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A New Flux Observer Based Vector Control in Induction Motors

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ABSTRACT A new flux observer based vector control system of an induction motor is constructed by using an observer in which the commanded stator currents are used to estimate the rotor flux. In this system, the flux observer is formulated by using a model of induction motor in a stationary co-ordinate system. By considering an observer of induction motor in a fixed co-ordinate system located on its secondary flux, a slip frequency controlled type of vector control system is also proposed. From these control schemes, the relation between the conventional slip frequency controlled type system and the observer based one is clarified. The steady-state error of the developed torque which is caused by the parameter change of induction motor is analyzed and discussed for the selection of observer gains. The poles of the observer error dynamics and those of the observer based vector control system are calculated analytically by neglecting the machine parameter change. In order to analyze the robust stability, a linear model of the observer based vector control system is proposed taking into account the machine parameter change. By using this model, the trajectories of the poles and zeros of the torque transfer function are computed and discussed. To test validity of the theoretical analysis, experiments are conducted by using a digital signal processor (TMS320C30) and a current controlled voltage source PWM inverter.

1. Introduction

Vector control (field oriented control) has made it possible to control the instantaneous torque of an induction motor and is widely used in various industrial areas. Vector control transforms the induction motor into a system that has the characteristics of a separately excited DC motor. To achieve the vector control, it is indispensable to know the exact value of the rotor flux. As the rotor flux can not be directly measured, a number of flux estimation methods has been proposed by using various kinds of observers [1]- [5]. However, the flux observer is not considered explicitly in the conventional slip frequency controlled type of vector control system. The vector control will be classified into two types according to a selection of the co-ordinate system for the model of the induction motor. A synchronously rotating co-ordinate system is used for the well-known slip frequency controlled type of vector control. On the other hand, a stationary co-ordinate system is used for the flux observer based vector control. Because of the use of the different co-ordinate systems, the theoretical relations between two control methods are not evident. In this paper, new flux observers based vector control systems are proposed by using the models of the induction motor described by not only a stationary co-ordinate system but a synchronously rotating one. From these control schemes, the relation between the conventional slip frequency controlled type system and the observer based one is clarified. The robustness against the parameter change of the proposed systems is discussed theoretically and experimentally by comparing the proposed system with the conventional slip frequency controlled one.

2. Vector control systems

2.1 Flux simulator based vector control

In this paper, it is assumed that the stator current can be controlled instantaneously and it is kept exactly equal to the reference value. A vector control system using a current model of the induction motor in a stationary co-ordinate system is proposed as shown in Fig. 1. In this figure, the current model is expressed as

$$p\begin{bmatrix} \psi_{r\alpha}^{'*} \\ \psi_{r\beta}^{'*} \end{bmatrix} = \begin{bmatrix} -\sigma_r^* & -\omega_r \\ \omega_r & -\sigma_r^* \end{bmatrix} \begin{bmatrix} \psi_{r\alpha}^{'*} \\ \psi_{r\beta}^{'*} \end{bmatrix} + \sigma_r^* M^{'*} \begin{bmatrix} i_{s\alpha}^* \\ i_{s\alpha}^* \end{bmatrix} \tag{1}$$

$$\theta^* = \tan^{-1}(\psi_{r\alpha}^{'*} / \psi_{r\beta}^{'*}) \tag{2}$$

In this system, the rotor flux is obtained by a real-time simulation of (1). When we consider a d-q co-ordinate system rotating synchronously with θ^* in (2), q-axis rotor flux $\psi_{rq}^{'*} = 0$, then the equation (1) is transformed as follows:

$$p\, \psi_{rd}^{'*} = -\sigma_r^* \psi_{rd}^{'*} + \sigma_r^* M^{'*} i_{sd}^* \tag{3}$$

$$\omega^* = \omega_r + \sigma_r^* M^{'*} i_{sq}^* / \psi_{rd}^{'*} \tag{4}$$

where, $\omega^* = p\,\theta^*$. From (3) and (4), we can get the conventional slip frequency controlled type of vector control system. The system of Fig.1 is equivalent to that of Fig.2.

