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Speed Sensorless Vector Control for AC servo Motor Using Flux observer

Jeng-Pyo Hong† · Soon-Jae Kwon* · Soon-Ill Hong**

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Abstract : This study describes the scheme of vector drive system without speed sensor for AC servo motor using theory of a flux observer and based on the field oriented vector control. The new method of speed estimation is presented from operate with the position and magnitude of the secondary flux which obtain from the voltage reference and detected current.

As the estimated speed is settled by the flux and the machine-specific parameters, this method don't need to adjust the gain of the parameter.

Based on the derived theory for vector control, the scheme for sensorless vector drive of AC servo motor is designed and realized. And the experiment verifies it passable to realize the sensorless vector drive based on a field-oriented type.

Key words : Field oriented vector control, Method of speed estimation, Sensorless vector drive, AC servo motor

Description of Signs

$i_s = (i_{ds}\ i_{qs})^T$: Primary current ,

$\phi_r = (\phi_{dr}\ \phi_{qr})^T$: Rotor flux

$v_s = (v_{ds}\ v_{qs})^T$: Input voltage

The motor constants are as follows.

$$A_{11} = -[R_s / \rho L_s + \frac{1-\rho}{\rho \tau_r}]I$$

$$A_{12} = -1/\rho[(1/\tau_r)I - \omega_r J]$$

$$A_{21} = [M/\tau_r]I \qquad A_{22} = [-1/\tau_r]I + \omega_r J$$

$$B_1 = [1/\sigma L_s]I \qquad \tau_r = L_r / R_r$$

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma = 1 - M^2 / (L_s L_r)$$

s, r, d and q are the variables or parameters of the stator, the rotor, axis d and axis q. M and ω_r are mutual inductance and rotating angular velocity respectively.

† Corresponding Author(Graduate school of Division of Mechanical Engineering Pukyong University, Pusan Korea), E-mail : ds5cad@mail1.pknu.ac.kr, Tel : 051)620-1431

* Division of mechanical Engineering PuKyong University, Pusan Koera

** Division of Electrical & control Engineering Pukyong University, Pusan Korea

1. Introduction

In general, the vector control of an induction motor requires a speed sensor. Installation of a sensor makes the system large-sized and high-priced, and causes noises in the signal wire. Because of these problems, recently there are active researches on the vector control of induction motors without using a speed sensor[1, 2].

Induction motor driving technology requires simplicity, general usability, high performance of V/F control, and stability in low-speed rotation as well as speed sensorless vector control.

The speed sensorless vector control of an induction motor is to conduct vector control by estimating the speed based on information from the model formula of the motor and using the value in the vector control. Current speed estimation is using the Model Reference Adaptive System (MRAS), but this method has faults in that it requires the adjustment of the gain parameter because it estimates speed based on the state of vector control and the adjustment is not simple [3,4].

In vector control, it is relatively easy to realize slip frequency vector control, which obtains the phase of the secondary magnetic flux vector by integrating the calculated angular frequency of the power source and controls torque by performing coordinate changes. However, this method is highly sensitive to secondary resistance varying with heat produced by the driving of a motor, and cannot obtain desired control performance in case the set value of the secondary resistance is different from its real value.

The characteristic of this method is its low sensitivity to changes in the parameters of a motor. In addition, because it can detect secondary magnetic flux vector on the stator coordinate using the parameters of a motor it is not affected by changes in the parameters[5, 6].

The objective of the present research is to realize a speed sensorless AC motor driving system that is highly efficient and stable.

This study describes the scheme of vector drive system without the speed sensor using theory of a flux observer and based on the field oriented vector control. The new method of speed estimation is presented to operate with the position and magnitude of the secondary flux vector which obtain from the voltage reference and detected current.

As the estimated speed is settled by the flux and the machine-specific parameters, this method don't need to adjust the gain of the parameter.

Based on the derived theory for vector control, the scheme for sensorless vector drive is designed and realized. And the experiment verifies it passable to realize the sensorless vector drive based on a field-oriented type.

2. The theory of speed sensorless vector control

The principle of sensorless speed control of an induction motor is to control speed by estimating the speed using secondary magnetic flux obtained from a flux observer and the current detected by a current sensor and comparing it with a preset speed.

The primary current vector of a motor is disintegrated into exciting current vector and torque current vector on a $\gamma-\delta$ rotor coordinate system, and by that, the magnetic flux is maintained constant, and the two currents are independent DC.

