IMPLEMENTATION OF ROBUST FLUX OBSERVER BASED FIELD ORIENTATION (FOFO) CONTROLLER FOR INDUCTION MACHINES

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ABSTRACT: At the end of 1988, for the first time in the world, we succeeded in the implementation of the Flux Observer based Field Orientation (**FOFO**) controller. The controller is centered about the flux observer which performs the direct coordinate transformation without using any flux sensors. The greatest advantage of this system is the extremely low sensitivity of the generated torque to changes in machine parameters. The key to our success is the desensitization of the flux observer. To this aim, we developed the novel variable pole allocation method of the flux observer. DSP is used for actual implementation.

INTRODUCTION

We can divide the high performance control strategies for induction machines into two major techniques: (1) slip frequency controlled type vector control, and (2) field orientation [1][2].

It is well known that the second method is inherently insensitive to the rotor resistance variation if the rotor flux or rotor current can be measured directly [3]. However, flux sensors can not provide a realistic solution for the use in general purpose squirrel cage induction machines.

The flux observers which estimate the rotor flux components have been investigated by many researchers [4]-[7]. However, almost all of them use only the observed flux amplitude for compensating the torque error in the slip frequency controlled type system. We have not yet seen any successful implementations where the actual flux feedback loops operate with enough stability.

Fig.1 illustrates the Flux Observer based Field Orientation (**FOFO**) controller block diagram which we proposed some years ago and succeeded in implementing recently. The flux observer plays the important role of generating the reference angle of rotor flux required for the direct coordinate transformation.

In this paper, we firstly propose a fast and robust estimation method of the rotor flux [8]-[10]. The flux observer is designed on the stator coordinate system using the Gopinath type minimum order observer theory [11]. Next, we develop the desensitization method of the flux observer to make it robust to the machine parameter variations, especially at lower rotational speed. Finally, we implement the actual controller by using DSP. We demonstrate with some laboratory results the dynamic responses of the proposed **FOFO** controller and the strong robustness of the motor torque to changes in the rotor resistance.

MODEL OF INDUCTION MACHINE

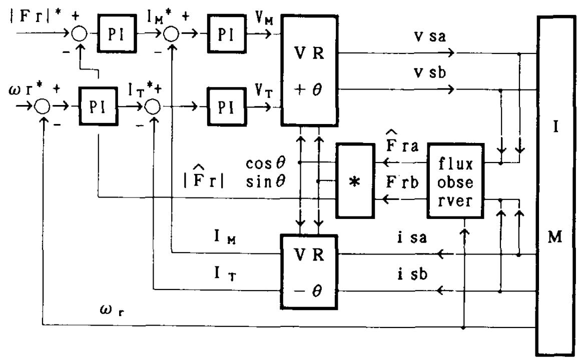
The basic circuit equations of induction machines are given by

$$\begin{vmatrix} \mathbf{v}_s \\ \mathbf{0} \end{vmatrix} = \begin{vmatrix} (R_s+pL_s)I & pMI \\ pMI-W_rMJ & (R_r+pL_r)I-L_rW_rJ \end{vmatrix} \begin{vmatrix} \mathbf{i}_s \\ \mathbf{i}_r \end{vmatrix} \quad \text{...........(1)},$$

$$F_r = M\mathbf{i}_s + L_r\mathbf{i}_r \quad \text{....................(2)},$$

where p is the time derivative.

The state and output equations are easily derived from eqs. (1) and (2) as



VR : Vector Rotator, IM : Induction Machine

$\boxed{*}$: $\cos\theta = \hat{F}ra/|\hat{F}r|$, $\sin\theta = \hat{F}rb/|\hat{F}r|$, $|\hat{F}r| = \sqrt{\hat{F}ra^2+\hat{F}rb^2}$

Fig.1 Proposed Flux Observer Based Field Orientation (FOFO) Controller.