2.2 Flux observer based vector control

A state observer theory which constructs the state form the measured input and output is applied to the torque control of induction motor. In this case, the rotor flux must be estimated. The voltage model of the induction motor in a stationary co-ordinate system is expressed by

$$\begin{bmatrix} e_{s\alpha}^* \\ e_{s\beta}^* \end{bmatrix} = (r_s^* + \sigma^* L_s^* p) \begin{bmatrix} i_{s\alpha}^* \\ i_{s\alpha}^* \end{bmatrix} + \frac{M^{'*}}{L_r^{'*}} p \begin{bmatrix} \psi_{r\alpha}^{'*} \\ \psi_{r\beta}^{'*} \end{bmatrix} \tag{5}$$

Substituting (1) in (5), the voltage model is rewritten as

$$\begin{bmatrix} e_{s\alpha}^* \\ e_{s\beta}^* \end{bmatrix} = (r_s^* + \frac{\sigma_r^* M^{'*2}}{L_r^{'*}} + \sigma^* L_s^* p) \begin{bmatrix} i_{s\alpha}^* \\ i_{s\alpha}^* \end{bmatrix} + \frac{M^{'*}}{L_r^{'*}} \begin{bmatrix} -\sigma_r^* & -\omega_r \\ \omega_r & -\sigma_r^* \end{bmatrix} \begin{bmatrix} \psi_{r\alpha}^{'*} \\ \psi_{r\beta}^{'*} \end{bmatrix} \tag{6}$$

By considering (6) as an output equation, a reduced order observer for the rotor flux estimation is obtained as

$$p\begin{bmatrix} \psi_{r\alpha}^{'*} \\ \psi_{r\beta}^{'*} \end{bmatrix} = \begin{bmatrix} -\sigma_r^* & -\omega_r \\ \omega_r & -\sigma_r^* \end{bmatrix} \begin{bmatrix} \psi_{r\alpha}^{'*} \\ \psi_{r\beta}^{'*} \end{bmatrix} + \sigma_r^* M^{'*} \begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} + K \begin{bmatrix} e_{s\alpha}^* - e_{s\alpha} \\ e_{s\beta}^* - e_{s\beta} \end{bmatrix} \tag{7}$$

where, $e_{s\alpha}$ and $e_{s\beta}$ are measured stator voltages. The observer gain K is assumed to have the following structure:

$$K = \begin{bmatrix} K_1 & -K_2 \\ K_2 & K_1 \end{bmatrix} \tag{8}$$

The block diagram of the proposed rotor flux observer is shown in Fig. 3. In this system, the commanded stator currents are used to estimate the rotor flux because of a noise reduction and easier computation at the start of the vector control algorithm. The observer based vector control system in a stationary co-ordinate system is proposed in Fig.4. When we consider a d-q co-ordinate system rotating synchronously with θ^*, q-axis rotor flux $\psi_{rq}^{\prime *} = 0$, then (6) is transformed as follows:

$$\begin{bmatrix} e_{sd}^* \\ e_{sq}^* \end{bmatrix} = \begin{bmatrix} r_s^* + \sigma_r^* M^{\prime *2} / L_r^{\prime *} + \sigma^* L_s^* p & -\omega^* \sigma^* L_s^* \\ \omega^* \sigma^* L_s^* & r_s^* + \sigma_r^* M^{\prime *2} / L_r^{\prime *} + \sigma^* L_s^* p \end{bmatrix} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} + \frac{M^{\prime *}}{L_r^{\prime *}} \begin{bmatrix} -\sigma_r^* \\ \omega_r \end{bmatrix} \psi_{rd}^{\prime *} \qquad (9)$$

and (7) is transformed as follows:

$$p\,\psi_{rd}^{\prime *} = -\sigma_r^* \psi_{rd}^{\prime *} + \sigma_r^* M^{\prime *} i_{sd}^* + K_1 (e_{sd}^* - e_{sd}) - K_2 (e_{sq}^* - e_{sq}) \qquad (10)$$

$$\omega^* = \omega_r + \sigma_r^* M^{\prime *} i_{sq}^* / \psi_{rd}^{\prime *} + K_2 (e_{sd}^* - e_{sd}) / \psi_{rd}^{\prime *} + K_1 (e_{sq}^* - e_{sq}) / \psi_{rd}^{\prime *} \qquad (11)$$

From (9) - (11), the observer based vector control system in a synchronously rotating co-ordinate system is proposed in Fig. 5. By comparing Fig. 2 with Fig. 5, it is found that the difference between the conventional vector control and the observer based one is caused by the prediction error term. If the observer gain K is zero, Fig. 5 is the same system as Fig. 2.

3. Analysis

3.1 Pole assignment

To derive the error dynamics of the observer shown in Fig. 3, it is assumed that the stator current is kept exactly equal to the reference value and the parameters of induction motor are identified accurately.

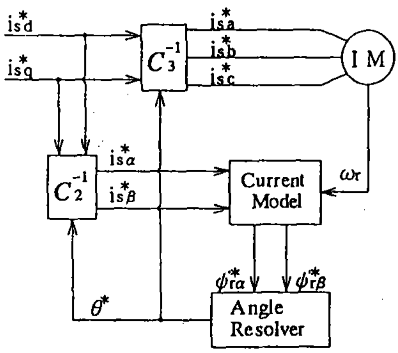


Fig.1 A vector control system (stationary co-ordinate system).

