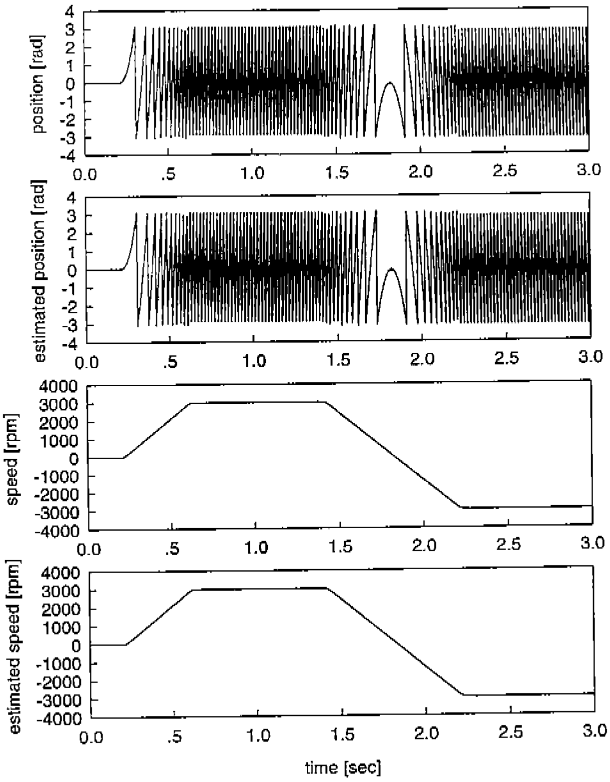

Fig. 3.2 Speed forward-reverse operation : high speed (from 3000 to -3000 rpm, 50% load)

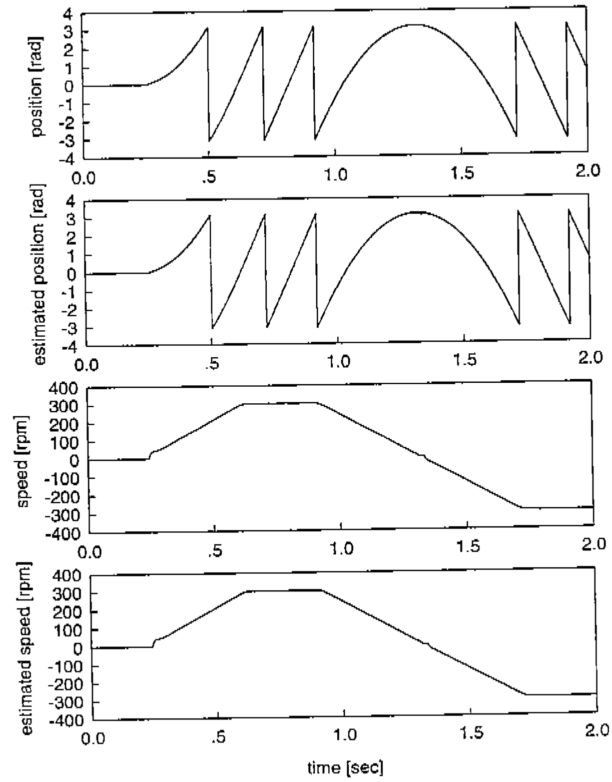

Fig. 3.3 Speed forward reverse operation : low speed (from 300 to -300 rpm, 50% load)

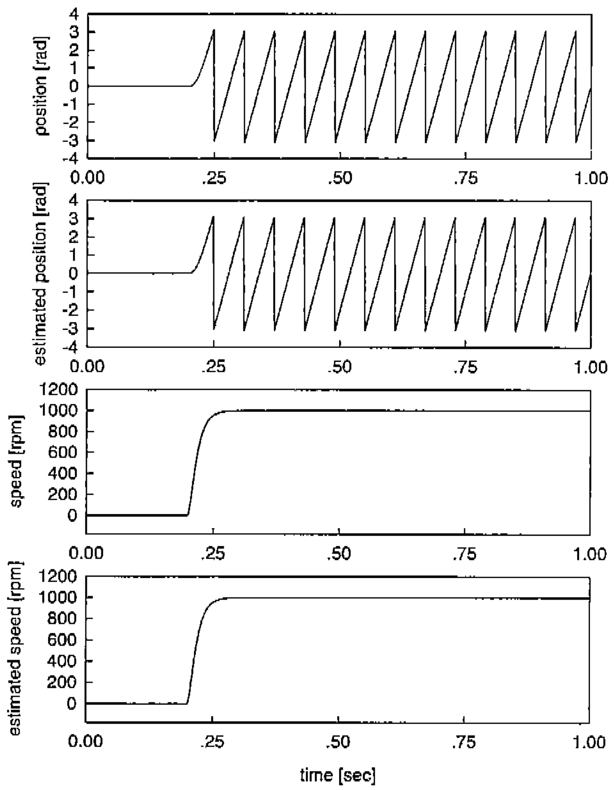

Fig. 3.4 Step speed response under parameter variation

(1000 rpm, 50% load, 90% of nominal flux)