$$(d/dt)\begin{vmatrix} i_s \\ F_r \end{vmatrix} = \begin{vmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{vmatrix}\begin{vmatrix} i_s \\ F_r \end{vmatrix} + \begin{vmatrix} B_1 \\ 0 \end{vmatrix} v_s \quad \ldots\ldots\ldots\ldots(3),$$

$$i_s = \begin{vmatrix} I & 0 \end{vmatrix}\begin{vmatrix} i_s \\ F_r \end{vmatrix} \quad \ldots\ldots\ldots\ldots(4),$$

where

$$\begin{aligned} A_{11} &= -(R_s/\sigma L_s)+R_r(1-s)/\sigma L_r)I, \\ A_{12} &= (M/\sigma L_s L_r)\{(R_r/L_r)I-W_r J\}, \\ A_{21} &= (MR_r/L_r)I, \\ A_{22} &= -(R_r/L_r)I+W_r J, \\ B_1 &= (1/\sigma L_s)I \quad \ldots\ldots\ldots\ldots\ldots\ldots(5a\text{-}e), \end{aligned}$$

$$I = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix}, \quad J = \begin{vmatrix} 0 & -1 \\ 1 & 0 \end{vmatrix} \quad \ldots\ldots(6a\text{-}b),$$

$$\sigma = 1-(M^2/L_s L_r)\text{: leakage coefficient} \quad \ldots\ldots\ldots\ldots\ldots\ldots(7).$$

The state variables are the primary current $i_s=(i_{as}, i_{bs})^T$ and the rotor flux $F_r=(F_{ar}, F_{br})^T$. The input is the primary voltage $v_s=(v_{as}, v_{bs})^T$. We can measure only i_s. Note that all variables are handled on the stator coordinate system.

BASIC DESIGN OF THE FLUX OBSERVER

The flux observer which estimates the rotor flux F_r can be designed using Gopinath's reduced order observer theory [11]. It is a combination of the flux simulator and the predictive error correction feedback.

$$\begin{aligned} F_r\hat{}\,' &= A_{21}i_s + A_{22}F_r\hat{} \\ &\quad + G[(d/dt)i_s-(A_{11}i_s+A_{12}F_r\hat{}+B_1 v_s)] \\ &= (A_{22}-GA_{12})F_r\hat{} + (A_{21}-GA_{11})i_s \\ &\quad - GB_1 v_s + G(d/dt)i_s \quad \ldots\ldots\ldots\ldots(8). \end{aligned}$$

^ means the estimated value. The block diagram is shown in **Fig.2**. In the case of no parameter variations, the dynamics of the estimation error: $e = F_r\hat{} - F_r$ take the form of

$$(d/dt)e = (A_{22} - GA_{12})e = -He \quad \ldots\ldots\ldots(9).$$

We can assign the observer poles to any conjugate complex numbers by choosing the observer gain G appropriately, because this system satisfies the observability condition.

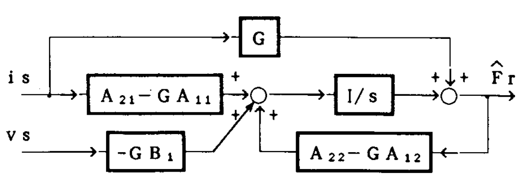


Fig.2 Configuration of the Flux Observer.

DESENSITIZATION OF THE FLUX OBSERVER

Error equation when machine parameters vary

In this section, we investigate the case where machine parameters are different from the nominal values used in the observer. When ' is attached to the actual values as

$$A_{ij}' = A_{ij} + \Delta A_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots(10),$$

the error equation (9) comes to have additional terms as

$$(d/dt)e = -He + S_1 F_r + S_2 i_s \quad \ldots\ldots\ldots(11),$$

where

$$S_1 = (H+A_{22})A_{12}^{-1}\Delta A_{12} - \Delta A_{22} \quad \ldots\ldots(12),$$

$$S_2 = (H+A_{22})A_{12}^{-1}\Delta A_{11} - \Delta A_{21} \quad \ldots\ldots(13).$$

These terms are caused by the machine parameter variations.