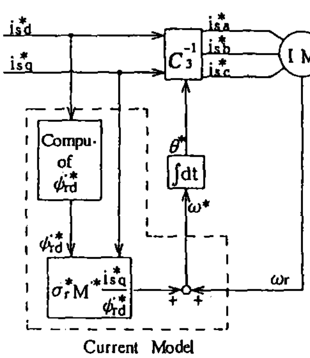


Fig.2 Conventional vector control system (rotating co-ordinate system).

From the voltage and current models of induction motor in a stationary co-ordinate system and (6) and (7), the error dynamics of the observer are

$$p \begin{bmatrix} \psi_{r\alpha}^{\prime *} - \psi_{r\alpha}^{\prime} \\ \psi_{r\beta}^{\prime *} - \psi_{r\beta}^{\prime} \end{bmatrix} = \begin{bmatrix} -\sigma_r & -\omega_r \\ \omega_r & -\sigma_r \end{bmatrix} \begin{bmatrix} \psi_{r\alpha}^{\prime *} - \psi_{r\alpha}^{\prime} \\ \psi_{r\beta}^{\prime *} - \psi_{r\beta}^{\prime} \end{bmatrix} + \begin{bmatrix} K_1 & -K_2 \\ K_2 & K_1 \end{bmatrix} \frac{M^{\prime *}}{L_r^{\prime *}} \begin{bmatrix} -\sigma_r & -\omega_r \\ \omega_r & -\sigma_r \end{bmatrix} \begin{bmatrix} \psi_{r\alpha}^{\prime *} - \psi_{r\alpha}^{\prime} \\ \psi_{r\beta}^{\prime *} - \psi_{r\beta}^{\prime} \end{bmatrix} \qquad (12)$$

If the rotor speed ω_r is constant, the error system (12) is a time-

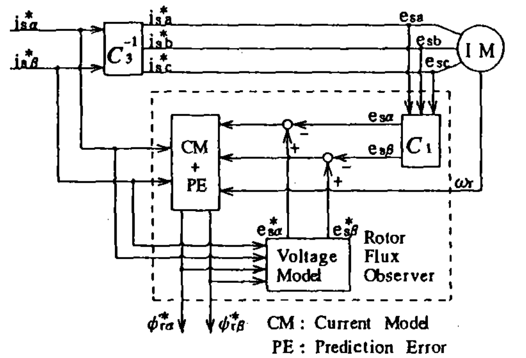


Fig.3 A flux observer of induction motor (stationary co-ordinate system).

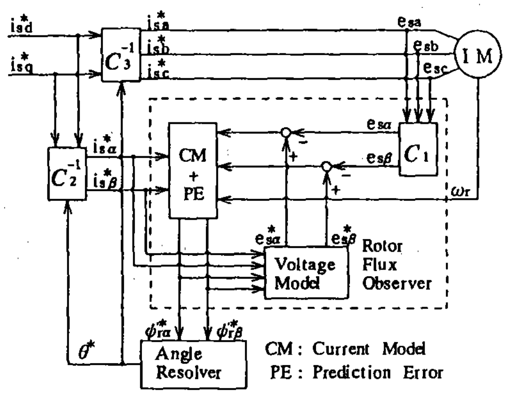


Fig.4 A observer based vector control system (stationary co-ordinate system) .

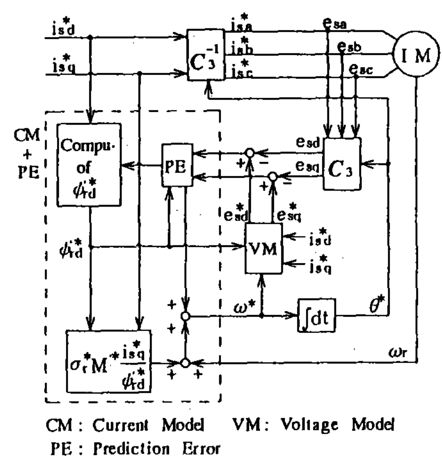


Fig.5 A observer based vector control system (rotating co-ordinate system) .

invariant linear system. The governing eigenvalues are computed to be

$$\lambda = -\left(\sigma_r + K_1 \frac{M'}{L'_r}\sigma_r + K_2 \frac{M'}{L'_r}\omega_r\right) \pm j\left(\omega_r - K_2 \frac{M'}{L'_r}\sigma_r + K_1 \frac{M'}{L'_r}\omega_r\right) \qquad (13)$$