If the direction of magnetic flux vector rotating at ω_0 coincides with axis γ, axis δ is taken as the phase advancing by $\pi/2$ and the phase angle between axis γ and d matching with the phase u of the stator coil is θ_0, then equation (1) is valid.

$$\theta_0 = \int \omega_0 dt \qquad (1)$$

On a $\gamma-\delta$ rotor coordinate, dynamic equation of AC motor is described as (2)

$$p\begin{pmatrix} i_{\gamma s} \\ i_{\delta s} \\ i_{\gamma r} \end{pmatrix} = \begin{bmatrix} -\frac{R_s}{\sigma L_s}-\frac{R_r(1-\sigma)}{\sigma L_r} & \omega_o & \frac{MR_r}{\sigma L_s L_r^2} \\ -\omega_0 & -\frac{R_s}{\sigma L_s}-\frac{R_r(1-\sigma)}{\sigma L_r} & -\frac{\omega_r M}{\sigma L_s L_r} \\ \frac{MR_r}{L_r} & 0 & -\frac{R_r}{L_r} \end{bmatrix} \begin{pmatrix} i_{\gamma s} \\ i_{\delta s} \\ \phi_{\gamma r} \end{pmatrix} + \frac{1}{\sigma L_s}\begin{pmatrix} v_{\gamma s} \\ v_{\delta s} \\ 0 \end{pmatrix} \qquad (2)$$

And source angular velocity is equation (3)

$$\omega_0 = \omega_r + \frac{MR_r}{\phi_{\gamma r} L_r} i_{\delta s} \qquad (3)$$

2.1 Rotor flux observer

In the state equation of the d-q coordinate system of an induction motor, the secondary magnetic flux was observed using same dimensional observer G, and the error between the real current of the stator and the estimated current represented as a feedback loop, which is equation (4).

$$\frac{d}{dt}\begin{pmatrix} \hat{i}_s \\ \hat{\phi}_r \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}\begin{pmatrix} \hat{i}_s \\ \hat{\phi}_r \end{pmatrix} + \begin{pmatrix} B_1 \\ 0 \end{pmatrix} v_s^* + G(\hat{i}_s - i_s) \qquad (4)$$

where $G=(G_1 G_2)^T$ is the observer gain, * is the command value, and, ∧ is the estimate of the state variable.

If the observer pole is arranged by adjusting the gain $(G_1 G_2)^T$ so that it seems to move in response to the rotation speed ω_r of the induction motor, the estimated speed can quickly converge into the rotation speed [6].

$$G_1 = g_1 I + g_2 I \quad G_2 = g_3 I + g_4 J \qquad (5)$$

Here is $g_1 = (k-1)(-\frac{R_s}{\rho L_s} - \frac{1-\rho}{\rho \tau_r} - \frac{1}{\tau_r})$,

$g_2 = (k-1)\omega_r$,

$g_3 = (k^2-1)(\frac{M}{\tau_r} + \rho[\frac{R_s}{\rho L_s} + \frac{1-\rho}{\rho \tau_r}]) + \rho g_1$ and $g_4 = \rho g_2$.

If the gain of the observer is taken as equation (5), the pole-placement of the observer is k times as large as the part of real values of the induction motor, and the estimate converges into the real number more quickly and accurately.

The magnitude and phase of estimated $\hat{\phi}_r$ obtained using the observer can be determined with equation (6) and (7).

$$\left|\hat{\phi}_r\right| = \sqrt{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2} \qquad (6)$$

$$\cos\hat{\theta}_0 = \frac{\hat{\phi}_{dr}}{\sqrt{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2}}, \quad \sin\hat{\theta}_0 = \frac{\hat{\phi}_{qr}}{\sqrt{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2}} \qquad (7)$$

Decoupled compensation : On a $\gamma-\delta$ rotor coordinate, motor model equation (2) yields the coupling components of $\omega_0 \sigma L_s$ and $\omega_0 \phi_{\gamma s}$. Those are compensated with equation (8) and (9).

$$v_{\gamma s} = v'_{\gamma s} - \omega_0 \sigma L_s i_{\delta s} \tag{8}$$

$$v_{\delta s} = v'_{\delta s} + \omega_0 \phi_{\gamma s} \tag{9}$$

Vector control is to maintain magnetic current $i_{\gamma s}$ constant. Because there is no magnetic flux when electricity is switched on, the rising time of magnetic flux after the power is turned on is delayed. PI controller as shown in equation (10) performs to reduce the discrepancy between command $|\phi_r|^*$ and estimated $\hat{\phi}_r$ to determine the exciting current command $i^*_{\gamma s}$.