When we focus our the attention onto the case where only R_r varies, eqs. (12) and (13) are simplified to

$$S_1 = HA_{12}^{-1}\Delta A_{12} \quad \ldots\ldots\ldots\ldots\ldots\ldots(14),$$

$$S_2 = HA_{12}^{-1}\Delta A_{11} \quad \ldots\ldots\ldots\ldots\ldots\ldots(15).$$

From these equations, we notice that it is effective to minimize the matrix norm $|H|$ for reducing the sensitivity of the observer.

Structure of the robust flux observer

When we assign the allocation of the observer's two poles at the specified points on the complex plane:

$$-\alpha \pm j\beta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16),$$

simple optimization, to minimize the matrix norm of H, under the restriction of keeping the pole allocation of as given by eq.(16) brings us to the skew-symmetric flux observer structure given by

$$-H = -\alpha I + \beta J \quad \ldots\ldots\ldots\ldots\ldots\ldots(17).$$

Pole allocation which realizes the robust flux observer

This section is the most important part of this paper. From eqs.(14) and (15), the matrix norm of HA_{12}^{-1} represents the sensitivity of the observer to the rotor resistance variation. This norm can be calculated as

$$|HA_{12}^{-1}| = \left(\frac{\sigma L_s L_r}{M}\right)^2 \frac{\alpha^2 + \beta^2}{(R_r/L_r)^2 + W_r^2} \quad \ldots\ldots(18).$$

Eq.(18) tells us that the sensitivity increases according to the decrease of rotor speed and at $W_r=0$ this matrix norm takes its maximum value.

We propose the pole allocation to keep the norm of eq.(18) to be a constant independent of the rotor speed as

$$|HA_{12}^{-1}| = \left(\frac{\sigma L_s L_r}{M}\right)^2 k^2 \quad \text{..........(19).}$$

One more condition is required to determine both α and β. Then we put

$$\beta = 0 \quad \text{...........................(20).}$$

Immediately, we can obtain

$$\alpha = k\sqrt{(R_r/L_r)^2 + W_r^2} \quad \text{.........(21).}$$

The pole allocation represented by eqs.(20) and (21) means the duplicated pole on the real axis which guarantees the convergence of unity damping factor without any overshoot. **Fig.3** shows that the real part ($-\alpha$) of the observer poles moves according to W_r.

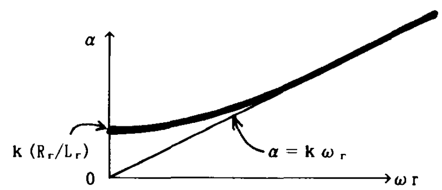


Fig.3 Pole Allocation of the Robust Flux Observer.

$$(\alpha = k\sqrt{(R_r/L_r)^2 + W_r^2},\ \beta = 0)$$

AVOIDANCE OF RIGHT HALF PLANE ZEROS TO KEEP THE TOTAL FEEDBACK SYSTEM STABLE

How should we determine the parameter k in the pole allocation eq.(21)?

In the total system of **FOFO** controller, the feedback loop exists from the estimated flux values to the inputs through the coordinate transformation. In the case where parameters vary from their nominal values, there may appear unstable zeros on the right half plane in the open loop system which can make the closed loop system unstable.

In the case with parameter variations, the induction machine system including the flux observer can be expressed as

$$(d/dt)\begin{vmatrix} i_s \\ F_r \\ \hat{F_r} \end{vmatrix} = \begin{vmatrix} A_{11}' & A_{12}' & 0 \\ A_{21}' & A_{22}' & 0 \\ A_{11}'+S_2 & A_{22}'+H+S_1 & -H \end{vmatrix} \begin{vmatrix} i_s \\ F_r \\ \hat{F_r} \end{vmatrix} + \begin{vmatrix} B_1 \\ 0 \\ 0 \end{vmatrix} v_s \quad \text{..............(22).}$$