When we assign the allocation of the eigenvalues to be

$$\lambda = -\alpha \pm j\beta , \qquad (14)$$

the observer gains are designed as

$$K_1 = \frac{L'_r}{M'}\left(\frac{\sigma_r \alpha + \omega_r \beta}{\sigma_r^2 + \omega_r^2} - 1\right) \qquad (15)$$

$$K_2 = \frac{L'_r}{M'}\,\frac{\omega_r \alpha - \sigma_r \beta}{\sigma_r^2 + \omega_r^2} \qquad (16)$$

However, the flux observer is used for the construction of the vector control system shown in Figs. 4 and 5. Therefore, it is more important to derive the error dynamics of these systems. When we consider a d-q co-ordinate system rotating synchronously with θ^*, the voltage and current models of induction motor are expressed as

$$p\begin{bmatrix}\psi'_{rd}\\ \psi'_{rq}\end{bmatrix} = \begin{bmatrix}-\sigma_r & \omega^* - \omega_r\\ \omega_r - \omega^* & -\sigma_r\end{bmatrix}\begin{bmatrix}\psi'_{rd}\\ \psi'_{rq}\end{bmatrix} + \sigma_r M'\begin{bmatrix}i_{sd}\\ i_{sq}\end{bmatrix} \qquad (17)$$

$$\begin{bmatrix}e_{sd}\\ e_{sq}\end{bmatrix} = \begin{bmatrix} r_s + \sigma_r M'^2/L'_r + \sigma L_s p & -\omega^* \sigma L_s\\ \omega^* \sigma L_s & r_s + \sigma_r M'^2/L'_r + \sigma L_s p\end{bmatrix}\begin{bmatrix}i_{sd}\\ i_{sq}\end{bmatrix} + \frac{M'}{L'_r}\begin{bmatrix}-\sigma_r & -\omega_r\\ \omega_r & -\sigma_r\end{bmatrix}\begin{bmatrix}\psi'_{rd}\\ \psi'_{rq}\end{bmatrix} \qquad (18)$$

Under the assumption of ideal current control, we can get $i^*_{sd} = i_{sd}$ and $i^*_{sq} = i_{sq}$ by considering the current transformation shown in Figs. 4 and 5. From (9) - (11), (17) and (18), the error dynamics of the vector control system are

$$p\begin{bmatrix}\psi'^*_{rd} - \psi'_{rd}\\ -\psi'_{rq}\end{bmatrix} = \begin{bmatrix}-\sigma_r & \omega^* - \omega_r\\ \omega_r - \omega^* & -\sigma_r\end{bmatrix}\begin{bmatrix}\psi'^*_{rd} - \psi'_{rd}\\ -\psi'_{rq}\end{bmatrix} + \begin{bmatrix}K_1 & -K_2\\ K_2 & K_1\end{bmatrix}\frac{M'}{L'_r}\begin{bmatrix}-\sigma_r & -\omega_r\\ \omega_r & -\sigma_r\end{bmatrix}\begin{bmatrix}\psi'^*_{rd} - \psi'_{rd}\\ -\psi'_{rq}\end{bmatrix} \qquad (19)$$

If ω_r and ω^* are constant, the eigenvalues are computed to be

$$\lambda = -\left(\sigma_r + K_1 \frac{M'}{L'_r}\sigma_r + K_2 \frac{M'}{L'_r}\omega_r\right) \pm j\left(\omega^* - \omega_r + K_2 \frac{M'}{L'_r}\sigma_r - K_1 \frac{M'}{L'_r}\omega_r\right) \qquad (20)$$

When we assign the allocation of the eigenvalues to be

$$\lambda = -\alpha \pm j(\omega^* - \beta) , \qquad (21)$$

the observer gains are given by (15) and (16).

3.2 Steady-state and stability analysis

This section is devoted to analyze the systems shown in Figs.4 and 5 for studying the effects of stator and rotor resistances variations.

System description To analyze the system, we make the following assumptions:

(1) The stator current is controlled exactly equal to the reference value.

(2) The rotor speed ω_r is constant.

(3) The parameters of induction motor are identified accurately except for stator and rotor resistances.

Taking the d-q axis rotating synchronously with θ^*, the induction motor is represented by (17) and (18). Under the above assumptions, following equations are obtained from (9) and (18).

$$e^*_{sd} - e_{sd} = b\, i^*_{sd} - a(\sigma^*_r \psi'^*_{rd} - \sigma_r \psi'_{rd} - \omega_r \psi'_{rq}) \qquad (22)$$

$$e^*_{sq} - e_{sq} = b\, i^*_{sq} + a(\omega_r \psi'^*_{rd} - \omega_r \psi'_{rd} + \sigma_r \psi'_{rq}) \qquad (23)$$

where, $a = M'/L'_r$, $b = r^*_s - r_s + (M'^2/L'_r)(\sigma^*_r - \sigma_r)$

The system can be described by (10),(11),(17),(22) and (23).