$$i^*_{\gamma s} = K_{p\phi}(|\phi_r|^* - |\hat{\phi}_r|) + K_{i\phi}\int(|\phi_r|^* - |\hat{\phi}_r|)dt \tag{10}$$

$K_{p\phi}, K_{i\phi}$: Magnetic flux feedback gain

2.2 The method of speed estimation

The rotational speed of an induction motor is estimated with the concept of slip angular velocity using the observable property of $\hat{\phi}_r$. Source angular frequency $\hat{\omega}_0$ can be derived from $(\hat{\phi}_{dr}\hat{\phi}_{qr})^T$ and the differentiated flux $(\dot{\hat{\phi}}_{dr}\dot{\hat{\phi}}_{qr})^T$ as in equation (11).

$$\hat{\omega}_0 = \frac{d}{dt}\tan^{-1}\frac{\hat{\phi}_{qr}}{\hat{\phi}_{dr}} = \frac{\dot{\hat{\phi}}_{qr}\hat{\phi}_{dr} - \dot{\hat{\phi}}_{dr}\hat{\phi}_{qr}}{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2} \tag{11}$$

In addition, because the slip angular velocity $\hat{\omega}_s$ is proportional to the generated torque $\hat{T}$, it can be found with equation (12).

$$\hat{\omega}_s = \frac{R_r}{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2}\frac{M}{L_r}(\hat{\phi}_{dr} i_{qs} - \hat{\phi}_{qr} i_{ds}) \tag{12}$$

Accordingly, the estimated $\hat{\omega}_r$ is obtained from equation (13).

$$\hat{\omega}_r = \frac{\dot{\hat{\phi}}_{qr}\hat{\phi}_{dr} - \dot{\hat{\phi}}_{dr}\hat{\phi}_{qr}}{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2} - \frac{R_r M}{L_r}\frac{\hat{\phi}_{dr} i_{qs} - \hat{\phi}_{qr} i_{ds}}{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2} \tag{13}$$

The real current detected with a current sensor is converted by the coordinate transformation into the primary current $(i_{\gamma s} i_{\delta s})^T$ on the axis of rotational magnetic flux, and feedback control is performed as Equation (14) and (15).

$$v'_{\gamma s} = R_s i^*_{\gamma s} + K_{\gamma s}(i^*_{\gamma s} - i_{\gamma s}) \tag{14}$$

$$v'_{\delta s} = R_s i^*_{\delta s} + K_{\delta s}(i^*_{\delta s} - i_{\delta s}) \tag{15}$$

$K_{\gamma s}, K_{\delta s}$: Current feedback gain

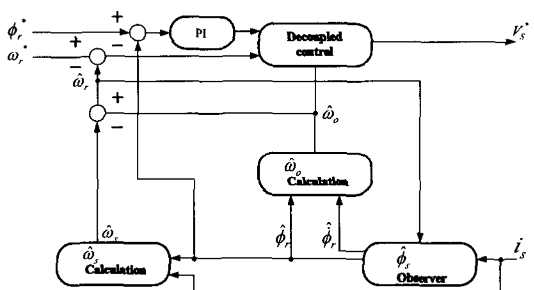

Fig. 1 Proposed algorithm for speed sensorless vector control

Fig. 1 shows the proposed speed sensorless vector control algorithm which is derived using a flux observer and primary current. The estimated speed in equation (13) requires the estimation of the rotor flux and the detected primary current. Only associated with the motor constants, the estimated speed does not require gain control.

3. Simulation and experimental results

A hardware block diagram of sensorless vector drive system of DSP, DAC, ADC, voltage source inverter and DC power boards are shown in Fig. 2. For an experiment, ϕ_r^* is set externally and i_d, i_q obtained from current sensors are entered into DSP. Estimated speed ω_r^* is calculated in DSP with the detected primary current and the rotor flux obtained from a flux observer.

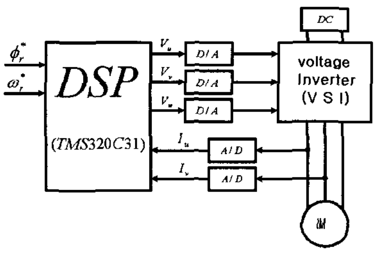

Fig. 2 DSP based induction motor Sensorless vector drive system.

The PWM carrier is 3[kHz] and the sampling period is 50[μs]. Initially magnetic flux is excited in advance before operation, and the state variables of the flux observer are set to initial values. The motor constants used in the experiment and the control gains obtained from the rule of trial and error are shown in Table 1 and 2.