From this state equation we can obtain the transfer function from the stator voltage v_s to the flux estimate $\hat{F_r}$. We are interested only in its numerator given by

$$[s(A_{21}'+S_2)-\{A_{22}'S_2-A_{21}'(H+S_1)\}]B_1 \quad \text{.............(23).}$$

Next, supposing that only R_r varies and removing B_1 which has no effect on the signs of right half plane zeros, eq.(23) is simplified to

$$s(A_{21}'+S_2)$$
$$-H\{A_{12}^{-1}(A_{22}'\Delta A_{11}-A_{21}'\Delta A_{12})-A_{21}'\} \quad \text{.............(24).}$$

Further we consider only the case where $W_r=0$, because the zero speed point is the severest point for this kind of robustness. Putting $W_r=0$ in eq.(24),

$$s(A_{21}'+S_2) + HA_{21}' \quad \text{.................(25)}$$

is obtained. The pole allocation of eqs.(20) and (21) at $W_r=0$ gives

$$H = \alpha I = k(R_r/L_r) > 0 \quad \text{.............(26),}$$

$$A_{21}' > 0 \quad \text{..........................(27).}$$

Hence, the condition of no right half plane zeros is given by

$$A_{21}' + S_2 > 0 \quad \text{.....................(28).}$$

Using the actual induction machine formulas:

$$A_{21}' = \{M(R_r+\Delta R_r)/L_r\}I \quad \text{...........(29),}$$

$$S_2 = A_{12}^{-1}(H\Delta A_{11}) = -(M/R_r)\Delta R_r H \quad \text{....(30),}$$

we finally obtain the relation:

$$k < 1 + (1/\delta) \quad \text{......................(31),}$$

where δ is the expected maximum ratio of the rotor resistance variation.

For example, if we estimate the maximum R_r variation to be 33%,

$$k < 4 \quad \text{.............................(32)}$$

is immediately obtained.

EXPERIMENTAL RESULTS

Experimental setup

Fig.4 shows the DSP based implementation of the **FOFO** controller. DSP is used because we need to make very fast floating point calculations (32 bits) and rapidly refer to the observer matrix table parameterized by W_r. The control period of the system is about 100 micro-seconds which is 20-50 times faster than the conventional microprocessor based system.

The name of the DSP is μPC77230 made by NEC, which has a 150[ns] machine cycle for every calculation, including 32bit floating point multiplication.

We developed two kinds of programs. One is the observer program written in the DSP assembly language which performs the real time operations of the flux observer. The other is the observer table calculation program written in C language, which generates the 259 types of different observers with respect to the rotational speed. We used the table look-up method and linear interpolation for obtaining the observers at any rotational speeds.

PC9801VX is the 80286 based personal computer which is used for: programming, compiling and execution of C-program; for programming, compiling and loading of the DSP programs; and for loading the observer data table.

The tested machine is a 4-pole 2kW induction machine which has the following parameters.

$$R_s = 0.877[\Omega],\ R_r = 1.47[\Omega],\ L_s = L_r = 165.142[mH],\ M = 160.8[mH],\ \sigma = 0.0519 \quad ....(33).$$

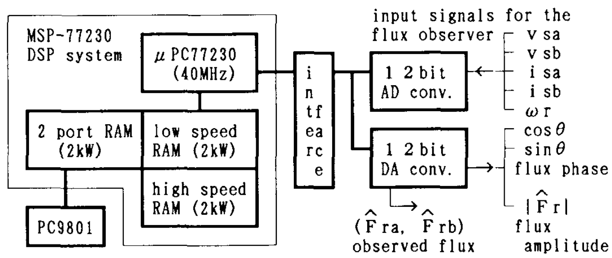


Fig.4 Setup of the Experimental System centered about DSP.