Steady-state analysis Letting $p = 0$ in (10) and (17), the steady-state solutions are obtained by

$$\begin{bmatrix}\sigma^*_r + a(K_1\sigma^*_r + K_2\omega_r) & -a(K_1\sigma_r + K_2\omega_r) & a(K_2\sigma_r - K_1\omega_r) & K_2 b\\ 0 & \sigma_r & \omega_r - \omega^* & 0\\ 0 & \omega^* - \omega_r & \sigma_r & -\sigma_r M'\\ \omega^* - \omega_r + a(K_2\sigma^*_r - K_1\omega_r) & a(K_1\omega_r - K_2\sigma_r) & a(-K_1\sigma_r - K_2\omega_r) & -\sigma^*_r M' - K_1 b\end{bmatrix}\begin{bmatrix}\psi'^*_{rd}\\ \psi'_{rd}\\ \psi'_{rq}\\ i^*_{sq}\end{bmatrix} = \begin{bmatrix}\sigma^*_r M' + K_1 b\\ \sigma_r M'\\ 0\\ K_2 b\end{bmatrix} i^*_{sd} \qquad (24)$$

Linear model Considering the small variations around the steady-state operating point and assuming that ω_r and i^*_{sd} are constant, we obtain the state equation from (10) and (17) such that

$$p\,\Delta x = A_1 \Delta x + B_1 \Delta u + B_2 \Delta u_2 \qquad (25)$$

where, $\Delta x = \left[\Delta\psi'^*_{rd}, \Delta\psi'_{rd}, \Delta\psi'_{rq}\right]^T$, $\Delta u = \left[\Delta i^*_{sq}\right]$

$$\Delta u_2 = \left[\Delta\omega^*, \Delta e^*_{sd} - \Delta e_{sd}, \Delta e^*_{sq} - \Delta e_{sq}\right]^T$$

$$A_1 = \begin{bmatrix}-\sigma^*_r & 0 & 0\\ 0 & -\sigma_r & \omega^* - \omega_r\\ 0 & \omega_r - \omega^* & -\sigma_r\end{bmatrix}$$

$$B_1 = \begin{bmatrix}0\\ 0\\ \sigma_r M'\end{bmatrix}, \quad B_2 = \begin{bmatrix}0 & K_1 & K_2\\ \psi'_{rq} & 0 & 0\\ -\psi'_{rd} & 0 & 0\end{bmatrix}$$

From (11), (22) and (23), the input vector Δu_2 is expressed by

$$\Delta u_2 = U_x \Delta x + U_u \Delta u \qquad (26)$$

where,

$$U_x = \begin{bmatrix} c & a(K_2\sigma_r - K_1\omega_r)/\psi'^*_{rd} & a(K_2\omega_r + K_1\sigma_r)/\psi'^*_{rd}\\ -a\sigma^*_r & a\sigma_r & a\omega_r\\ a\omega_r & -a\omega_r & a\sigma_r\end{bmatrix}$$

$$U_u = \begin{bmatrix} \sigma_r^* M' / \psi_{rd}^{**} + K_1 b / \psi_{rd}^{**} \\ 0 \\ b \end{bmatrix}$$

$$c = a\,(-K_2 \sigma_r^* + K_1 \omega_r) / \psi_{rd}^{**} + (\omega_r - \omega^*) / \psi_{rd}^{**}$$

Equations (25) and (26) give the linear model of observer based vector control system such that

$$p\,\Delta x = (A_1 + B_2\,U_x)\,\Delta x + (B_1 + B_2\,U_u)\,\Delta u \qquad (27)$$

The poles and zeros of transfer function can be calculated using (27) and output equation. The transformation of (27) to a sampled data system also makes it possible to calculate the transient responses in a much shorter time than the direct numerical integration of nonlinear equations.