Table 1 Constants of motor.

R_s	R_r	L_s	L_r	M
5.86[Ω]	5.30[Ω]	0.146[Ω]	0.164[Ω]	0.134[Ω]

$D = 1.31.\times 10^5 [Nms]$

$J = 7.546 \times 10^{-5} [Nms^2]$

Table 2 Gains of controller.

K_p	K_i	K_{pq}	$K_{i\phi}$	$K\gamma s$	$K_{\delta s}$
0.1	0.01	5	50	20	20

In the experiment, ω_r^* is 1200[rpm], $\phi_r^* = 0.145[Wb]$, $i_{\gamma s}^*$ is 1[A], and the limit of torque current command $i_{\delta s}^*$ ± is 1[A].

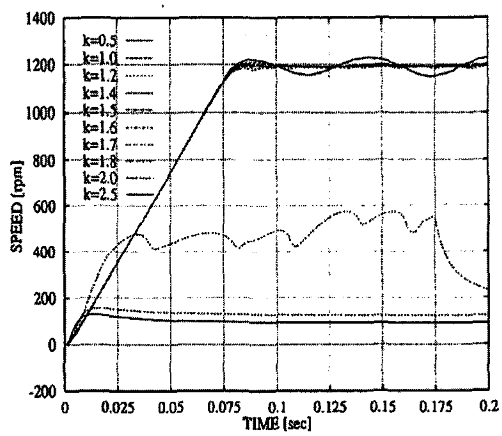

Fig. 3 Speed response as parameter with k = 0.5 ~ 2.5.

Fig. 3 is the result of a simulation of speed response when k on the poles of the flux observer varies between 0.5 ~ 2.5. The result shows that while k is between 1.2 ~ 1.6 the speed response is stable though slightly changing, but out of the range it fluctuates intensely or does not reach the preset speed. Within the range of k between 1.2 ~ 1.6, both

1.5 and 1.6 are considered most stable.

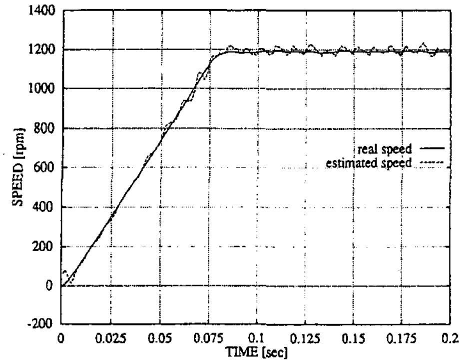

Fig. 4 Response of real speed and estimated speed.

Fig. 4 shows the real speed and estimated speed in the simulation when k = 1.5. The estimated speed generates errors within a specific range but it gives a reasonable estimate of the real speed and the real speed is quite stable. This result suggests that the system in Fig. 1 that utilizes the proposed speed estimation method is practicable.

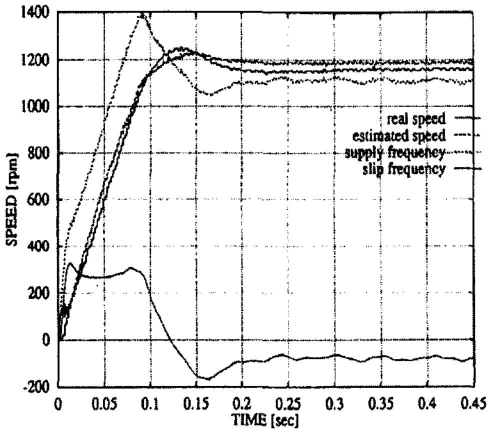

Fig. 5 Experimental results

Fig. 5 is the experimental result of an experiment of sensorless vector control under the condition that the proportional factor of the gain of the flux observer, k = 1.5 and the proportional gain of each controller is the same as that in the above simulation. The result shows that the estimated speed is a bit vibrating but coincides nearly with the real value measured, and the real value is satisfactory in a normal state.

4. Conclusions

The present research realized a magnetic field orientation-typed sensorless-vector control system by applying the theory of a flux observer to an induction motor. This study proposed a new speed estimation method using the state variables of rotor flux obtained with a observer and the state variables of current detected with a current sensor and without using a speed sensor. Different from MRAS method, the proposed speed estimation method does not require the gain control of parameters and has a simple algorithm because the parameters of the motor are independent. It was verified through experiments that speed response was most stable when the gain proportional factor k of a secondary magnetic flux observer designed for speed estimation was 1.5, and the control performance was adequate.

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