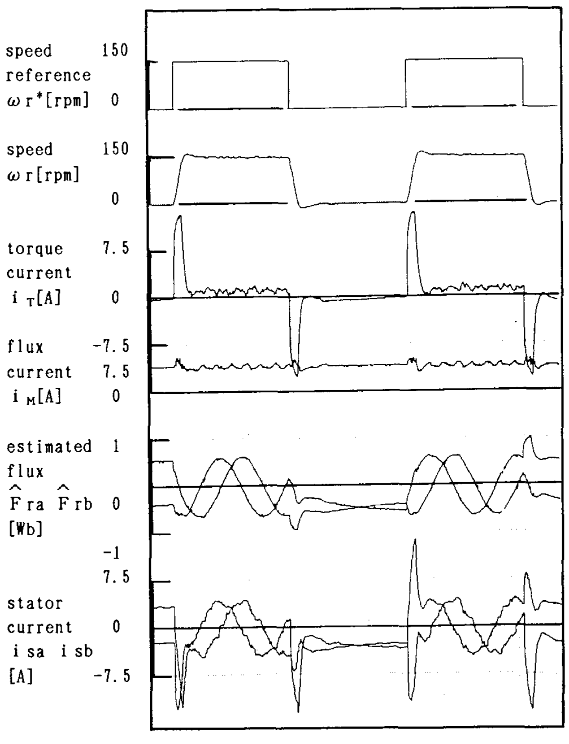


Fig.5(a) Responses of the Slip Frequency Controlled Vector Controller. (Speed reference is 1Hz rectangular waveform.)

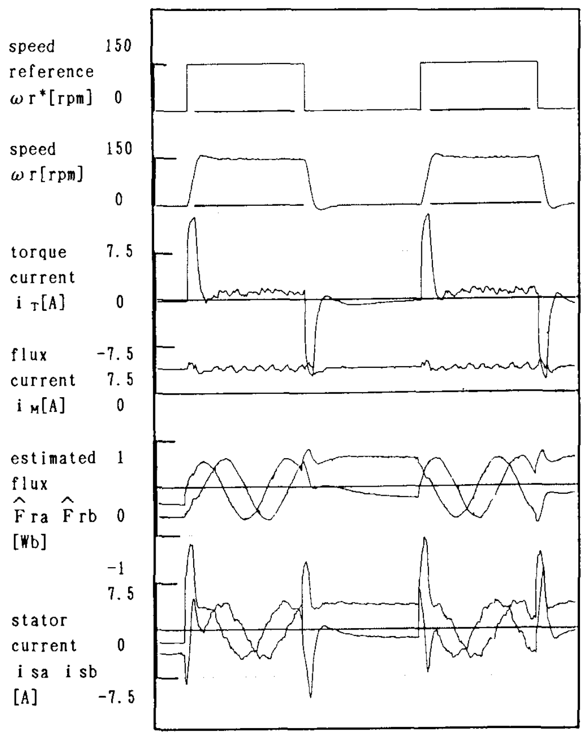


Fig.5(b) Responses of the Flux Observer Based Field Orientation (FOFO) Controller (The observer is designed on k=2.) (Speed reference is 1Hz rectangular waveform.)

Speed control responses

Fig.5(a) and **5(b)** show the speed responses of the conventional slip frequency controlled type vector controller and the proposed flux observer based field orientation (**FOFO**) controller respectively. We can not find any difference between them.

The flux components in **Fig.5(a)** are observed but not used for control. In contrast, in **Fig.5(b)**, the observed flux components are not only observed but also immediately used for the important direct coordinate transformation. Needless to say, it does not have any concept of frequency and we don't need a sine/cosine wave oscillator.

Robustness to machine parameter variation

Fig.6 is the measuring system for stationary torque errors to changes in the rotor resistance. The tested induction motor is connected to the load-side dc generator and the generation of a constant torque is commanded by the induction motor. The rotation is maintained at a constant speed by the dc machine. Apart from small friction losses the armature current of the dc motor is equal to the torque which is actually generated by the induction motor. The rotor resistance can be easily increased because we have utilized a wound rotor type induction motor.

Obtained measured data in **Fig.7** show the advantage of the proposed **FOFO** controller very clearly. In the proposed system, slight decreases in the generated torque can be observed even when the rotor resistance increases by as much as 250% of its nominal value used in the observer. In contrast to this, the slip frequency controlled type has the notorious degradation in the performance of generated torque.