4. Computed results

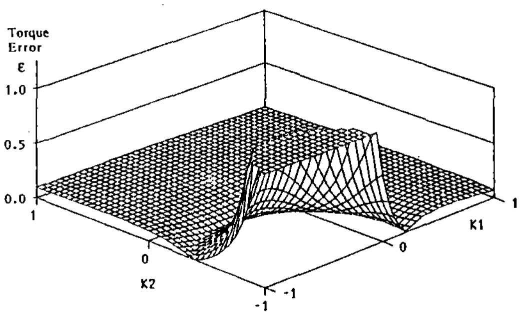
The induction machine used for this study is a 220V, 4 pole, 2.2 kW machine having the following nominal parameters: r_s = 0.662Ω, r_r' =0.645Ω, $L_s = L_r'$ =0.086H, M' = 0.082H. The moment of inertia J is 0.0617kg-m^2 including that of load. The exciting current command i_{sd}^* is fixed at 3.2A.

The steady-state error ε of torque defined by following equation is shown in Figs. 6 and 7 for the rotor speed N =200rpm and N =1000rpm respectively.

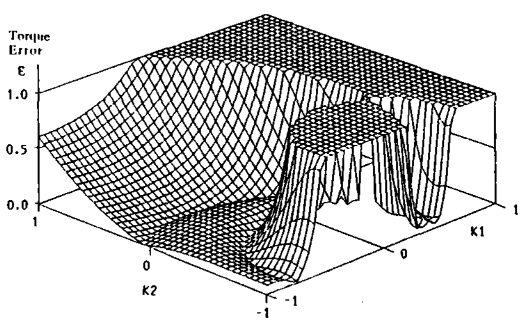
$$\varepsilon = \left| T_e - T_e^* \right| / T_e^* \qquad (28)$$

where, $T_e^* = PM'^2 i_{sd}^* i_{sq}^* / (2 L_r')$.

When the value of ε is larger than 1, the value is plotted at 1 in those

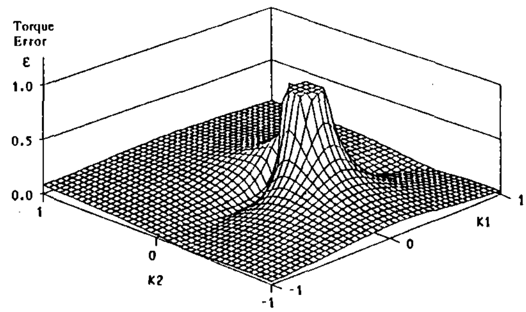


(a) N = 20rpm, s = 0.7, $r_s / r_s^* = r_r' / r_r^{**}$ = 0.8

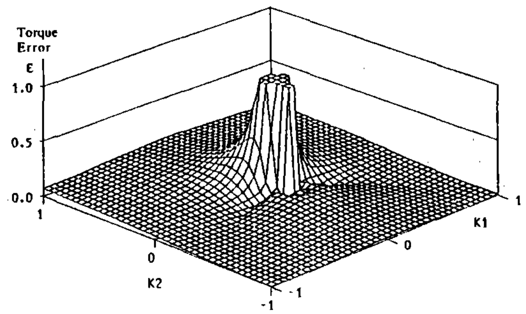


(b) N = 20rpm, s = 0.7, $r_s / r_s^* = r_r' / r_r^{**}$ = 2.0

Fig.6 Steady-state error of torque.



(a) N = 1000rpm, s = 0.1, $r_s / r_s^* = r_r / r_r^{**}$ = 0.8



(b) N = 1000rpm, s = 0.1, $r_s / r_s^* = r_r' / r_r^{**}$ = 2.0

Fig.7 Steady-state error of torque.

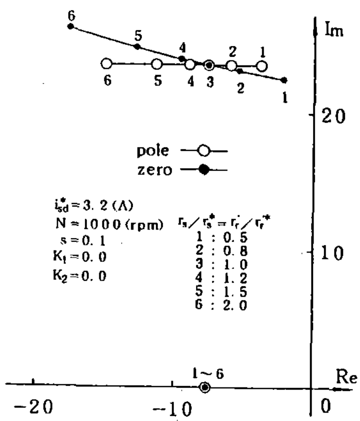


Fig.8 Trajectories of poles and zeros of the conventional vector control system.

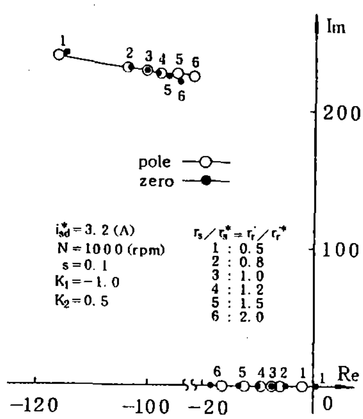


Fig. 9 Trajectories of poles and zeros of the observer based vector control system.

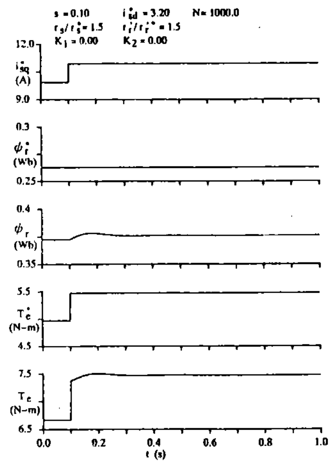


Fig.10 Transient responses for the step change of torque current command of the conventional vector control system.

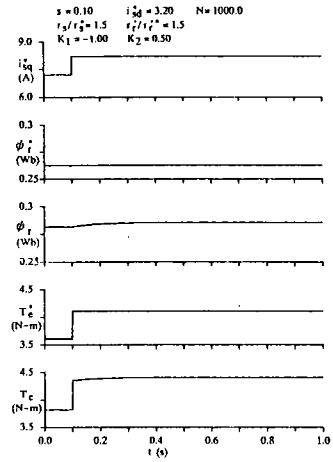


Fig.11 Transient responses for the step change of torque current command of the observer based vector control system.

figures. If the motor resistances are identified accurately ($r_s = r_s^*$, $r_r' = r_r'^*$), the actual torque T_e is equal to its ideal torque T_e^*. In the case of conventional vector control ($K_1 = K_2 = 0$), the torque error ε is especially large at $N = 1000$rpm. If the observer gains are selected adequately, the steady-state torque error is decreased sufficiently.

Trajectories of poles and zeros of the transfer function $\Delta T_e(s) / \Delta i_{sq}^*(s)$ are shown in Figs. 8 and 9 for the conventional vector control and the observer based one respectively, as a function of actual motor resistances. When $r_s = r_s^*$ and $r_r' = r_r'^*$, the poles of induction motor are completely compensated by the zeros and the torque transfer function becomes constant. In this case, a pair of complex poles shown Figs. 8 and 9 is equal to the eigenvalue of (20) surprisingly. It is recognized that the transient performance is improved by using the observer, even if the machine parameters change.

The transient responses to the step change of torque current command i_{sq}^* by 1A are computed by (27) and shown in Figs. 10 and 11. It is confirmed that the responses of the linear model agree well with those of a nonlinear model. In these figures, the amplitudes of rotor flux are computed by

$$\psi_r^* = M' i_{sd}^* \qquad (29)$$

$$\psi_r = \sqrt{\psi_{rd}'^2 + \psi_{rq}'^2} \qquad (30)$$

It is confirmed that the steady-state and transient characteristics are improved by using the observer.

5. Experimental Results

To test validity of the theoretical analysis and show the merits of the proposed method, experiments have been conducted. The experimental system shown in Fig. 12. The same induction motor described in the section 4 is used for the experiment. In order to control the stator currents, a hysteresis comparator turns on and off the transistors. The digital signal processor (DSP) TMS320C30 is used for the implementation of the control system. The sampling or interrupt period which is determined by the synchronizing signal generator µPD71054 is 256 µs. Two kinds of softwares are developed. One is an observer based vector control program written in the DSP assembly language. The other is a monitoring program for the personal computer PC9801 which is written in C language. The computation algorithm of the observer is obtained by transforming the continuous differential equations (9) - (11) to the sampled-data ones. A model following servo (MFS) controller is applied as a speed controller [6].

Figure 13 shows the transient responses of the conventional vector control system for the step change of the speed command N^{**}. The system is obtained easily by setting $K_1 = K_2 = 0$ in the observer based system. The time constant of MFS controller is 0.1 s. In order to

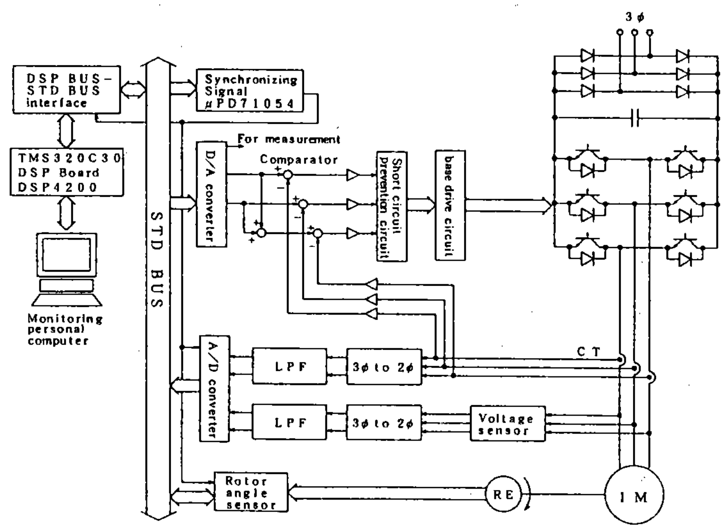
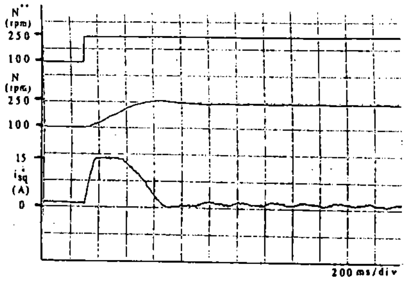
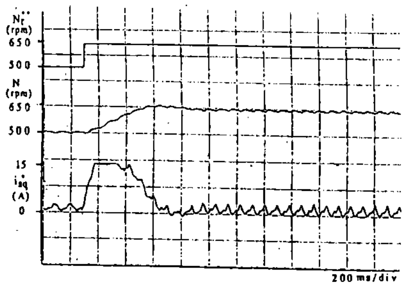