Even at the point of $W_r=0$, the most severest operating condition, the **FOFO** controller can provide extreme robustness by choosing the parameter k appropriately.

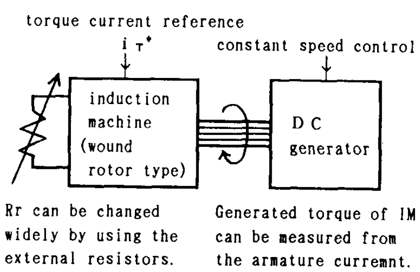


Fig.6 Measuring System for Stationary Torque Errors to Changes in the Rotor Resistance.

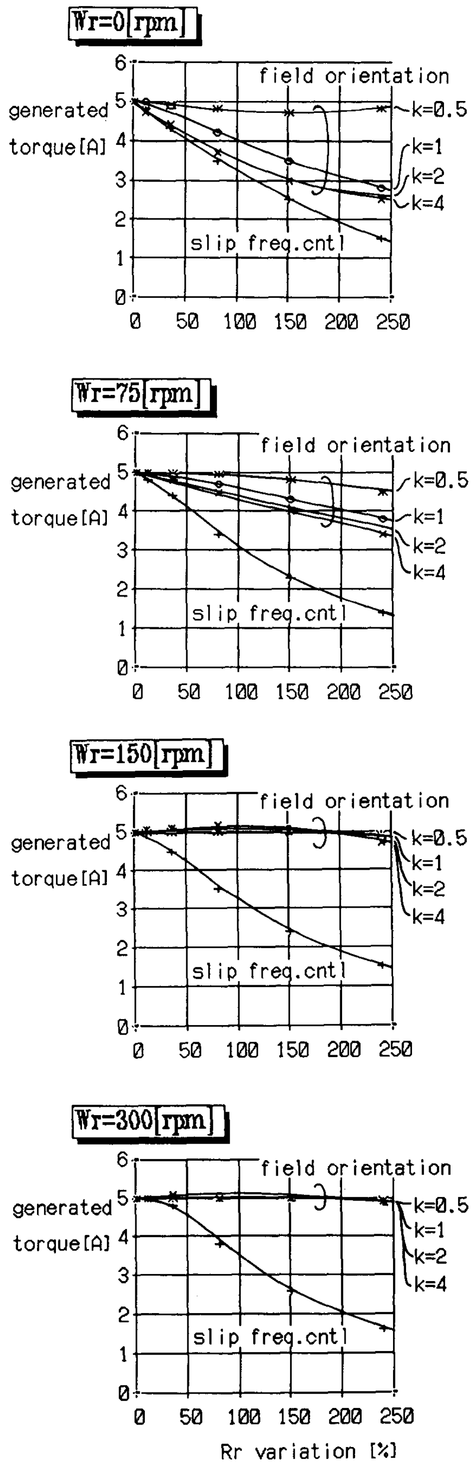


Fig.7 Stationary Torque Errors due to Changes in Rotor Resistance at Various Rotational Speeds.

CONCLUSION

We proposed and implemented the Flux Observer based Field Orientation (FOFO) controller. Its greatest advantage is its extremely low sensitivity to the machine parameter variations. Our method can provide a powerful solution to the biggest problem inherent in the conventional slip frequency controlled type vector controller.

Finally, we repeat the major reasons for our success:

(1) The flux observer is the simple Gopinath type minimum order observer designed on the stator coordinate system. The theoretical development is based upon linear state space, where the rotational speed is assumed to be constant.

(2) We developed an effective method to desensitize the observed flux against the variation of parameter variations. This is done by appropriately assigning the observer's two poles where we can keep the norm of the sensitivity matrix constant.

(3) We used DSP (Digital Signal Processor) to implement the flux observer. The control period is about 100 micro-seconds which is 20-50 times faster than the conventional micro-processor based system.

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