Fig.12 Setup of the experimental system.

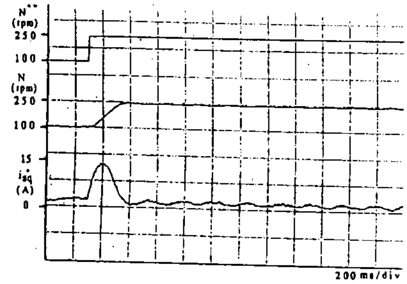


(a) N^{**} = 100rpm to 250rpm.

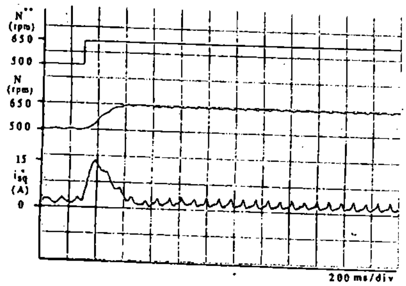


(b) N^{**} = 500rpm to 650rpm.

Fig.13 Transient responses of the conventional system.



(a) N^{**} = 100rpm to 250rpm.



(b) N^{**} = 500rpm to 650rpm.

Fig.14 Transient responses of the observer based system.

examine the effect of machine parameter change, the value of the rotor resistance in the controller is 1.5 times as much as the nominal one. The torque current command i_{sq}^* is limited to 15 A. Figure 14 shows the transient responses of the proposed method at the same condition except for observer gains $K_1 = -0.512$ and $K_2 = 0$. It is found that the speed responses of the conventional method are slower than the proposed method for lack of the motor torque.

6. Conclusions

The main conclusions drawn from this study are as follows:

(1) We proposed the flux observer based vector control system in which the current commands and the prediction error of stator voltage are used to compute the rotor flux.

(2) The proposed systems are constructed by using the models of the induction motor described by not only a stationary co-ordinate system but a synchronously rotating one. From these systems, the difference between the conventional vector control and the observer based one was clarified.

(3) The validity of the proposed method was demonstrated clearly by analytical and experimental results. Especially, the dominant poles of the proposed system are derived analytically.

Nomenclature

$*$: commanded or reference quantities

p : differential operator (d/dt)

Δ : small amount about a steady-state operating point

r_s, r_r' : stator and rotor resistances

L_s, L_r' : stator and rotor self- inductances

M' : mutual inductance

σ : leakage factor $1 - M'^2/(L_s L_r') = 0.0909$

σ_r : reciprocal of rotor time constant $r_r'/L_r' = 7.5$

$e_{s\alpha}, e_{s\beta}$: stator voltages in stationary co-ordinate system

$i_{s\alpha}, i_{s\beta}$: stator currents in stationary co-ordinate system

$\psi_{r\alpha}', \psi_{r\beta}'$: rotor fluxes in stationary co-ordinate system

e_{sd}, e_{sq} : stator voltages rotating co-ordinate system

i_{sd}, i_{sq} : stator currents rotating co-ordinate system

ψ_{rd}', ψ_{rq}' : rotor fluxes rotating co-ordinate system

ω_r : rotor electrical angular velocity

T_e : electromagnetic torque

$$C_1 = \sqrt{\frac{2}{3}} \begin{bmatrix} 0 & -\sqrt{3}/2 & \sqrt{3}/2 \\ 1 & -1/2 & -1/2 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} \cos\theta^* & \sin\theta^* \\ -\sin\theta^* & \cos\theta^* \end{bmatrix}$$

$$C_3 = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\theta^* & \sin(\theta^* - 2\pi/3) & \sin(\theta^* - 4\pi/3) \\ \cos\theta^* & \cos(\theta^* - 2\pi/3) & \cos(\theta^* - 4\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

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